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CRITICAL ELEMENTS IN SITE CHARACTERIZATION

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CRITICAL ELEMENTS IN SITE CHARACTERIZATION

To design and implement a ground-water protection program that assures adequate protection of public health, welfare, and the environment, a great deal of information should be known about the site, the facility located on the site, and the setting of the site within physiographic and demographic boundaries. The process by which information having a bearing on monitoring system performance at a facility is collected, analyzed, and assimilated into requirements for system design is termed <u>site characterization</u>. Elements of site characterization include:

- Knowledge of how contamination arises, both from the facility and from other sources within the region,
- Knowledge of how contamination moves, both locally and within the region, and how the various transport systems interact, and
- Knowledge of how contamination impacts ground-water quality, as a special subset of total impacts on health, welfare and the environment.

The universe of site characterization, then, includes modules describing:

- Sources of contamination,
- Pathways for transport, and
- Impacts and effects.

Detailed knowledge of these three elements, both on a local scale and on a regional scale, would indicate that the universe is sufficiently well understood that an adequate ground-water protection strategy can be devised.

The complexity of the site characterization problem can be obtained by referring to Exhibit 1, which denotes the variety of interactions affecting a particular site study. Obviously, this document cannot address all of the possible interactions between local and regional sources, transport pathways, and potential adverse effects. In fact, the degree of detail necessary in performing various elements of site characterization will depend on the particular objectives being pursued. For example, greater depths of knowledge about the facility, the site, and the setting generally will be required in an assessment monitoring case than for detection monitoring purposes. More detailed studies also will be required for:

- Complex facilities, involving multiple and varied waste management units, waste streams, and constituents, and
- Complex settings, involving complex physiography or sensitive environments.

Rather than attempting a comprehensive discussion of site characterization, the material presented below discusses elements of the site characterization process that are considered critical to most ground-water protection problems.

Exhibit 1 Universe of Site Characterization



1. REGIONAL AND LOCAL FACILITY PROFILES

A. REGIONAL CONDITIONS

A knowledge of the regional context of a facility is important for two reasons:

- Background levels of contaminants have an effect on the level of ground-water protection necessary,
- Changes in background levels must be known if observed changes in monitored parameters are to be interpreted correctly.

Thus, it is necessary to understand major sources of contamination within the region and the properties of the region that affect transport of contaminants.

(1) Regional Sources

Any description of a facility setting should begin with a discussion of sources of both general and specific contaminants within the region. General contamination should be addressed because comprehensive analysis is necessary in assessment monitoring and because of potential chemical interactions with specific contaminants sought in detection monitoring. Thus, regional profiles of contaminants other than those observed at a particular site should be developed. For example, the presence of hydrocarbons from petroleum refineries in the region surrounding a facility could have a significant effect on the transport properties of organic waste constituents (see discussion of facilitated transport below).

In addition to an inventory of industrial facilities and contaminants found in a region, the following data should be developed:

- Maps of the site, in relation to other potential sources of relevant contaminants,
- Known or suspected contamination sources in the area other than industrial facilities (waste handling and disposal facilities, CERCLA sites, etc.),
- Regional contamination contour and ground-water maps according to aquifer classification,
- Natural sources of contamination, such as ore bodies and geologic formations.

Location and contamination maps within a region should be prepared to the same scale as geohydrologic maps. In areas where large amounts of data on contamination are available, the variability over time of contaminant levels should be analyzed. These analyses could have a significant impact on interpretations of observed variability in parameters monitored at a specific facility.

(2) Regional Conditions

Knowledge of regional geohydrology is necessary for understanding how ground-water systems originate (recharge), dynamically interact (flow), and terminate (discharge). The regional flow will dictate the direction and velocity of contaminant transport in the background and in potential impact areas of contamination from the site. In addition, the regional scale is essential in determining recharge and discharge phenomena, which play large roles in ground-water contaminant concentrations. Also, details of the regional flow system are necessary to properly evaluate the effects of other regional sources on the ground water. For example, details of recharge, discharge, and flow within the region would be required to assess the situation depicted in Exhibit 2. Only by developing a thorough understanding of the regional system (recharge, flux, water table, flow direction, flow velocity, source releases and discharge) could one properly integrate local site observations into an adequate ground-water protection strategy.

Regional considerations are particularly critical in cases where natural or man-made flow-diverting structures have a large influence on ground-water flow. Consider the case, shown in Exhibit 3, where a permeable paleochannel diverts contamination arising from regional sources and prevents their detection in the background wells for the site. The regional contamination plume, however, would be detected in the downgradient monitoring wells at the site. Note that neither the flow direction at the site nor the general regional flow pattern would predict this effect; detection of contamination in the site monitoring wells would indict the site unless details of the diversions in regional flow were known. Next, consider the same case except that an artificial flow diversion mechanism (pumping well) has been added (Exhibit 4). The induced "regional" and site flow directions would indicate that the original background and downgradient monitoring wells are now improperly located. In this case, proper interpretation of contaminant profiles has been increased in complexity.

An example of a complex flow diversion system that has been observed is depicted in Exhibit 5. Large-diameter irrigation wells effectively divert ground-water flow and contaminant migration during the period from May to October, whereas the natural flow system controls migration during the winter and spring. These effects, together with the highly permeable nature of the aquifer, resulted in several effects:

- Greater diffusion of the contaminant plume,
- An effective lowering of plume velocity and contaminant concentrations,
- Contaminant levels that were highly seasonally dependent,
- Need for dynamic (non-steady state) models, and
- Need for an exceedingly complex interception scheme for corrective action.





Exhibit 3 Influences of Regional Sources and Flow-II



Exhibit 4 Influences of Regional Sources and Flow-III



Exhibit 5 Influence of Irrigation Wells in Nebraska (Simplified)



The actual problem was considerably more complex than depicted because of the presence of several hundred irrigation wells within the region of interest, each of which was pumped intermittently.

(3) Summary

Regional sources and flow systems must be considered in developing ground-water protection strategies at a site. There are a number of points that are critical to consider:

- Sources and flow regimes should be described at least within the drainage basin encompassing the site. Often, adjacent drainage basins also must be addressed in developing an understanding of flow.
- Natural systems requiring considerable detail for proper understanding include:
 - High-permeability formations and deposits (fracturing, faulting, solution channels, paleochannels),
 - Variable interconnections of multiple aquifers,
 - Perched zones, and
 - Lakes and rivers (discharge vs. recharge),
- Manmade flow diversion can be created by numerous activities, including:
 - Water supply and irrigation systems,
 - Dams and dikes,
 - Lakes and impoundments,
 - Injection wells, and
 - Corrective actions such as slurry walls and pumping wells.
- Regional chemistry should address parameters other than specific indicator species at a site.

B. Local Facility Profiles

A great deal of information regarding the facility located at a site will be necessary to develop ground-water protection strategies. Much of the information should be readily available from facility records, process descriptions, and general geotechnical studies at a site. However, it is likely that considerable data collection and analysis will be required especially for the permitting process. Some of the critical needs for adequate site characterization purposes are described below.

(1) Waste Characterization

Both the chemical and physical properties of a waste greatly influence the magnitude of potential releases, transport, and ultimate adverse effects of contaminants. The general characteristics needed to describe ultimate effects, and other important parameters for an assessment include:

- The total composition of wastes (not just indicator constituents),
- Form and phases (liquid, solid, slurry, solution, etc.), including ancillary data such as percent solids, percent water and/or other liquids, and mixed-solvent concentration ranges,
- Chemical composition of each phase, including normal and upset concentration ranges,
- Percent organic carbon, if organic constituents are potential contaminants,
- Density and viscosity, including the presence of phases or stratigraphic variations,
- Quantities and generation/disposal rates within each waste management unit (WMU) at a facility, and
- For treatment systems, the composition, quantity, and flow rate of influent, effluent, and in-process materials should be known.
- (2) Facility Characteristics

Facility characteristics include those physical systems at a site which might influence the release and transport of contaminants. Waste handling, treatment, storage, and disposal systems must be described in enough detail that such influences can be quantified. Aspects which are critical to the ultimate ground-water protection strategy include:

- Engineering design of each facility and a description of complete facility operation,
- Geotechnical considerations such as soil type, structure, and recharge potential,
- Degree of containment within each WMU; calculation of failure modes, failure rates, and release estimates during the life of the facility,
- Siting of WMU's at a facility: topographic influences, drainage control, secondary containment, etc.,
- Influence with and relationship between other facilities and operations at a site,

- Influence of past facility and site activities and operations; history of past waste treatment, storage, and disposal opera tions, including quantities, rates, compositions, previous corrective actions, process changes, etc., and
- An analysis of current and future corrective actions required at the site.

In many cases, a fairly complete history of activities at a site may need to be developed. For example, at one facility the historical input loading of wastes to impoundments was a critical part of analyzing observed ground-water contamination. It was known that wastes had been disposed in several impoundments at the site over the past 40 years, although quantities had not been recorded. To provide input into a contaminant transport model used to analyze current contamination, future effects, and the benefits of various corrective actions, a detailed history of the disposal activities was developed, as follows:

- Current production rates of wastes were determined, according to the processes used at the site,
- Past annual production rates of wastes were estimated by comparing current and past annual product outputs, taking into consideration known changes in processes and waste handling methods,
- The history of active impoundments at the site was reconstructed from aerial photographs; allocations of wastes to simultaneously-active impoundments were made on the basis of size and other factors such as accessibility and magnitude of activity evident in the photographs, and
- The annual input loading to each of several impoundments was derived and used in the subsequent modeling effort.

The complexity of facility design and operation analyses will depend on the type, number, and location of other activities at the site. For example, a permit application is being developed for a new landfill at a site where corrective actions are underway at adjacent older landfills. Site characterization performed prior to establishing design requirements for the new landfill included:

- Evaluation of failure rates of the older landfills as a function of design,
- Estimates of failure rates for the proposed facility, as a function of design alternatives,
- Influence of current (pre-corrective action) and future (post-corrective action) ground-water contamination on the operation of a detection monitoring system,

- Assessment of total risk, and added risk from a new landfill, afforded by the site, and
- Influence of alternative corrective actions at the older landfills, in the event the current action fails, on design and monitoring requirements.

In summary, a complete description and detailed engineering analysis including the combined effect of multiple operations will be necessary for each facility. The complexity of the problem and, therefore, the amount of needed detective work, will be increased several-fold if the site has a history of operations that could affect the current or future situation.

C. Use of Conceptual Models in Site Characterization

Models, being "cartoons of reality," are depictions of a problem which are simple enough that the problem is tractable, yet contain enough detail that all important aspects are included. A conceptual model of a facility is a visual or verbal representation that summarizes essential site characteristics without unnecessarily burdening the beholder with details. The complexity needed in a conceptual model depends both on the complexity of the system being modeled and on the aspects of the problem that must be understood. For example, the conceptual model, "Atoms are miniature billiard balls," may be perfectly adequate for understanding simple gaseous diffusion, but it would not be sufficient for interpreting UV-visible spectra. In the latter case, a somewhat more complex model, "Atoms are miniature solar systems," may be sufficient. Neither conceptual model, however, would be an appropriate representation of, say, semiconductor operation or DNA molecular reproduction.

Conceptual models of a site should be developed at each stage of site characterization. An initial conceptual model of the site should be formed in response to the question: "What might I expect to find at this site?" As the description of facility, waste, and other site characteristics unfolds, the model can be "tested" against the observations and conclusions, which will show either a good fit with the model or discrepancies that require further exploration and/or more complex models. Once a site has been well-characterized, the conceptual model should at least qualitatively represent observations and expectations.

Shown in Exhibit 6 is a preliminary conceptual model of a site. Obviously, not every rock, sand grain, water molecule, and waste constituent is shown, but the rudimentary characteristics of ground-water flow, geologic fabric, and contaminant transport are represented. This model was used to develop an initial monitoring system concept. The bases for the model were:

- Inferred regional flow from topography and limited regional measurements,
- General geologic descriptions in the vicinity,
- Expected contaminant migration through glacial till and in the aquifer, and

Exhibit 6
Simple Conceptual Model



 Typical transmissive properties of regional geologic formations.

Following initial site characterization efforts, a more complex conceptual model was both necessary and possible, as shown in Exhibit 7. This concept provided a summary of observed phenomena and served as a guide for subsequent investigations.

D. Mathematical Models

In many cases, the complexity of a site cannot be adequately represented by visual or verbal conceptualizations. In many cases where a more quantitative analysis is required, mathematical treatments are necessary. Although simple cases of flow and contaminant transport can be solved analytically, mathematical models and approximate solutions are needed to address most practical situations. For detailed descriptions of flow and contaminant movement, it is essentially impossible to "keep in mind" all of the minutae that influence the results, without the aid of computer models. Although hydrologists generally do a good job of digesting facts and understanding gross features of a hydrologic system, they tend to integrate linearly and (often) irreversibly and irreproducibly. Consequently, results often contain large, hidden uncertainties, which can lead to erroneous conclusions and corrective action strategy development.

On the other hand, sophisticated mathematical models tend to demand large quantities of site characterization data. If sites are quite complex, the mathematical constructs and data input requirements can be exceedingly complex. For example, a hydrologist's conceptual model of a complex site is shown in Exhibit 8, and the finite-element grid (for one of three layers) that was required in the mathematical model of the site is shown in Exhibit 9. Obviously, a great deal of effort was required to properly characterize this site.

E. Data Needs and Data Uncertainties

Characterization of a site, especially one of moderate-to-high complexity, tends to be a phased process in which the following approach is carried through several iterations:

- Develop a conceptual model of the site,
- Conduct field investigations to confirm or refute the model, and
- Discover discrepancies between model and data, forcing consideration of more complex conceptualizations.

Only rarely and for very simple sites are all expectations fulfilled by a single round of studies. In general, a single investigation, the results of which completely support a conceptualization, is suspect as the basis for designing a ground-water protection strategy. At a minimum, a discussion of uncertainties and discrepancies in the data should be performed. Any deviation between observations and expectations based on the conceptual model or







Exhibit 9 Finite Element Model Grid



the mathematical model should be listed and explained fully. Weaknesses in the conceptualization or the mathematical treatment should be discussed.

In addition to a qualitative analysis based on expected source and flow behavior, one of the best techniques for analyzing a set of site characteristic data is by multivariate statistical analysis. For example, the techniques of kriging provide an estimate of the spatial variation in data, and an estimate of how uncertainties vary over space, without introducing biases or theories of the observer into the analysis. A kriging analysis evaluates the amount of information present in the data itself. For example, consider the case of plotting potentiometric contours from water level measurements. Any hydrologist can draw such maps by connecting points, estimating how the data would vary between observations, and generally producing an accurate representation of the hydrologic regime. However, a great deal of subjectivity goes into even the simplest of contour plotting.

Two features of the problem contribute to the uncertainty, largely in an unknown manner:

- Reliance on the hydrologist's conceptualization, which is a qualitative feature that varies with the particular observer, and
- Reliance on understanding all essential aspects of the hydrologic situation. One assumes there are no "hidden" features that make the potentiometric surface behave in an unusual manner.

Presumably, an estimate of the uncertainties could be obtained by having a large number of hydrologists independently plot the contour maps, and then analyze the differences among the results. However, this type of analysis is seldom feasible.

Kriging is an analytical method that eliminates these two problem areas by considering the variability in the data set alone. Variability in data is considered to arise from two effects: differences owing to the manner in which the physical system varies over space (systematic variability), and differences owing to improper representations and measurements (random variability). The relationship between each data point and its neighbors is considered in terms of these two elements, and the set of variations is described mathematically and analyzed statistically. In addition to producing "best" plots of the data, the method also provides maps of uncertainties in the data. Examples of kriging analysis outputs are shown in Exhibit 10.

Any differences between contour maps produced by kriging and the hydrogeologist generally will be due to measurement errors or misconceptualization (or improperly applied statistics; hydrogeologists are not always wrong!). There is a real value in hydrologists and statisticians working together to resolve discrepancies and arrive at an understanding of site characteristics. Exhibit 11 depicts a potentiometric surface produced by a hydrologist which summarizes the results of a year-long site study. Exhibit 12 shows the results of kriging the data. In this case, the kriging analysis indicated the presence of an unknown and unusual formation that governed ground-water flow in the lower left portion of the figure, a situation which was confirmed subsequently. This formation severely impacted the three-dimensional model of the site characteristics and the establishment of a corrective action at this location.

A kriging analysis can provide several benefits to processing and interpretation of site characterization data. It can:

- Identify the need for additional field measurements,
- Establish the validity of existing data,
- Produce "best fit" contour plots, digitized data surfaces, and uncertainty maps, and
- Allow selection of additional measurements to reduce uncertainties to the greatest extent.

F. Methods For Collecting Needed Data

Once data needs have been established, appropriate methods for collection of the necessary information should be identified. Exhibits 13 through 19 are typical types of data that may be needed, some of the most important uses of the data, and typical means by which these data are acquired. Not all of these data may be necessary in any given instance, but much of the information is critical to developing an adequate ground-water protection strategy. The next section discusses some of the more relevant information relating to hydrogeologic settings and ground-water impacts.

2. HYDROGEOLOGIC SETTINGS, SUBSURFACE HYDRAULICS, AND GROUND-WATER QUALITY IMPACTS

The process of characterizing a site sufficiently to resolve the placement and/or performance of a monitoring well is a complex, time-dependent study requiring application of numerous laws of physics, chemistry, and hydrodynamics. For exact treatment, many of the phenomena require application of second-order differential equations relating mass, energy or momentum, space, and time. One result of this complexity is that all but the simplest systems cannot be solved analytically. Therefore, approximations and simplifications are needed for all practical problems.

Fortunately, simplifications of the problem exist. However, under the combined effect of all the interactive processes, the problem may remain quite complex. A simplified view of the three basic processes is provided in Exhibit 20, which shows the context of the three essential time-dependent steps of contaminant release, transport through the unsaturated zone, and transport within the saturated zone. This Section focuses on critical aspects of flow and transport phenomena as they impact on ground-water quality and monitoring system design.

A. BASIC PRINCIPLES OF DARCIAN FLOW

Essential differences exist between flow of water in a surface stream and in an aquifer. Whereas stream flow is a turbulent process, ground water flows in essentially a laminar fashion. That is, flow is described by essentially

Exhibit 10 Kriging Outputs



Exhibit 11 Hand-Drawn Potentiometric Surface







EXHIBIT 13 WASTE AND FACILITY INFORMATION

Information Needed	Purpose or Rationale	Collection Method
Waste Characteristics:		
Туре	Determine physical/ chemical/toxicological properties	Site history, waste manifests, sampling
Form	Determine physical/ chemical properties	Site history, sampling
Quantities	Determine magnitude of potential releases	Site inspection
Chemical and Physical Properties	Determine environmental mobility, persistence, and effects	Handbooks, laboratory analysis
Concentrations	Determine quantities and concentrations potentially released to environmental pathways	Site history, sampling
Facility Characteristics:		
Type of Waste/ Chemical Containment	Determine potential re- lease modes, magnitude of potential releases	Site inspection, remote sensing
Integrity of Waste/ Chemical Containment	Determine probability of release	Site inspection, non- destructive testing
Drainage Control	Determine probability of release to surface water	Site inspection
Engineered Structures	Provide possible conduits for release to environ- ment	Site inspection
Site Security	Determine potential for release by direct contact	Site inspection
Known Discharge Points (Outfalls, Stacks)	Provide points for acci- dental or intentional discharge	Site inspection

EXHIBIT 14 - GEOLOGIC INFORMATION

Information Needed	Purpose or Rationale	Collection Methods
Structural Features:		
Folds, Faults	Delineate barriers or ground-water flow controls and recharge/discharge areas	Existing geologic maps, field mapping, surface and subsurface geophys- ical techniques, drilling, coring, and sampling boreholes
Joints, Fractures, Interconnected Voids, Solution Channels	Predict major boundaries, avenues of ground-water flow	
Stratigraphic Characteristi	.cs:	
Thickness, Aerial Ex- tent, and Correlation of Units	Determine geometry of aquifers and confining layers, aquifer recharge and discharge	Existing geologic maps, field mapping, surface and subsurface geophys- ical techniques, drilling, coring, and sampling boreholes
Mineral Composition, Grain-Size Distribu- tion, In-Situ Density, and Moisture Content	Determine ground-water quality, movement, occur- rence, productivity, and extent (horizontal and vertical) of aquifers and confining units	Laboratory analysis of field samples obtained from boreholes, and existing literature

EXHIBIT 15 HYDROLOGIC INFORMATION

Information Needed	Purpose or Rationale	Collection Methods
Ground-water Occurrence:		
Aquifer Boundaries and Locations	Define flow limits and potential recharge/dis- charge areas, degree of confinement	Stratigraphy and struc- ture data from well logs, water level mea- surements in monitor wells and piezometers
Aquıfer Ability to Transmit Water	Delineate the potential quantities and rate of contaminant transport and feasibility of remedial actions	Pumping and injection tests of monitoring wells
Ground water Movement:		
Direction of Flow	Identify pathways of contaminant migration	Water level measure- ments in monitoring wells
Rate of Flow	Determine maximum poten- tial migration rate and dispersion of contaminants	Hydraulic gradient, permeability, and effective porosity from water level con- tours, pump test re- sults, and laboratory analyses

Ground-water Recharge/Discharge:

Location of Recharge/ Discharge Areas	Delineate areas of water inflow and outflow in the ground water system which is important to contami- nant movement	Compare water levels in monitoring wells, piezometers, lakes and streams
Rate	Calculate unit volume of water moving through aquifer(s)	Water balance calcula- tions aided by geology and soil data

Ground-water Quality:

pH, Total Dissolved	Determines if aquifer is a	Analysis of groundwater
Solids, Dissolved Or-	potential or actual drink-	samples from monitoring
ganics, Salinıty,	ing water source, may help	wells
Specific Contaminant	define contaminant plume(s)	
concentrations		

EXHIBIT 16 SURFACE WATER INFORMATION

	Information Needed	Purpose or Rationale	Collection Methods
Drai	inage Patterns:		
	Overland Flow, Topo- graphy, Channel Flow Pattern, Tributary Relationships	Determine if overland or channel flow can result in on-site or off-site flow, and if patterns form contaminant pathways	Topographic maps, aerial photographs, and site visits
Sur	face Water Bodies:		
	Flow, Stream Widths and Depths, Channel Elevations, Flooding Tendencies	Determine volume and velocity, transport times. dilution potential, and potential spread of contamination	Public agency data catalogs, maps and handbook for background data, perform field studies for site- specific areas
	Structures	Determine if manmade structures affect contam- nant transport	Public agency maps and records
	Surface Water/Ground- water Relationships	Establish areas of "losing" and "gaining" surface waters to predict contami- nants pathways and deter- mine remedial action	Public agency reports and surveys
Sur	face Water Quality:		
	pH, Temperature, Total Suspended Solids, Sus- pended Sediment, Dis- solved Organics, Nutrients, Salinity, Tubidity, Specific Contaminant Concentra-	Provide a baseline and in- formation on the capacity of the waterway to carry contaminants	Public agency (pri- marily Federal) data storage systems, and handbooks

tions

EXHIBIT 17 GEOCHEMICAL AND SOILS INFORMATION

Information Needed	Purpose or Rationale	Collection Methods
Soil Characteristics:		
Type, Holding Capacity, Temperature, Chemical and Sorptive Proper- ties, Biological Activity, Engineering Properties	Estimate the effect of the properties on infiltration and retardation of leach- ates and the release of gaseous contaminants	Reports and maps by Federal and county agencies, primarily the Soil Conservation Service (SCS)
Unsaturated Zone Characteris	stics:	
Permeability, Varia- bility, Porosity, Moisture Content, Chemical Character- istics, and Extent of Contamination	Estimate of leachate transport which is sensi- tive to the physical and chemical properties of the host media	Existing literature, primarily SCS, bore- hole logs, geophysi- cal surveys
Soil Chemistry Characterist:	ics:	

Solubility, Ion	Predict contaminant	Chemical 'analysis, col-
Speciation, Adsorption	movement through soils,	umn experiments, leach-
Coefficients, Leach-	and availability of con-	ing tests
ability, Exchange	taminants to biological	
Capacity, Mineral	systems	
Content, Partition		
Coefficients		

EXHIBIT 18 ATMOSPHERIC INFORMATION

Information Needed	Purpose or Rationale	Collection Methods
Local Climate Trends:		
Precipitation Temperature Wind Speed and Direction Cloud Cover and Solar Radiation Presence of Inversion Layers	Define important pathways for transport by defining recharge, Aeolian erosion, and evaporation potential Weather patterns will affect hydrology	National Climate Center (NCC) of National Oceanic Atmospheric Administration, local weather bureaus
Weather Extremes:		
Storms Floods Winds	Evaluate potential for and consequences of weather extremes	NCC, State Emergency Planning Offices
Hazardous Air Pollutants	Concentrations of hazard- ous pollutants indicate potential pathways of transport and form a base- line for monitoring	Local Air-Monitoring station, EPA reports, and data bases
Release Characteristics of Air Pollutants:		
Direction and Speed of Plume Movement Rate, Amount, and Temperature of Release Nature of Contaminant Relative Densities	Characterize the plume movement and the popu- lation it will affect	Release facility, weather services, and direct méasurement

EXHIBIT 19 ENVIRONMENTAL AND HEALTH INFORMATION

Information Needed	Purpose or Rationale	Collection Methods
Fauna and Flora	Determine presence of plants and animals that may be consumed by man; Determine presence of endangered species	Public records of area plants and animals Survey of plants and animals on or near site
Critical Habitats	Determine if there are areas on or near the site that must be protected	Public records of site environment Survey of site
Land-Use Character- istics	Determine if terrestrial environment could result in human utilization of land; e.g., presence of game animals, agricultural land	Ara maps and survey of site
Water-Use Character- istics	Determine if aquatic en- vironment on or near site could result in human utilization of water; e.g., presence of game fish, recreational waters	Area maps and survey of site
Water-Wells	Health impacts	Public records and site survey
Human Density	Human health risks	Maps and site survey, EPA data bases, census data

Exhibit 20 Flow and Transport Characteristics



straight lines (at least over short distances). The basic empirical relation describing flow is Darcy's law, which may be written in terms of flux (V) as:

 $V = K \Delta h / \Delta X$

where: K = hydraulic conductivity h = hydraulic head X = distance of flow path.

Thus, $\Delta h/\Delta X$ = hydraulic gradient.

Also, $K = \frac{k d g}{\mu}$

where: k = permeability, d = density, $\mu = viscosity,$ and g = acceleration due to gravity.

Finally, the flow velocity v_{i} is given by:

v = V/n

where: n = porosity = volume of voids/total volume.

Almost all flow problems can be solved using one or more variations of Darcy's law, if the various factors can be measured or predicted. Some practical aspects of the most important terms are as follows:

- <u>Hydraulic conductivity</u>, K, is the proportionality constant relating hydraulic gradient to flux. It is a measure of the ease with which fluids will pass through a formation and, thus, is dependent both on the fluid and the formation properties. <u>Permeability</u>, k, on the other hand, is a property only of the formation. <u>Transmissivity</u>, for a confined aquifer, is the hydraulic conductivity times the aquifer thickness. Exhibit 21 shows how hydraulic conductivity may vary for flow of water through various formations.
- <u>Porosity</u>, n, as the ratio of pore volume to total volume, is actually the <u>bulk porosity</u> of the formation. However, not <u>all</u> pores in a formation are involved in the transport of water. The <u>effective porosity</u> represents the fraction through which water can pass; i.e., it is the "drainable" porosity. Materials may have a high bulk porosity but very low effective porosity and permeability if the pores are not connected. Fractured formations may have low porosity but high permeability.
- The principal driving force behind ground-water flow is the <u>hy-</u> <u>draulic gradient</u>, or the difference in hydraulic head per unit distance. Head is the force exerted on a water molecule by gravity and other more complex factors. The hydraulic gradient is a vector quantity and affects both the magnitude and direction of ground-water flow.

EXHIBIT 21

Aquifer Hydraulic Conductivity Variations

Generic Classification	Data Range in Orders of Magnitude	Mean Value, cm/s
Fractured crystalline silicates	3.0	1.53 x 10 ⁻³
Fractured-solutioned carbonates	4.0	6.42 x 10 ⁻²
Porous consolidated carbonates	4.6	1.16 x 10 -2
Porous consolidated silicates	3.0	1.79 x 10 ⁻³
Porous unconsolidated silicates	5.9	5.55 x 10 -2
Fractured consolidated silicates-shale	4.0	2.4 x 10 ⁻³
- The <u>flux</u>, V, is the quantity of water flowing through a formation per unit cross-sectional area. Flux differs from the <u>flow velocity</u>, v, because the formation is not totally porous.
- The <u>potentiometric surface</u> is a map of the hydraulic head in a confined aquifer. The <u>water table</u> is the elevation where fluid pressure equals atmospheric pressure, in the uppermost aquifer. Analysis of flow using these concepts assumes that flow is completely horizontal. It is preferable to analyze flow using equipotential surfaces (and lines, for cross-sections). Flowlines are perpendicular to equipotential surfaces. The resulting diagrams are called flow nets. Flow-net analysis requires that the hydraulic head be mapped or estimated throughout the subsurface volume of interest.

B. MEASUREMENT OF HYDROLOGIC PARAMETERS

Even the simplest of ground-water systems requires either measurement or estimation of hydraulic gradient, hydraulic conductivity or permeability, and porosity. Of these parameters, only porosity varies over a narrow enough range to be estimated reasonably accurately; estimates from literature values likely will not vary more than 50 percent from actual values. About the only precise method for measuring porosity is by use of tracers in <u>in situ</u> measurements. However, measurements of reasonable accuracy can be made in the laboratory.

The hydraulic conductivity can vary over about 12 orders of magnitude and typically can vary over 2 to 4 orders of magnitude at any given site. In fact, the hydraulic conductivity will vary greatly depending on the exact location and the manner in which it is determined. Generally, K is determined by well testing, either by slug tests or, more accurately, by pump tests. Models and equations exist for relating the actual field measurements (drawdown, water level rise and fail) to conductivity or permeability. However, considerable uncertainties may exist even under the best of circumstances, for the following reasons:

- Data analysis methods are based on theoretical conditions which may not prevail at the point of measurement (improper selection of analytical methodology),
- Derived conductivities are valid only within the vicinity of the measurements and may vary widely across a site (sampling error too large), or
- Derived hydraulic conductivities may depend on the method of drilling and installing wells (uncertainties in the actual property being measured).

As an example. Exhibit 22 shows the range of transmissivities obtained from well tests at the same site. It is noted that the reported values vary by about four orders of magnitude, and there is a statistical difference between the two methods of well installation. Other observations from this experience include:

Exhibit 22 Transmissivity Distribution for Rotary Wash and Air Drilled Wells



- Well tests in large-diameter wells generally provide more consistent data,
- Longer-duration tests generally provide more representative data,
- Wells drilled by air rotary methods provide better data than those drilled by mud rotary techniques, and
- Pump testing is preferable to slug testing because a greater portion of the subsurface is tested, and the measurements are more controllable.

Hydraulic gradients are obtained by mapping hydraulic head (water levels in monitoring wells) across an area or region. The gradient, or the slope of these surfaces, is a valid concept only if the measurements are time equivalent and stratigraphically equivalent.

C. HYDROGEOLOGIC SETTINGS; FACTORS AFFECTING GROUND-WATER OCCURRENCE AND FLOW

A hydrogeologic setting is a composite description of major geologic and hydrologic factors which affect and control the occurrence and movement of ground water. In simple terms, a hydrogeologic setting is a mappable unit with common hydrogeologic characteristics. The setting provides a reasonable ini- tial conceptual model of a region.

A number of physical characteristics affect the movement of water into, through, and from an area. The major controlling features, for which data must be available in order to analyze ground-water problems, are:

- <u>Geologic structure</u>, or the occurrence of formations and strata which can either hold and transmit water, or which can act as aquitards, is a key controlling factor. Grain size and fracturing affect the porosity, slope can affect the hydraulic gradient, and mineral content can affect ground-water quality.
- <u>Recharge</u> is the input of water to an aquifer. The primary source of ground water is precipitation which infiltrates through the surface of the ground and percolates to the water table. Net recharge indicates the amount of water per unit area of land which penetrates the ground surface and reaches the water table. This recharge water is thus available to transport a contaminant vertically to the water table and horizontally within the aquifer. In addition, the quantity of water available for dispersion and dilution in the vadose zone and in the saturated zone is controlled by this parameter. Recharge generally occurs more readily in areas with unconfined aquifers than in areas with confined aquifers. A secondary source of recharge is the infiltration of water from surface streams.
- <u>Discharge</u> from an aquifer can occur to other aquifers or to the surface in springs, seeps, or streams. The location of discharge points and estimates of the discharge rate are important to an analysis of flow problems.

- The <u>topography</u>, or the slope of the land at a site, is useful in estimating ground-water flow. Gradient and direction of ground-water flow can often be inferred for the water table aquifer from the general slope of the land. Typically, steeper slopes signify higher ground-water velocity. Topography also influences soil development and, hence, affects contaminant attenuation and is a key controlling factor in determining runoff versus recharge.
- <u>Depth to ground water</u> is the depth to the water surface in an unconfined aquifer or to the top of the aquifer where the aquifer is confined. The water surface is the point where all the pore spaces are filled with water. As shown in Exhibit 23, the depth to water determines the depth of material through which a contaminant must travel before reaching the aquifer.

D. NATURAL FACTORS AFFECTING WATER QUALITY

In addition to other human activities in a region, a variety of naturallyoccurring phenomena can affect the quality of ground water at a site. Those factors which are especially important in establishment of ground-water monitoring programs are:

- <u>Dissolved Inorganic Constituents</u>. Principal constituents include bicarbonate, silicates, chloride, sulfate, sodium, magnesium and calcium ions, and carbon dioxide, but hundreds of potential contaminant species are possible. These materials may be leached from geologic formations or introduced by infiltration of water from the surface. Key parameters describing the dissolved species (in addition to specific analyses) are the total hardness, total alkalinity, and total dissolved oxygen. In addition to including many regulated contaminant species, dissolved inorganic materials affect the pH, redox potential, and ionic strength of ground water, all key parameters in evaluating contaminant transport.
- <u>Dissolved Gases</u>. The most important dissolved gases are oxygen, carbon dioxide, methane, and hydrogen sulfide. These gases are indicators of geochemical conditions (e.g., redox potential) in the ground water.
- <u>Dissolved Minerals</u>. Ground water in the vicinity of ore bodies can leach significant quantities of iron, arsenic, lead and other contaminant species. These contaminants are generally setting-specific.
- <u>Dissolved Organics</u>. Organic materials, principally fulvic and humic acids and other products of bacterial action and decay (including hydrocarbons), may be found in trace to significant quantities in ground water. These species may play a key role in complexing and solubilizing inorganic constituents. At a minimum, the total organic carbon content of the ground water should be specified.

Exhibit 23 Depth to Water in a Confined and Unconfined Aquifer



Natural factors can affect the chemical nature of ground water as a medium for dissolution and transport of contaminants, as well as the utility of the water for consumption, recreational and agricultural purposes. For example, streams and shallow ground water in some regions of Colorado are highly acidic (pH = 4), making it unfit for consumption and a good leaching medium (better than the Toxicity Characteristic Leaching Procedure) for hazardous constituents from minerals. Similarly, ground water may be high in alkali (southwest U.S.), organic matter and sulfur (Louisiana), iron and sulfur (Ohio Valley), or various carbonates (Blue Ridge region).

E. GROUND-WATER FLOW SYSTEMS IN VARIOUS HYDROGEOLOGIC SETTINGS

Various classification schemes have been developed to describe the occurrence and availability of ground water. Among the most useful of these are geographic systems encompassing hydrogeologic settings, such as the classical regional system shown in Exhibit 24. Example descriptions of flow regimes in some of these regions are described below.

Region 3. Columbia Lava Plateau (Exhibit 25)

This region occupies northeastern California, eastern Washington, southern Idaho, and northern Nevada. This area is underlain by a thick sequence of lava flows interbedded with unconsolidated deposits and is overlain by thin soils.

Depth to the ground water generally ranges from 5 feet to 100 feet with an average around 50 feet. The large sequence of lava flows is the principal water-bearing unit. Movement of ground water occurs primarily through the interflow zones. Hydraulic conductivity commonly ranges from 200 to 3,000 m/day. The recharge rate ranges from 5 to 300 mm/yr (0.2 to 10 in/yr) with recharge occurring through losing streams and discharge occurring through springs and seepage. Topography of the plateau ranges from 2 percent to 18 percent with an average of 5 percent.

Region 6. Nonglaciated Central Region (Exhibit 26)

The geographical area of this region extends from the Appalachian Mountains in the east to the Rocky Mountains in the west. The topography is complex, ranging from valleys and ridges to the Great Plains. The surface is mostly underlain by thin regolith over fractured sedimentary rocks. Ground water is obtained primarily from fractures in the bedrock. Depth to the ground water ranges from 5 feet to 100 feet with an average of approximately 30 feet. Hydraulic conductivity commonly ranges from 3 to 300 m/day. The recharge rate ranges from 5 to 500 mm/yr (0.2 to 20 in/yr) with recharge occurring upland between streams and discharge occurring through springs and into other aquifers. The topography of this region ranges from 0 to 12 percent with an average of approximately 6 percent.

Region 8. Piedmont Blue Ridge Region (Exhibit 27)

This region extends from Alabama in the south to Pennsylvania in the north. The Piedmont part of the region consists of low hills and ridges,







Hydrogeologic Cross-Section A-A'

EXHIBIT 26

Major aquifers in the continental United States



Exhibit 27 Typical Piedmont Flow System



whereas the Blue Ridge part of the region is mountainous. The area is underlain by thick regolith over fractured crystalline and metamorphosed sedimentary rocks. The depth to the ground water is variable, ranging from 5 to 100 feet. Ground water is obtained from the regolith and fractured bedrock. Yields to wells are generally small with hydraulic conductivity ranging from .001 to 1 m/day (.003 to 3 ft/day). Recharge occurs in areas above stream flood plains and rates range from 30 to 300 mm/yr (1 to 10 in/yr). Discharge occurs as seepage springs.

Region 12. The Hawaiian Islands (Exhibit 28)

The Hawaiian Islands are underlain by lava flows segmented in part by dikes, interbedded with ash deposits, and partly overlain by alluvium. Basal ground water floats as a lens-shaped body on underlying seawater and it is the principal source of ground water on the islands. Ground water also can be perched in dike-bounded compartments. Depth to the ground water is quite deep, around 800 feet. The ground water system is recharged by precipitation with the recharge rate ranging from 30 to 1000 mm/yr (1 to 40 in/yr). Hydraulic conductivity is high, ranging from 200 to 3,000 m/day (500 to 10,000 ft/day).

3. CONTAMINANT PROPERTIES AFFECTING TRANSPORT

As discussed previously, a key aspect of the site characterization process is understanding and predicting the movement of contaminants in ground water. The previous sections have focused on determining how, where, and how fast ground water moves. These factors are vital because ground water provides the transport medium for the contaminants. There are a number of other properties, however, which must be considered because of their impact on contaminant movement. These properties are independent of the properties which affect ground water movement and include chemical properties of the aquifer media as well as chemical and physical properties of the contaminants themselves. This section will identify those properties, discuss why these properties are important, and explain how data on these properties can be obtained.

A. Physical Properties

Physical properties of interest include density, solubility, viscosity, and surface tension. The importance of each of these properties and illustrative examples are discussed below. Density

Density is an important property because it determines whether a contaminant will float or sink. Such a determination is important in conceptual model development for addressing the question, "Where do I look for contaminants?". Just as with surface water, contaminants which are less dense than water will float on the surface of the water, requiring that the surface of the water be monitored. Those contaminants which are more dense will sink, requiring that the bottom of the water column be monitored.

Consideration of density effects in developing a monitoring program is illustrated in the following example. Suppose that a hydrologic characterization has determined that a site is located in an active discharge zone and

EXHIBIT 28



GROUND-WATER OCCURRENCE AND DEVELOPMENT IN A TYPICAL VOLCANIC ISLAND.

that there is a net upward movement of water, as shown in Exhibit 29-A. If it is assumed that contaminants will move as the water moves, one would expect that contaminants introduced at the surface would remain near the ground-water surface and be transported toward the discharge point. It would reasonably be expected that monitoring would only have to occur at the ground-water surface in order to detect any migration of contaminants from the site. If, however, the contaminants are more dense than water (e.g., chlorinated solvents), they will tend to migrate downward in spite of the upward ground water gradient, as shown in Exhibit 29-B. In such cases, monitoring at the surface of the ground water might be necessary to detect release of contaminants from the facility while monitoring at the bottom of the aquifer would be necessary to assess the extent of the contaminants less dense than water (e.g., light hydrocarbons) remaining on the surface of the water regardless of a net downward movement of ground water.

While density effects are most pronounced with contaminants that do not mix well with water (i.e., contaminants that either float or sink), these effects can also occur with mixtures or solutions of contaminants and water. The latter most commonly occurs with highly soluble ionic wastes (i.e., salts) which can dissolve in water to such an extent that the resultant solution is more dense than the ground water and will sink. As the dense plume sinks, however, it undergoes mixing with ground water which serves to reduce the density of the plume and reduces the density effects.

As an example of the above, consider the conditions in Exhibit 29 with a dense inorganic plume. As the plume leaves the site, density effects cause it to be drawn downward against the ground-water flow. As it sinks, it is subject to some lateral movement from the horizontal component of the ground-water velocity. In addition, by flowing counter to the ground water, the plume is subject to mixing with the uncontaminated ground water. As mixing occurs, the density of the plume is reduced to the extent that it cannot overcome the upward flow and begins to rise. This situation is illustrated in Exhibit 30. As shown in this exhibit, it is possible for the plume to miss both shallow and deep monitoring wells.

Data on the density of contaminants are generally obtained from published sources but are easily determined in the laboratory. Laboratory determination might be appropriate if the waste consists of a mixture of chemicals since published data generally give only the densities of individual contaminants. In determining the density of waste mixtures, it is important to consider whether the mixture will separate after release to water. (Separation can be determined by simple testing in the laboratory.) If separation occurs, it will be necessary to determine the density of each component of the waste.

Solubility

Solubility is an important property to consider during site characterization. In terms of developing or testing a conceptual model, solubility effects are related to the question "How much contaminant should I look for?". That is, solubility determines how much of the contaminant can be transported by the water. In addition, solubility concerns can also affect

Exhibit 29 Contaminant Movement in Discharge Area



Exhibit 30 Movement of Dense Soluble Contaminant Plume in Discharge Area



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the answer to the question "Where do I look for the contaminant?". If the mass of contaminant introduced to the water is greater than the amount that can be dissolved by the water, the difference must go somewhere and must be accounted for by the monitoring program.

The effects of solubility are illustrated in the following examples. Suppose a contaminant having a solubility of 100 mg/L is leaking from a facility at a rate of 1 kg/day. The ground-water flow is such that 1,000 L/day flow beneath the site and mix with the contaminant before reaching the site boundary and monitoring wells, as shown in Exhibit 31. Dividing the contaminant flux by the ground-water flux yields an average expected contaminant concentration at the monitoring well of 1,000 mg/L, or 10 times the solubility limit. Because the solubility cannot be exceeded, the other 900 mg/L or 0.9 kg/day will form a second phase, separate from the water. Several things can happen to this second phase. If the contaminant is denser than water, it may sink and miss the monitoring well. If the contaminant is approximately the same density as water, the second phase may be carried along with the water but at a different velocity because of differences in viscosity.

Solubility effects must also be considered in assessing the monitoring data. In the above example, an analyst might look at the monitoring results and plume size and conclude that 0.1 kg/day of contaminant are being released from the site. Corrective actions based solely on these data would not address 90 percent of the released contaminant.

Consideration of solubility effects is particularly important when dealing with inorganic (i.e., metallic) contaminants. Phase separation with inorganic contaminants usually involves precipitation of the contaminants onto soil or aquifer media. That is, if the solubility limit is exceeded, the contaminant will transfer to the solid phase rather than remain with the liquid. In the above example, the 0.9 kg/day excess of contaminant would accumulate on the aquifer material beneath the site. In performing assessment monitoring, therefore, it would be important to sample the soil and aquifer media beneath the site.

Consideration of geochemical interactions is an important aspect of determining contaminant solubility. When introduced to ground water, contaminants, especially inorganic contaminants, can undergo a number of simultaneous chemical reactions until an equilibrium concentration is reached. These reactions include dissolution/precipitation, oxidation/reduction, complexation, ion exchange, and adsorption. The net result of all these reactions is that the contaminant remains in solution in any of a number of possible forms and amounts. This solubility is dependent on the amount of contaminant present, the pH, oxidation/reduction potential (Eh), and temperature of the ground water, and the concentration of other ionic species in the ground water. Exhibit 32 presents an example of the solubility of various chromium species under specific oxidizing conditions. Exhibit 33 shows the solubility of various chromium species under specific reducing conditions. A comparison of Exhibits 32 and 33 shows tremendous differences in overall solubility and in the identity of the species which are most soluble.

Exhibit 31 Mixing of Release and Flux to Produce Downgradient Concentration



Exhibit 32 Solubility of Various Chromium Species Under Reducing Conditions



Exhibit 33 Solubility of Various Chromium Species Under Oxidizing Conditions



The effects of geochemical reactions on site monitoring can be illustrated by considering the following example. A leaking storage impoundment contains acidic chrome plating wastes. Because of the acidic and oxidizing nature of the wastes, chromium is present in high concentrations in the hexavalent form. As the plating waste migrates downward through the soil column it remains in the hexavalent form because of the oxidizing conditions found in the soil. The chromium concentration is reduced somewhat, however, because of reactions with soil minerals. Upon entering ground water, the wastes encounter reducing conditions and the hexavalent chromium is reduced to trivalent chromium, which is much less soluble. After undergoing further reactions with the minerals in the aquifer media and the chemicals in the ground water, the amount of soluble chromium remaining is below the analytical detection limit. Under these conditions, the presence or absence of chromium in ground water could not be used to determine whether or not the impoundment was leaking.

The solubility of organic contaminants is usually obtained from published values, but can be determined in the laboratory with relative ease. Special care must be given when determining the solubility of organic mixtures. With mixtures, the organic chemical may dissolve in each other as well as in the water, giving results much different than the water solubility alone. The solubility of such mixtures should be determined by laboratory measurement.

Determination of the solubility of inorganic contaminants is more complex, particularly with those contaminants undergoing numerous geochemical interactions. Published solubility data can generally be used with simple salts which are highly soluble and not very reactive (e.g., sodium sulfate). For other contaminants, the geochemistry must be evaluated under site specific conditions. As expected, evaluation of the numerous geochemical reactions which can occur can be exceedingly complex, particularly when there are a number of contaminants present. Such evaluations are best made with the use of geochemical computer models. Exhibit 34 shows the output of one such model. This exhibit represents one of a series of simulations performed to evaluate the fate of inorganic contaminants in landfill leachate upon reaching ground water. These simulations were performed for specific ground-water conditions of pH, Eh, temperature, and ionic composition. The horizontal axis represents the concentration of copper in the leachate as it enters the ground water. The vertical axis represents the final copper concentration after the contaminant has reached equilibrium. In the example shown in Exhibit 34, an initial contaminant concentration of 25 mg/l will be reduced to 12 mg/l by geochemical reactions. In addition, the contaminant concentration can never exceed 19 mg/l under these conditions regardless of how much contaminant is introduced to the aquifer.

Viscosity

Viscosity can be an important consideration for those contaminants which are immiscible with water and form separate phases. In these cases, the viscosity of the contaminant will determine how rapidly the contaminant is transported through the aquifer media. Such considerations are important for designing monitoring programs, evaluating monitoring data, and designing corrective actions. For example, consider a release of an immiscible contaminant from a site. Assessment monitoring will be needed to determine the impacts of

Exhibit 34 Reduction of Copper Concentrations from Unsaturated Zone to Saturated Zone



that release. The determination of impacts will require an evaluation of the time required for the contaminant to reach possible receptors. The hydrologic characterization will define the ground-water velocity, but if the contaminant has a different viscosity than water, it will move at a different velocity and affect the travel time estimates.

As discussed earlier, the permeability of the aquifer material is a measure of how easily fluid can pass through the medium. Permeability is an intrinsic property of the medium and is independent of the fluid passing through. Because water is typically the fluid passing through the medium, permeability is often replaced by a related term, hydraulic conductivity. Unlike permeability, hydraulic conductivity is applicable only to fluids having the viscosity of water. In order to determine the rate of flow of fluids other than water, therefore, the viscosity of the fluid must be known.

Viscosity values have been published for many contaminants. Viscosity also can be measured in the laboratory with relative ease. Laboratory measurement should probably be performed with mixtures of chemicals since the viscosity of the mixture is likely to be different than the viscosity of any of the components.

Surface Tension

Surface tension is an important property for evaluating the migration of contaminants that are immiscible with and less dense than water. The surface tension of a contaminant determines the degree to which a chemical will spread and how strongly the contaminant will be drawn into the unsaturated soils by capillary forces. The greater the surface tension of the contaminant, the less it will spread on the surface of the water. Such considerations would be important in evaluating the impacts of contaminant releases and in designing assessment monitoring programs. For example, it is important to know how widely a plume will spread when designing a monitoring program to evaluate the movement of that plume. With respect to the effect of capillary forces, the greater the surface tension, the higher a contaminant will be drawn up into the unsaturated zone by capillary forces. Consideration of this factor would be important in determining the relative distribution of a spilled contaminant between the unsaturated and the saturated zones.

B. Chemical Properties

Several chemical properties of the contaminants are important because they affect fate and transport processes in ground water. The most important of these processes are adsorption and degradation. These processes, the chemical properties which affect them, and data sources for these properties are discussed below. Illustrative examples are also provided.

Adsorption

Adsorption refers to the process whereby contaminants are transferred from solution to the surface of a solid. In ground-water transport, adsorption determines the relative distribution of contaminants between the ground-water and the soil and affects the contaminant transport velocity. With respect to monitoring, adsorption must be considered to address the question "Where do I look for contamination?"

In environmental studies, the Freundlich sorption model is frequently used to describe adsorption:

$$C_s = K_D \cdot C_w^{-1}$$

where C_{c} = the concentration in the solid

 $C_w =$ the concentration in the water $K_D =$ the sorption coefficient

n = a constant (sometimes written 1/n).

For organic compounds, n is usually between 0.7 and 1.1. If n is unknown (the usual case), n is assumed to be unity, and the model becomes linear ($C_s = K_D C_{tr}$).

The sorption coefficient K_D may vary with the size, structure, and charge of the contaminant; the temperature, pH, oxidation potential, and composition (particularly dissolved organic matter and salts) of the ground water; and the pH, particle size distribution, surface area, and composition (particularly clay and organic matter) of the soil or aquifer media.

Organic compounds of low solubility and some inorganics sorb primarily onto (or react primaily with) organic matter in the soil or aquifer material. Thus, a sorption coefficient. K_{oc} , corrected for the organic carbon content of the solid, appears to be relatively independent of properties of the solid.

 $K_{oc} = K_{D}/f_{oc}$

where K_{oc} = sorption coefficient on organic carbon in soil

 f_{oc} = fraction organic carbon in solid.

The concept of K_{oc} is usually valid for f_{oc} greater than 0.01. Because K_{oc} is independent of the soil properties, it can be estimated from contaminant properties including solubility and octanol/water partition coefficient, K_{ow} .

Sorption coefficients have not been published for most contaminants. Laboratory determinations can be made using batch or column procedures to determine K_D values for specific contaminants on specific media. The time and expense involved with these determinations generally limit their applicability. As an alternative, several methods are available to estimate K_D values from chemical properties of the contaminant. With organic contaminants chemical properties are generally used to estimate K_{OC} because this constant is dependent only on chemical properties and not on soil properties. Values for K_{OC} can generally be estimated from the solubility of the contaminant, S, or from its octanol/water partition coefficient, K_{OV} .

tions exist depending on the particular class of contaminants being considered. These correlations are available in the literature. Two correlations that are commonly used include:

 $\log K_{oc} = -0.55 \log S + 3.64$ where S is the solubility in mg/l and

$$\log K_{\rm oc} = 0.937 \log K_{\rm ov} - 0.006$$

Determination of K_{D} values for inorganic contaminants is much more difficult. As discussed earlier, the use of geochemical models is generally necessary because of the numerous reactions that can occur.

Related to the sorption coefficient is the retardation factor, R, which is defined as the ratio of the velocity of water to the velocity of the contaminant. The retardation factor is calculated from the sorption coefficient, the bulk density of the aquifer material, and the effective porosity of the aquifer material by:

$$R = 1 + B \cdot K_{D}$$
$$\frac{n_{e}}{n}$$

where B = the bulk density of the aquifer material (kg/L);

 $K_{\rm m}$ = the sorption coefficient, and

 n_{a} = the effective porosity of the aquifer.

The contaminant transport velocity is determined by dividing the ground-water velocity (calculated as described earlier) by the retardation factor.

The importance and use of adsorption data is illustrated by the following examples.

Contaminants have been discovered to be migrating from a facility. Assessment monitoring has been performed to carefully delineate the extent of the plume, as shown in Exhibit 35. The contaminant concentration isopleths were multiplied by the volume of the plume to determine the total mass of contaminant present in the plume. This calculation yields a result of 1,000 kg. Disposal records available for the facility indicate that 10,000 kg of this contaminant were disposed. Comparison of these two quantities leads to the conclusion that the majority of the contaminant is still present in the facility, and corrective actions are designed accordingly.

The above analysis ignores the distribution of contaminant mass on the aquifer material. Suppose the contaminant has a K_D of 1.25 L/kg and the aquifer material has a bulk density of 1.6 kg/L and an effective porosity of 0.25. Calculations performed using these values show that there will be 9 times more contaminant mass associated with the solid phase than with the liquid phase. In this example, therefore, there will be an additional 9,000 kg of contaminant adsorbed on the aquifer material. Comparison of this total with the disposal records then shows that the entire mass of contaminants has left the facility.

Exhibit 35 Delineation of Contaminant Plume to Calculate Contaminant Mass



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As another example, consider a facility where detection monitoring has revealed elevated conductivity, indicating possible migration of contaminants from the facility. Assessment monitoring is being planned to determine if specific contaminants have left the facility. Hydrogeologic data are used to calculate a ground-water travel time of 6 months from the boundary of the Was Management Unit to the monitoring well. The contaminant sorption coefficient and aquifer characteristics are used to calculate a retardation factor of 30. The resulting contaminant travel time is 15 yr. Because the facility has not been in operation that long, it is impossible for the contaminant to have reached the monitoring well. This situation is illustrated in Exhibit 36.

When a number of contaminants are present it is important to consider the retardation factor of each contaminant when evaluating monitoring programs and assessing corrective actions. For example, consider a site where wastes containing three major constituents are disposed of. These constituents have sorption coefficients in the aquifer material at the site of 3, 10, and 30. There is a sudden release of waste from the site introducing all three contaminants into the ground-water. In order to evaluate possible corrective actions, it is necessary to evaluate the migration of these contaminants offsite to downgradient residential wells. Initially, the contaminant plume at the site would contain all 3 contaminants, as shown in Exhibit 37-A. With time, however, the contaminants would begin to separate because of different retardation factors, similar to the effect of a chromatographic column. After several years, the plumes might be expected to appear as shown in Exhibit 37-B.

Degradation

Once released from a site, contaminants may undergo several possible degradation reactions. These reactions may result in the formation of more or less toxic, stable, or transportable chemicals with consequent aggravation or alleviation of the hazard. Or, alternatively, some components may not react at all but will persist in the environment. The disappearance or transformation of contaminants in ground water must be considered when designing or implementing a monitoring program. Specifically, these considerations address the question "Which contaminants do I look for?".

Numerous reactions are possible for the several thousand chemicals that may be present in hazardous wastes. These reactions can be divided into two major categories: those that are caused by interactions among the different chemicals comprising the waste and those that occur because of interactions between the chemical and the environment. This discussion will focus on the second category -- typical reactions controlled by environmental conditions. The types of reactions to be discussed are biodegradation, oxidation/ reduction, and hydrolysis.

Biologically mediated reactions are possibly the most important processes for transforming organic hazardous materials in the unsaturated and saturated zones. Biodegradation can be important for inorganic materials as well. Biodegradation may involve conversion to other components which are more or less toxic and persistent, and biodegradation does not necessarily eliminate hazards from the environment. For example, trichloroethylene can be transformed biologically to vinyl chloride, which is considered to be more toxic

Exhibit 36 Relative Migration of Plumes of Mobile and Attenuated Contaminants



Exhibit 37 Multiple Contaminant Plumes



than the parent compound. For some organic compounds, complete degradation or mineralization to $\rm CO_2$ and $\rm H_2O$ may occur. In this case, biodegradation eliminates the hazardous contaminant once the reaction sequence is complete. Biodegradation reactions include oxidation/reduction, hydrolysis, dehalogenation, alkylation, acylation, dimerization, and nitration. Frequently, it is difficult to determine whether these reactions are purely chemical, purely biological, or a combination of the two processes.

Microbial reactions are highly compound-specific since they are usually based on enzymatic reactions. However, certain rules of thumb have been devised for estimating the relative rates of biodegradation for different chemical classes, structures, or properties. In general, branched, short chain, and saturated compounds are less readily degraded as are water-insoluble compounds since these tend to be less readily available to organisms. Alcohols, aldehydes, acids, esters, amides, and amino acids are more susceptible to biodegradation than the corresponding alkanes, olefins, ketones, dicarboxylic acids, nitriles, amines, and chloroalkanes. These statements are general, of course, and reaction rates are dependent on specific conditions and biological species available, i.e., in one habitat a chemical may persist whereas in another it may degrade quickly. Chemical groups which are poorly degradable include amine, methoxy, sulfonate, nitro, nitroso, ether, halogens, and meta-substituted benzene rings.

Microbial populations and metabolic rates (and, consequently, biodegradation rates) are affected by a number of environmental variables. These include:

- Temperature -- rates increase with increasing temperature within the tolerance limits of a given organism,
- pH -- many but not all bacteria favor slightly alkaline conditions whereas fungi tend to prefer slightly acidic conditions,
- Moisture -- necessary for survival of most organisms, also a factor in temperature, pH, and Eh control, hydrolysis and oxidation reactions, transport of compounds,
- Eh -- presence or absence of O₂ will determine whether aerobic or anaerobic processes are involved in biodegradation,
- Salt concentration -- may suppress activity unless species is salt tolerant,
- Availability of nutrients -- necessary for growth,
- Availability of the compound to be degraded -- may be affected by sorption due to organic matter or clays or by complexation with organic matter,
- Presence of inhibitors -- e.g., metals or other components that are toxic to the microorganism, and
- Presence of another carbon (and energy) source for cometabolism.

The rate of biodegradation depends on the structure and concentration of the compound, metabolic capacity or cell concentration of the microbial community, and environmental conditions. The rate is very difficult to quantify because it is often difficult to determine which species are actually involved in degradation of a particular compound, to determine the number of bacteria involved, and to separate the effects of biotransformation from chemical transformation. In addition, the rate can be time dependent. There is usually an initial lag period (hours to weeks) from the introduction of a chemical to the initiation of biodegradation because the organisms need time to produce the required enzymes or to grow until there are sufficient cells to produce significant degradation. Once the lag period is past, degradation occurs rapidly as the microbial population increases. One case in which this does not hold is cometabolism a process that occurs when microorganisms transform a compound without using it as a nutrient source. In cometabolism, there is no population increase and transformation rates are slow. The chemistry of biotransformation in the environment is not well known. Laboratory studies using microbial cultures typically indicate trends or possibilities but, because of their relative lack of complexity (usually including lack of diversity of microorganisms), lab studies may not be very useful for prediction of actual field transformations.

In addition to biological reactions, contaminants may be subject to degradation or transformation by chemical oxidation/reduction reactions in the environment. The working definition of oxidation or reduction depends on whether inorganic or organic molecules are being discussed. For inorganic molecules, oxidation is defined either as a loss of electrons or an increase in oxidation number; reduction is a gain of electrons or a decrease in oxidation number. For organic molecules, oxidation is defined as the conversion of a functional group in a molecule from one category to a higher one (see Exhibit 38) and usually involves a gain of oxygen and/or a loss of hydrogen. Reduction is just the opposite, Reduction and oxidation are paired reactions -- 1.e., any oxidation of one compound must also involve a reduction of another compound. Oxidation/reduction (redox) reactions may have significant effects on the properties of hazardous contaminants. For organic components, the reaction may change the functional groups present in the molecule; for inorganic components, the reaction may change the oxidation state of the metal. For example, trivalent chromium, which generally complexes with other ions, precipitates and is then adsorbed, can be oxidized to hexavalent chromium, which is soluble in water, is not readily adsorbed on sediments, and is quite toxic.

Redox reactions depend on the presence of oxidizing or reducing species in the environment. The thermodynamic redox potentials can be used to predict which reactions are possible. The reaction rates depend on the concentration of the reactive species and the concentration of the chemical. In oxidation reactions, typical reactive species are free radicals (RO_2 , RO, HO), ozone,

and singlet oxygen (i.e., oxygen in an excited state in which its electrons have absorbed energy).

The classes of organic compounds that tend to be susceptible to oxidation include phenols, aromatic amines, electron-rich olefins, and alkyl sulfides. Oxidation of the following organic compound classes is not an important mechanism: saturated alipyhatic hydrocarbons, haloalkanes, alcohols, esters, and ketones.

"Oxidation States" of Functional Groups

Increasing Oxidation State			
R-H	- C=C	C≡C- RCC	OH CO ₂
R-OH		- C - " O	
R-Cl	R ₂ CCl ₂	– CCI ₃	CCI 4
R-NH ₂	R – N – R ' H	R – N ≡ N ⁺	R – NO ₂

Hydrolysis of organics involves the reaction of water with an organic molecule, RX, in which the OH group substitutes for the X group causing formation of an R-OH bond: $RX + H_2O \rightarrow ROH + H^+ + X^-$. For inorganic compounds, hydrolysis is more formally defined as the reaction between water and the ion of a weak acid or a weak base. (For example, Fe³⁺ + 3H₂O \rightarrow

Hydrolysis is a very important mechanism for transformation of some organics in ground water. Derivatives of carboxylic acids such as esters, amides, and carbamates are susceptible to hydrolysis, as are nitriles, alkyl halides, epoxides, amines, and phosphoric acid esters. Other organic groups are resistant to hydrolysis; these include aliphatic saturated and unsaturated hydrocarbons, aromatic hydrocarbons, carboxylic acids, alcohol and glycols, aldehydes, aromatic amines, ethers, halogenated aromatics, ketones, aromatic nitro compounds, and phenols. Hydrolysis reactions usually involve the formation of smaller, more polar compounds. These reaction products will probably have a tendency to be less volatile and more soluble than the reactants and will have associated changes in mobility in environmental media.

Hydrolysis also is very important for inorganic salts since it can lead to the formation of acidic, basic, or neutral solutions which can influence a wide variety of reactions. Simple solutions of soluble sulfides or carbonates will be basic; simple solutions of Cl, NO_3^- , or SO_4^- salts of the common heavy metals (Fe, Pb, Cd) will be acidic.

Kates of hydrolysis reactions for different organic compound classes are available in the literature as hydrolysis half-lives (the time it takes for half of a given quantity of material to hydrolyze). Hydrolysis half-lives may range from about 1 second for certain alkyl halides to 2 years for other alkyl halides, to 10^6 years for some phosphoric acid esters.

Rates and mechanisms of hydrolysis reactions may be affected by several factors: pH, temperature, presence of other organic compounds or trace metals, and sorption. Increased temperature causes an increase in the hydrolysis rate. A useful rule of thumb is that a 10° change in temperature causes the rate constant to increase 2.5 times at typical temperatures. The presence of other organic compounds or trace metals may result in catalysis of some hydrolytic reactions. For example, humic and fulvic acids may catalyze some hydrolysis reactions in soils, possibly due to the presence of phenolic or amine groups. Hydrolysis reaction rates in soils have been observed to be considerably faster in a few cases than rates in solution. In other cases, sorption may protect chemicals from hydrolysis.

A number of examples are available to illustrate the effects and importance of degradation reactions. One increasingly common example involves the organic compounds trichloroethylene (TCE) and perchloroethylene (PCE), both of which are common hazardous wastes. These two compounds can undergo a series of biologically mediated dehalogenation reactions leading to the formation of vinyl chloride, as shown in Exhibit 39. Such transformations can have an impact on the collection and interpretation of monitoring data. At a large industrial complex, TCE sludges had been disposed of in a series of trenches which had leaked into the ground water. An intensive assessment monitoring program was initiated to determine the extent of the resultant contamination.





Wells installed at and immediately downgradient of the trenches showed high levels of TCE. Wells installed at some distance downgradient showed dramatically reduced levels of TCE, suggesting that the contamination was being attenuated by the soils at the site. Further evaluation of the monitoring data, however, revealed significant levels of 1,2-dichloroethylene (1,2 DCE) in the downgradient wells. There was some question as to the origin of this contaminant, since it had never been used at the site and there was no record that it had ever been disposed of in the trenches. In fact, the monitoring wells near the trenches showed very low levels of 1,2 DCE. The relative distribution of the two chemicals in ground water was as shown in Exhibit 40.

The interpretation of the monitoring data was aided by obtaining data on the degradation mechanisms of TCE and PCE. These data, including half-lives, were used to construct a family of curves showing the relative amount of each of the contaminants with time. These curves are shown in Exhibit 41. The relative half-life data shown in Exhibit 41 and ground water travel time data obtained from site investigations were used to determine that the trenches were indeed the source of the 1,2 DCE. That is, the travel time from the trenches to the center of mass of the 1,2 DCE plume compared well with the time to degrade TCE to produce the peak concentration of 1,2 DCE. These results indicated that the contamination from the trenches was more widespread than indicated by the TCE data.

The above example illustrates the importance of identifying possible degradation mechanisms for the contaminants which are to be monitored. The importance of understanding these mechanisms was illustrated at a different site at the same complex. While this site also had received TCE and was leaking, downgradient wells did not show the presence of 1,2 DCE. Further investigation into the mechanisms of TCE degradation suggested that the process depended on the availability of an alternate source of organic carbon and energy. The first disposal area was located upgradient of a trash landfill, which was suspected of leaching organic-rich leachate into the ground water and creating conditions favorable for microbial growth. No such facility existed next to the second disposal site and there were no organics present in the ground water other than the TCE. It was postulated that the degradation of TCE to 1,2 DCE was not occurring at the second disposal site because of the absence of an alternate organic substrate.

The occurrence of the 1,2 DCE as a product of the biological degradation of TCE was further investigated using additional site monitoring data. Exhibit 41 shows that the biological degradation of TCE results in both the trans and cis isomers of 1,2 DCE, but favors formation of the cis isomer. Higher yield of the cis isomer is evidence of a biologically mediated reaction since a purely chemical reaction would favor the trans isomer. Further analysis of ground-water samples using a method which could differentiate between the two isomers revealed that the cis isomer was indeed the dominant form.

Consideration of degradation mechanisms is also important in determining the impacts of contaminant releases. At a facility similar to the one above, the compound 1,1,1-trichloroethane (TCA) had been used as a degreasing solvent and had been disposed of in on-site trenches, which subsequently leaked into

Exhibit 40 Contaminant Plumes Showing Movement of Degradation Products







1-68
the ground water. A major advantage of TCA over TCE is that it is far less toxic and is considered much safer. While specific ground-water standards have not been formally established, the priority pollutant criteria published by EPA are 2.7 ug/L for TCE (at a 10^{-6} cancer risk) and 18,400 ug/L for TCA. (TCA is not a carcinogen.) At this particular site, TCA had migrated to off-site residential wells at levels on the order of 100 ug/L, below taste and odor thresholds and well below the priority pollutant criterion. Because of the relatively low levels found in these wells, the TCA contamination was not felt to be a health hazard. Further investigation, however, revealed the presence of 1,1-dichloroethylene (1,1 DCE) in these domestic wells at levels on the order of 10 ug/L, which is much higher than the EPA priority pollutant criterion for dichlorethylenes of 0.033 ug/L (at a 10^{-6} cancer risk). Further investigation revealed data suggesting that 1,1 DCE was a degradation product of TCA. On the basis of this information, the TCA contamination was indeed posing a threat to public health and corrective actions were instituted.

The combined effects of contaminant degradation and unique geohydrologic conditions were illustrated in a site characterization study. At this site, TCE wastes had escaped from an impoundment into the ground water. Assessment monitoring at the site revealed a plume of TCE contamination downgradient from the impoundment, as shown in Exhibit 42. It was believed that the TCEcontaminated ground water was discharging to the creek and that the creek was the downgradient boundary of the ground-water contamination. No TCE contamination was found downgradient of the creek. Monitoring data collected further downgradient did, however, reveal an additional contaminant plume, at greater depth, and consisting almost entirely of vinyl chloride (VC). An investigation was conducted to determine whether the downgradient VC plume was related to the facility since this would affect the extent of corrective actions required.

The geohydrologic portion of the investigation revealed the presence of a low permeability zone beneath the creek, preventing discharge to the creek and forcing the ground water to flow downward. The contaminant travel time from the facility to the center of mass of the VC plume compared well with the time required to degrade TCE to VC. The conclusion of the investigation was that the downgradient VC contamination was related to the facility and corrective actions were designed accordingly.

The above example also illustrated the importance of considering contaminant degradation when selecting analytical methods. Several of the analytical methods for determining TCE will not detect vinyl chloride. Use of these methods would not have revealed the additional downgradient contamination arising from the impoundment and requiring corrective action. Additionally, the unusual geohydrologic characteristics of the downgradient region would not have been discovered had the investigators not considered the effects of contaminant behavior.

Exhibit 42 Multiple Contaminants Plumes Showing Degradation Products



4.0 REFERENCES

- Cole, C.R., F.W. Bond, S.M. Brown and G.W. Dawson, 1984. <u>Demonstration</u> <u>Application of Groundwater Modeling Technology for Evaluation of Remedial</u> <u>Action Alternatives</u>. U.S. Environmental Protection Agency Contract No. 68-03-3116.
- Cole, C.R., F.W. Bond, S.M. Brown and G.W. Dawson, 1983. "The Use of Groundwater Modeling for Evaluation of Remedial Action Alternatives." <u>Land Disposal of Hazardous Wastes - Proceedings of the Eight Annual</u> Research Symposium. EPA-60019-83-002.
- Dawson, G.W., 1983. "Risk Management and the Landfill for Hazardous Waste Disposal." Journal of Hazardous Materials, Vol. 8, No. 1.
- Dawson, G.W. and C.J. English, 1984. "Innovative Approaches to Remedial Action for Solvent Leaks From Underground Tanks" in <u>Proceedings of the</u> HAZMAT Southwest Conference, Houston, TX.
- Dawson, G.W. and C.J. English, 1986. "A Comparative Evaluation of Methods for Determining Alternative Concentration Limits" in <u>Proceedings of the</u> <u>Superfund '86 Conference</u>, Washington, D.C.
- Dawson, G.W. and B.W. Mercer, 1986. <u>Hazardous Waste Management</u>. Wiley -Interscience Co., New York, NY.
- Devary, J.L. and R. Schalla, 1983. "Improved Methods of Flow System Characterization" in <u>Proceedings of Management of Uncontrolled Hazardous</u> <u>Waste Sites National Conference</u>, Washington, D.C.
- Devary, J.L. and W.V. Harper, 1985. "A Hybrid Approach to Uncertainty in Far Field Groundwater Flow" in <u>Proceedings of Symposium on Groundwater Flow</u> and Transport Modeling: A Critical Evaluation of the State-of-Art, Albuquerque, NM.
- McKown, G.L., J.L. Devary, and R. Schalla, 1985. "Applied Uncertainty Analysis at Hazardous Waste Sites" in <u>Proceedings of the HAZMAT 85 Conference</u>, San Diego, CA.
- McKown, G.L., R. Schalla, and C.J. English, 1984. "Effects of Uncertainties of Data Collection on Risk Assessment" in <u>Proceedings of the 5th</u> <u>National Conference on Management of Uncontrolled Hazardous Waste Sites</u>, Washington, D.C.
- Schalla, R. McKown, G.L. Meuser, J.M. Parkhurst, R.G., Smith, C.M. Bond, F.W., and C.J. English, 1984. <u>Source Identification, Contaminant</u> <u>Transport Simulation, and Remedial Action Analysis, Anniston Army Depot,</u> <u>Anniston, AL</u>. Contractor Report No. DRXTH-AS-CR-83265, U.S. Army Toxic and Hazardous Materials Agency, Aberdeen Proving Ground, MD.
- U.S. EPA, 1985. <u>Guidance on Remedial Investigations under CERCLA; Chapter 7,</u> <u>Site Characterization</u>. EPA Report No. 540/G-85/002, Cincinnati, OH.

GROUNDWATER MONITORING SYSTEM DESIGN

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INTRODUCTION

Designing systems for monitoring groundwater and contaminant movement is complicated by countless quantitative variables and qualitative considerations. Because of these complications, the design of monitoring systems sometimes appears to be more of an art than a science. The objective of this paper is to discuss some of the data sources for, and key factors in, monitoring system design. Section 1 provides an overview of indirect data-gathering methods, including background information, aerial photographs, environmental surveys, geophysics, and soil-gas surveys. Section 2 provides an overview of direct and rock sampling, data-gathering methods, including soil hydrologic measurements, and aquifer testing. Section 3 discusses some of the considerations in combining indirect and direct data to design a monitoring system. Finally, Section 4 discusses approaches to preventing and correcting selected problems with monitoring systems.

SECTION 1

INDIRECT METHODS

Indirect methods provide generalized information about, or specific data that can be correlated to, groundwater movement and subsurface contaminant migration on and near a site. Indirect methods fall into five general categories:

- Background records and literature.
- Aerial photography.
- Environmental surveys.
- Geophysical techniques.
- Soil-gas analysis.

These methods are generally inexpensive and efficient approaches to obtaining information about a site. For this reason, it is prudent to use applicable indirect methods early in the course of a site investigation.

1.1 BACKGROUND RECORDS AND LITERATURE SEARCH

Many areas of the country have, at some time, been the focus of some type of geologic or environmental investigation. It is advantageous to determine what these previous studies have revealed about the conditions existing on the site, such as site use history or underlying geologic conditions. Many sources of background information exist, and there are various ways of accessing them. Libraries, both public and private; local planning commissions; universities, regional and especially those with geology and/or geography departments; and Federal, state, and local agencies with an orientation toward environmental protection, soil, or geologic science, are but a few of the hundreds of available sources of literature. Table 1-1 lists some of the Federal sources of maps and reports. Bibliographies obtained from pertinent reports can be used to guide the investigator to other sources of data. Informal interviews with people knowledgeable about a particular site may be a valuable adjunct to any literature search, but they should always be treated with some skepticism.

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Sources	of	Maps,	Reports	, and	l Re	lated	Background	Information
			(After R	ера	and	Kufs,	1985)	

Topic	Source*
Climate	NCC, NOAA
Clinometric (Slope)	GS, SCS
Floodplains	CE, GS, SCS
Geodetic Control	CE, GS
Geologic	GS
Geophysical	GS, NOAA
Groundwater	GS
Land Use	GS, SCS
River Basin/Watershed Surveys	BR, GS, SCS, TVA
Soils	SCS
Topography	GS
Water Resources	GS

*Many of these types of maps and reports are also available from state and local government agencies and universities:

- BR: U.S. Bureau of Reclamation P.O. Box 25007 Denver, Colorado 80225
- CE: U.S. Army Engineer District Corps of Engineers, Chicago 219 South Dearborn Street Chicago, Illinois 60604

U.S. Army Engineer District Corps of Engineers, Nashville P.O. Box 1070 Nashville, Tennessee 37202

U.S. Army Engineer District Corps of Engineers, Omaha 6014 U.S. Post Office and Courthouse Building Omaha, Nebraska 68102

U.S. Army Engineer District Corps of Engineers, Vicksburg P.O. Box 60 Vicksburg, Mississippi 39180

Table 1-1 (continued)

GS:	Eastern National Cartographic Information Center U.S. Geological Survey Reston, Virginia 22092
	Mid-Continent National Cartographic Information Center U.S. Geological Survey 1400 Independence Road Rolla, Missouri 65401
	Rocky Mountain National Cartographic Information Center U.S. Geological Survey Federal Center, Building 25 Denver, Colorado 80225
	Western National Cartographic Information Center U.S. Geological Survey 345 Middlefield Road Menlo Park, California 94025
NCC:	U.S. National Climatic Center Federal Building Asheville, North Carolina 28801
NOAA :	U.S. National Oceanographic and Atmospheric Administration Office of Public Affairs 14th Street, NW Washington, DC
SCS:	U.S. Soil Conservation Service Information Division P.O. Box 2890 Washington, DC 20013
TVA:	Tennessee Valley Authority Mapping Services Branch 111 Haney Building Chattanooga, Tennessee 37401

1.2 AERIAL PHOTOGRAPHS

Aerial photographs and images are valuable, albeit often neglected, sources of information for designing groundwater monitoring systems. The primary uses of aerial photographs include providing information about:

- Historical development of site.
- Indications of waste or leachate.
- Geologic, topographic, and hydrologic features.

Table 1-2 summarizes the uses of four types of aerial images. Additional information concerning available aerial images is summarized in the <u>Map Data Catalog</u>, published by the U.S. Geological Survey.

Interpreting the chronology of a site's development is generally not a difficult procedure, provided the appropriate aerial photos are available. Identifying indications of waste or leachate and interpreting the significance of geologic, topographic, and hydrologic features, however, do require more experience.

Indicators of waste or leachate can be spatial (e.g., physical changes such as gaps in vegetation or snow cover) or spectral (e.g., color or tonal changes in water or vegetation). In general, spatial indicators are more consistent and useful than spectral indicators (Sangrey and Philipson, 1979), but spectral indicators may be more sensitive to subtle changes in site conditions.

Interpretation of geologic, topographic and hydrologic conditions at a site can be quite involved. For example, Table 1-3 summarizes some of the key features of various rock types as observed in aerial photos. Because of the time and skill required to evaluate hydrogeologic features. advanced photointerpretation studies are seldom undertaken unless no other sources of background information exist, the site is very large (i.e., hundreds of acres), or the site is underlain by fractured or cavernous bedrock. In the case of fractured bedrock or Karst Terrane, fracture trace analyses are often conducted so that predominant fracture or solution orientations can be identified. Mean orientations can be calculated using procedures described in Mardia (1972).

Availability	and Usefulness of the Four Most	
Commonly	Used Types of Aerial Images	

Type of Image	Relative Availability	Potential Usefulness	Technical Considerations
Oblique photos	Highly variable but generally poor.	Evaluation of site history and physical features.	Size and distance distortion caused by oblique angle.
Perpendicular photos	Excellent for black and white; poor for color.	Evaluation of site history, physical features and geo- morphology; some- times useful for detection of contam- ination effects.	Sometimes difficult to distinguish features; photos must be at an appro- priate scale.
Stereoscopic photos	Fairly good.	Same as for per- pendicular photos.	Generally allow less ambiguous interpre- tation than per- pendicular photos.
Infrared images	Fairly poor.	Detection of con- tamination effects.	Require some experience to interpret.

Key Features of Various Lithologies as Observed in Aerial Photographs (after NWWA, 1986)

Rock Type	Landforms	Drainage Pattern	Drainage Density	Vegetation	Photo Tone	Special Keys
Humid Climates	<u>.</u>					
Shales (fine-grained clastics)	Low relief valleys, smooth and rounded	Dendritic, parallel	Medium to fine	Heavy	Medium to dark	
Limestones (carbonates)	Intermediate to low relief, rounded	Internal, dendritic, trellis	Medium to fine	Heavy to medium	Light to medium	Sink- holes
Sandstones (coarse- grained clastics)	High relief, massive, rounded	Dendritic, trellis	Coarse	Heavy	Light to medium	
Intrusive igneous rocks	Rounded, outcrops, subdued topography	Dendritic, angular, radial	Medium to fine	Medium to dense	Light, uniform	Uniform tone and topog- raphy
Extrusive igneous rocks	Subdued and undulating topography	Dendritic	Medium	Medium to dense	Dark	Dark tone, dense vege- tation

Table 1-3 (continued)

Rock Type	Landforms	Drainage Pattern	Drainage Density	e Vegetation	Photo Tone	Special Keys
Arid Climate						
Shales (fine-grained clastics)	Low relief slopes and valleys, angular dissection	Dendritic, parallel	Medium to fine	Barren	Medium to dark	Badlands
Limestones (carbonates)	High relief, angular	Dendritic, trellis, angular	Coarse to medium	Sparse	Light	Ridges
Sandstones (coarse- grained clastics)	High relief, bold cliffs, massive, angular	Dendritic, angular, trellis	Coarse	Sparse	Light	Cliffs
Intrusive igneous rocks	Massive outcrops, bald domes	Dendritic, angular, annular, radial	Coarse to medium	Sparse	Light uniform	Fracture pattern, light tone lack of banding
Extrusive igneous rocks	Inclined flows, flat topped plateaus, cliffs	Dendritic, parallel	Coarse to medium	Sparse	Dark	Flow pattern, surface texture, columnar jointing

The most time-consuming aspect of site evaluations using aerial photographs involves obtaining photographs of appropriate dates and scales. There are many governmental and private sources of aerial photographs. The most commonly used Federal Government sources are listed in Table 1-4. In general, aerial photographs obtained from governmental sources are relatively inexpensive (less than \$50) but have long delivery times (4 to 10 weeks). Aerial photographs obtained from private sources can be obtained very quickly (2 days to 2 weeks) but are relatively expensive (\$20 to \$200). Typically, both governmental and private photographs must be used to evaluate a site thoroughly.

1.3 ENVIRONMENTAL SURVEYS

The first on-site activity in developing a groundwater monitoring system is to conduct a general reconnaissance of the site. As part of this reconnaissance, environmental surveys that are essential to the design of the monitoring system are identified. Environmental surveys that are particularly relevant to designing monitoring systems are:

- Existing-well surveys.
- Geologic/hydrologic/soil surveys.
- Biological surveys.

1.3.1 Existing-Well Surveys

Often it is necessary or advisable to incorporate existing wells into a monitoring system. When this is the case, the construction of the well and the subsurface stratigraphy are documented adequately so that water quality data can be interpreted without ambiguity. When construction details are not documented adequately, there are several field tests that can be conducted to evaluate the usability of the well. Some of these tests are summarized in Table 1-5.

1.3.2 Geologic/Hydrologic/Soils Survey

Because a site's geology and soil conditions are closely interrelated to site hydrology, it is important to perform a survey of the geologic/hydrologic/soil conditions found on and near a site before designing a monitor well system. Several stages are necessary to complete such an investigation successfully.

The geologist should have reviewed the available literature on the hydrogeology of the site area prior to conducting the site investigation. Such a review provides a preliminary understanding of the distribution of soils, sediments and rock, general surface water drainage, and groundwater flow, which will serve to guide the site investigation.

Federal Government Sources of Aerial Photographs and Images

National Archives and Records Service Cartographic Branch 8 Pennsylvania Avenue, NW Washington, DC 20408 (for photographs taken prior to 1942) EROS Data Center U.S. Geological Survey Sioux Falls, South Dakota 57198 Agricultural Stabilization and Conservation Service U.S. Department of Agriculture 205 Parley's Way Salt Lake City, Utah 84109 Soil Conservation Service U.S. Department of Agriculture Cartographic Section 6505 Delcrest Road Hyattsville, Maryland 20782 Environmental Monitoring Systems Laboratory (EMSL) P.O. Box 15027 Las Vegas, Nevada 89114 Environmental Photographic Interpretation Center (EPIC) P.O. Box 1587 Vint Hill Farm Station Warrenton, Virginia 22186 National Enforcement Investigation Center (NEIC) Building 53, Box 25227 Denver, Colorado | 80225

Table	1 - 5
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	Test	Description	Results
1.	Surface Integrity	Qualitative determination of how easily the well moves within the borehole and how the well is secured.	Evaluate security provisions and integrity of surface grout seal.
2.	Sounding	Measurement of well depth.	Evaluate siltation and accuracy of log.
3.	Plumbness and Align-, ment	Logged using an inclinometer or tested using plumb bobs and cylindrical dummies.	Evaluate straightness of the well and its deviations from vertical.
4.	Geophysical Logs (grout seals)	Cement-bond (sonic) logs of energy in sound pulses as they travel through casing, grout, and voids; density (gamma-gamma) logs measure natural radioactive emissions from clays; neutron logs measure neutron attenuation from a source to identify rock, grout, water, and voids.	Evaluate gaps in grout seals.
5.	Geophysical Logs (casing leaks)	Temperature logs measure temperature changes in groundwater; flow meter logs measure movement of water within the well; acoustic emission logs measure noise levels; caliper logs measure well diameters; and television logs provide visual displays of the interior of the well.	Evaluate leaks and other imperfections in well casings, joints, and screens.

Field Tests for Evaluating Existing Monitoring Wells

Tabl	e	1	- 5	
(cont	i	nu	ed)

	Test	Description	Results
6.	Step- Drawdown Pump Tests	Measurements of changes in water levels while pumping and during recovery.	Evaluate well efficiency.
7.	Packer Tests	Measurements of water injection rates over small well intervals.	Evaluate locations and size of casing leaks.
8.	Hydraulic Connection Tests	Measurements of changes in depth to water in clustered wells as one of the wells in the cluster is pumped.	Evaluate inadequate well seals.

The next step necessary to detail the geology beneath a site is the collection of direct information identifying the lithology and standard 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.

Direct field methods usually include walking through the site, mapping visible outcrops on a topographic map, identifying the observed lithology, and measuring the geometric attitude and orientation of beds at each location. Other direct methods can include sampling shallow soil for geomechanical or geochemical analysis. A classification of the surface soils found on-site according to the U.S. Department of Agriculture, Soil Conservation Service, or other recognized standard is necessary. Any soil samples collected during an exploratory survey and later during well drilling should be logged according to the same classification.

1.4 GEOPHYSICAL SURVEYS

1.4.1 Methods

1.4.1.1 Metal Detection

Many types of metal detectors are commercially available, but all have a similar mechanism of operation. Two coils, a transmitting coil and a receiving coil, set up an electrical field that will be distorted by any metallic object that enters the field. This distortion is detected by a sensing circuit which can activate an audible or visible indicator.

Metal detectors will detect any kind of metallic substance, including both ferrous and nonferrous metals. They have a fairly short range depending on the size of the metallic object. Quart-sized buried objects can be detected to a depth of approximately 3 feet. Large metal objects such as 55-gallon drums or large piles of buried metal can be detected at a depth of as much as 10 to 20 feet. An experienced operator can usually make a reasonable estimate of the depth and size of a target, but because many variable factors exist, detailed calibration of this method is not possible.

Some of the factors influencing the operation of a metal detector include some natural soil conditions, surface metallic debris, pipes, fences, vehicles, and buildings.

1.4.1.2 Magnetometry

Magnetometers measure the strength of the earth's magnetic field and anomalies created by buried ferromagnetic objects. Where detectable, a deeply buried ferromagnetic object will typically produce a positive anomaly south of its location and a negative anomaly north of its location (in North America). Shallowly buried objects produce positive anomalies where they are buried. Key factors in a magnetometer's ability to detect buried ferrous metal include the mass, depth, shape, and orientation of the object.

Three types of magnetometers are used to explore sites for buried ferrous metal - total field magnetometers, vertical field magnetometers and gradiometers. Total field magnetometers (e.g., proton precession, cesium) measure the strength of the geomagnetic field in both vertical and horizontal planes. Vertical field magnetometers (e.g., fluxgates) measure only the vertical component of the magnetic field. Gradiometers combine two total-field or vertical-field magnetometers so that differences in the vertical field over a small distance are measured while the strength of the horizontal field is held constant. All three types of magnetometers have been used to map buried and other iron deposits. Gradiometers are the least drums sensitive to cultural interferences (e.g., fences, rail lines) although the other two types are usually adequate and are more commonly used.

1.4.1.3 Electromagnetic Conductivity (EM)

EM methods measure the electromagnetic conductivity of subsurface materials. EM conductivity devices typically have two wire coils and a control box. A magnetic current is created by passing an alternating current through one of the wire loop is in close proximity to an earth loops. When this material, a current is induced. The current strength is dependent upon the conductivity of the material being tested. This induced current is picked up by the other wire coil, the receiver. By measuring the difference in voltage between coils and knowing their spacing, the conductivity of the earth material can be calculated. This measurement is repeated over a number of points on a grid to allow the determination of subsurface conditions.

The ability of earth material to conduct electrical currents primarily depends on the amount, ionic concentration, and distribution of water found in the pore spaces surrounding the materials being tested. Minerals found in the sand and silt fractions of a rock or soil are generally poor conductors of electricity. Dry clays are also poor conductors but become better conductors when wet. The effect of organic matter on conductivity measurements has not been determined.

There are two types of EM survey techniques:

- Profiling When lateral changes in conductivity along a set depth from the surface are measured.
- Sounding Where vertical changes in conductivity are measured.

The type of survey performed is based on the spacing and orientation of the transmitter and receiver coils around each grid node. Because EM equipment generally comes with fixed electrode spacing, it is most often used for profiling. Commonly available coil separations are 3 feet (e.g., Geonics EM-38); 12 feet (e.g., Geonics EM-31); and 32, 66, and 131 feet (e.g., Geonics EM-34), which allow profiling to a depth of 200 feet under ideal conditions. Sounding surveys are generally performed with resistivity equipment although sophisticated EM devices (e.g., Geonics EM-37, EM-42) are available for depth sounding.

In order to map contaminant plumes, a contrast in conductivity must exist between the contaminant plume and local geohydrologic background values. Leachates with high total dissolved solids usually have high conductivity, but an uncontaminated saturated clay lens may exhibit the same response. In mapping depth to water table and groundwater flow direction, the great change in conductivity between saturated and unsaturated materials is usually sufficient to allow the water table to be mapped (Repa and Kufs, 1985).

Limitations of EM conductivity include (Pease and James, 1981):

- Ability to detect nonconductive pollutants is limited.
- Ability to detect plumes is limited if there is not a sharp contrast between the plume and natural groundwater.
- Lateral variations in stratigraphy complicate interpretation.
- Shallow conductive objects may result in anomalous readings.

1.4.1.4 Resistivity

Resistivity surveys involve applying an electrical current into the subsurface and measuring the voltage passing between a set of electrodes. By comparing the values for current and voltage, the apparent resistivity of earth materials between electrodes can be calculated. Since the resistivity of soils and rocks is predominantly controlled by porosity, permeability, amount of water, and concentrations of dissolved solids in the water, the method provides a tool to evaluate depths to water tables and extent of contaminant plumes.

Resistivity equipment can be used for "sounding" or "profiling." In profiling, the electrodes are moved over the site in an evenly spaced grid pattern. If site conditions are homogeneous, apparent resistivity values should remain nearly consistent. Any changes can be interpreted as being caused by subsurface heterogeneity (clay lenses in sands, etc.) or contaminated groundwater. In sounding, the spacing of the electrodes is increased with the center of the array remaining in a constant location. The two most commonly used electrode configurations are the Wenner array and the Schlumberger array. Each Wenner array electrode is separated by a constant distance called the "A" spacing. In the Schlumberger array, the voltage electrode spacing is constant while the current electrode spacing varies.

The Schlumberger array is generally preferable to the Wenner array unless ground conditions are simple (Johnson and Johnson, 1986). Changes in apparent resistivity after each electrode spacing change are usually interpreted as the presence of various layers. Three to four different layers can commonly be resolved with this technique.

While not as mobile as EM methods, resistivity methods allow any depth of measurement (up to the limits of the equipment) to be explored. However, there are limits to its use, including:

- Limited ability to detect nonconductive pollutants.
- Rocks, trees, buildings, etc., may restrict grid patterns.
- Surface conditions, such as concrete roads, parking lots, etc., may prevent electrode insertion.
- Power cables and lines can cause interference.

1.4.1.5 <u>Seismic</u>

Seismic reflection and refraction methods are both used to help determine stratigraphic and lithologic conditions. Seismic reflection, however, is primarily used to determine deep stratigraphic relationships (500 feet to 40,000 feet) below the surface. Since monitor wells are rarely drilled below a depth o£ 300 feet, seismic reflection is rarely used in site investigation work. Seismic refraction can be used to help define natural geohydrologic conditions, including thickness and depth of soil and rock layers and depth to bedrock or water table.

The seismic refraction method measures the time it takes a compressional wave to travel through a specific medium (i.e., soil or rock) over a known distance (i.e., the distance between geophones. The energy source in seismic refraction work can be explosive charges or heavy blows on a metal plate. These waves travel downward through the earth and are refracted back to the surface from the interfaces between different layers. One of the waves travels parallel to the ground surface and its time of arrival to the geophone array is recorded. Deeper moving waves will arrive at the geophones at a later time. Solutions to the seismic time-travel equations (defining the corresponding subsurface stratigraphy and lithology) are usually done on a computer. Depths to 300 feet can be probed using refraction techniques.

Determining the depth to bedrock, the depth to groundwater in alluvium, and the location of faults are the major uses of seismic refraction methods in groundwater studies. This method is especially applicable in locating buried valley aquifers, and in some cases, lateral lithologic changes in aquifers can be mapped. Monitoring well depths, well screen intervals, and suitable well locations can be determined from this type of data.

Since the seismic method measures small ground vibrations, it is susceptible to vibration noise from a variety of natural and cultural sources. Active industrial facilities are, consequently, poor sites for seismic surveys. In addition, it is a relatively slow method to perform in the field. It is best utilized when working at depths beyond the range of other geophysical methods.

1.4.1.6 Ground-Penetrating Radar (GPR)

GPR systems generate short-duration impulses of electromagnetic energy that penetrate through and reflect off earth layers having different dielectric properties. The reflections are recorded as continuous cross sections along a traverse. GPR is very effective for delineating shallow site stratigraphy and may, under certain conditions, be able to detect the surface of the water table. GPR has also been used in several geologic environments to map low-density, nonaqueous phase hydrocarbons (Stanfill and McMillan, 1985). Penetration depths over 100 feet have been attained under ideal conditions although 10 to 30 penetration is The presence οf feet of more common. fine-grained materials and electrically conductive groundwater can attenuate GPR signals, thus reducing penetration at some sites to a few feet. GPR systems also require that the survey grid be clear of trees, brush, tall grass, or other objects that may hinder towing the transmitter module.

1.4.1.7 Borehole Geophysical Devices

A variety of devices have been designed to yield data by taking measurements within the confines of a well. These borehole logging tools include:

- Temperature probes.
- Specific conductance probes.
- Downhole television camera.
- Caliper plogging tools.
- Resistivity logging tools.
- Gamma logging tools.
- Neutron logging tools.
- Downhole fluorometers.

Other types of downhole devices have been developed for use in the petroleum exploration field but are not generally used in environmental work.

Temperature probes contain a thermistor and can determine the water temperature in a well to ± 0.1 °C. This type of probe can be employed in a well in fractured rock to identify areas of fracture flow. In shallow systems, water temperature differences may exist in different fractures that intersect a well. The temperature probe may help locate these fractures. Probes can fit into a 1-inch well.

Specific conductance probes measure the conductance of water, a parameter that is an indication of ionic substances dissolved in water. While specific conductance measurements are commonly taken on water samples with a hand-held probe, downhole specific conductance measurements can be used to trace flows in both unconsolidated and fractured rock aquifers. The presence of a salt introduced into a nearby well can sometimes be detected in the pumping well during a tracer test. Time-travel and directional data can be determined from such a test. Probes can be used in a 1-inch diameter well.

Downhole fluorometers are devices that can detect the presence of fluorescent compounds by using an internal ultraviolet light source and filtered fluorescent detector. These devices can be used in a manner similar to the specific conductance probes for flow tracing. In a test like this, a fluorescent dye is used instead of a salt. Models exist that can be used in a 4-inch well.

Downhole television cameras allow the direct examination of a well or borehole for determining whether there are well construction problems, locating fractures, or determining fracture densities. Downhole TV can be used in a 2-inch well.

Caliper, resistivity, gamma, and neutron logs are described in Table 1-6. Excellent reviews of these and other traditional borehole logging tools are found in Kelley (1969) and Keys and MacCary (1971).

1.4.2 Factors in the Selection of Geophysical Techniques

The geophysical techniques described in the previous subsections each measure a distinct property of earth or fill materials. Typically, these measurements are not highly correlated. As a consequence, it is usually advantageous to several different geophysical utilize survey methods in evaluating a site. Table 1-7 summarizes some of the factors to consider in selecting complementary geophysical methods.

Traditional Borehole Logging Devices

Device	Principle of Operation	Use	Limitations
Caliper	Measures variations in the diameter of a bore- hole. Softer rock, such as shale, will create a slightly larger diameter hole than sand.	Detects lithologic differences, used in wet or dry or open or cased wells.	Not conclusive information when taken alone; must be used with other loggers.
Resistivity (Electric Logs)	Measures the natural electrical resistance of formations and fluids. Responds to changes in conductivity.	Can detect zones of conductive contaminants or porosity differences. Used in fluid-filled open holes.	Cannot be used in cased or dry wells. Affected by drilling mud.
Gamma	Measures natural gamma ray emissions in rocks surrounding boreholes. Shales and igneous rocks are high gamma emitters. Sands and silts are mod- erate emitters. Carbon- ates are low emitters.	Can detect lithological differences in an open or cased borehole; can be used in dry or wet holes or holes with drilling mud.	Affected by borehole diameter. Cannot usually detect thin (less than 2-feet thick) beds.
Neutron	Measures the reaction of rocks and fluids to to neutron bombardment. Responds to clay content or shaliness and pore water in tested rocks.	Used to determine both lithologic differences and porosity; can be used in fluid-filled or dry holes, open or cased.	Affected by borehole diameter and by drilling muds.

Factors in the Selection of Complementary Geophysical Methods

Application	Primary Methods	Secondary Methods	Technical Considerations
Detection of buried metallic waste	Metal detection, magnetometry	GPR, EM, Resistivity	EM and GPR respond to nonmetallic deposits, making interpretation ambiguous; resistivity often too inefficient for this application.
Detection of buried non- metallic waste	GPR, EM	Resistivity	GPR attenuated by clay-rich soil; resistivity often too inefficient for this application.
Evaluation of subsurface geology	GPR, Seismic	Resistivity, EM	GPR is attenuated by clays; seismic methods require wave-velocity contrasts; EM is typically not sensitive enough to depth variations.
Detection of water table	GPR	EM, Resistivity, Seismic	GPR works best in uniform deposits; EM and resistivity require conduc- tive groundwaters; seismic will work only in uniform unconsolidated deposits.
Detection of leachate plumes	EM, Resistivity	GPR	EM and resistivity require conduc- tive deposits; some organic deposits can be mapped as EM lows.

A critical factor in the selection of a geophysical technique is the suitability of the technique to the site's hydrogeology. Research on the effectiveness of metal detection, electromagnetic conductivity, and ground-penetrating radar under different site conditions has indicated that the effectiveness of these techniques is reduced when the conductivity of the soil/pore fluid exceeds 20 micromhos/meter (Lord and Koerner, 1986). Table 1-8 summarizes the results of this research.

Johnson and Johnson (1986) point out that many geophysical surveys of hazardous waste sites have been unsuccessful or misleading. The problems most frequently encountered with these studies include:

- <u>Incorrect geophysical method used</u> -- Caused by insufficient understanding of site conditions, objectives of survey, or geophysical technology.
- <u>Inadequate Data Quality</u> -- Caused by high ambient noise, poor field procedures, improper use of equipment, faulty equipment, inexperienced operators, or adverse site conditions.
- <u>Inadequate Data Quantity</u> -- Caused by insufficient understanding of survey objectives, site conditions, or the technology used.
- <u>Faulty Data Interpretation</u> -- Caused by insufficient understanding of site conditions and geophysical interpretation methods.

Johnson and Johnson cite experienced personnel as the key to successful geophysical surveys.

1.4.3 Evaluation of Geophysical Data

Geophysical data can be evaluated in three ways: graphically, using method-specific techniques, and by statistical modeling.

Graphical interpretation involves evaluating strip charts or computer-generated cross sections (GPR, seismic); plotting the geophysical measurements on a site map (magnetometry, metal detection, EM); and visually checking for patterns, correspondence to site features, and correlations to other geophysical measurements. Often, geophysical anomalies can be accentuated by preparing first-derivative (i.e., measurement slope) maps. Most of the geophysical data collected at hazardous waste sites is interpreted graphically because it is simple and usually effective.

Relative Effectiveness of Four Geophysical Methods for Detecting Buried Steel Objectives (After Koerner and Lord, 1986)

Pore Space Water	Percent Saturation	Media	Magneto- metry	Metal Detection	Electro- magnetic Conduc- tivity	Ground Pene- trating Radar
Fresh	0-20	Granuļar soi	l Excellent	Excellent	Excellent	Excellent
Fresh	50-100	Cohesive soi	l Poor	Excellent	Poor	Excellent
Fresh	100	Water	Excellent	Excellent	Excellent	Excellent
Brackish	10-50	Granular soi	l Excellent	Excellent	Fair	Excellent
Brackish	100	Water	Excellent	Poor	No good	No good
Saline	50-100	Granular soi	1	No good	No good	Poor
Saline	100	Water	Excellent	No good	No good	No good

Method-specific techniques involve the use of computer programs to filter out spurious signals (GPR, seismic) or theoretical models to determine depth, size, or orientation of a geophysical anomaly (magnetometry, EM, resistivity). Method-specific techniques are not used often because they require advanced training to evaluate, and the additional information they might provide can usually be obtained more effectively by drilling or test pitting.

Statistical modeling involves mathematically filtering and comparing different types of geophysical measurements (magnetometry, metal detection, EM) to derive more meaningful interpretations of diverse anomalies. For example, Kufs et al. (1986) used statistical modeling to process complex geophysical data from a former open dump. Statistical modeling of geophysical data is a recent development that will probably not be used often because of the advanced training required and the adequacy of graphical methods.

1.4.4 Cost of Geophysical Surveys

The cost of conducting a geophysical survey will depend on a number of factors, including type of survey, presence of an existing survey grid, size and topography of the site, and surface conditions. The surface of a site (i.e., presence of trees, brush, tall grasses, snow cover) is particularly important for GPR and can have a great impact on cost. Table 1-9 lists typical costs for the geophysical techniques most commonly used at hazardous waste sites.

1.5 SOIL GAS SURVEYS

Soil gas surveys are quickly growing in popularity as a method of determining the existence and extent of volatile contaminants in soil and groundwater. Gases and vapors released or generated from volatile liquids diffuse through pore spaces toward zones of lower concentrations. The concentrations of these vapors are influenced by a number of factors such as:

- Volatility of contaminant.
- Proximity to source and time since release.
- Porosity and permeability of earth materials.
- Distribution of pressure gradients within pore spaces.
- Meteorological conditions.

Survey	Typical Cost Range/Day ¹	Field Capacity/Day Sour	cce²
Magnetometer or Metal Detection	\$1,935-\$3,890	50-150 stations	А
Conductivity continuous profiling\(EM-31)	\$1,950-\$4,000	3,000-8,000 linear feet	A
Conductivity discrete profiling (EM-34)	\$1,970-\$3,960 \$1,800-\$4,800	50-150 stations 100-160 stations	A B
Conductivity sounding (EM-37)	\$2,400-\$3,750	8-10 stations	В
Resistivity	\$2,090-\$4,655 \$1,500-\$6,000	10-15 stations 6-12 stations	A B
GPR	\$2,585-\$6,100	5,000-10,000 linear feet (manual survey)	А
	\$1,500-\$6,000	5-10 linear miles (truck-mounted survey)	В
Seismic Refraction	\$1,750-\$4,200	10-12 12-geophone stations	В
Seismic Refraction	n \$1,840-\$6,750	8-15 12-geophone stations	В
Microgravity	\$ 800-\$3,750	40-50 stations	В

Costs for Selected Geophysical Surveys

¹Travel costs and establishment of site grid are not included; includes establishment of base station, periodic calibration, and preparation of report.

²Sources: A = Bopp (personal communication); B = Benson (1986)

Contaminants such as gasoline contain volatile hydrocarbons that vaporize rapidly, whereas diesel fuel and other distillates are composed of low volatility hydrocarbons that do not vaporize as quickly. Meteorological factors such as precipitation, barometric pressure changes, wind, and evaporation will also have an effect on vapor migration. Krauss et al. (1986) describe a case in which ambient temperature and soil moisture had significant impacts on the measurement of TCE vapors in soil. However, little is known about the relative importance of these influences except that they vary widely according to site-specific conditions and are difficult to assess (Scheinfeld et al, 1986).

The results of diffusion studies of hydrocarbon vapors include Bisque (1984) and Levine (1985). In these studies, trace volatiles from gasoline and diesel fuel samples, introduced at depth in undisturbed soil media, were collected at the surface to determine upward migration rates. In all cases trace quantities were detectable at the surface within hours from a depth of 10 feet (Scheinfeld et al, 1986).

The depth from which soil gas can be detected is variable. In sandy or gravely material, a survey can detect a contaminant buried as much as 100 feet deep. In clay or silt materials, the maximum detectable depth is much less.

Soil gas surveys involve a gas or vapor collection method and an analytical method. The results of a survey could, depending on the method used, give quantitative, semigualitative, or qualitative results.

Gas collection approaches include:

- <u>Surface readings</u> Measurements made at or just above the soil surface by portable instruments. These measurements are routinely made at hazardous waste sites yet are seldom made in the controlled and systematic manner.
- ¢ Temporary probes - Small diameter tubes driven into the ground and sampled, usually with a portable instrument. These tubes are typically removed immediately after sampling and are decontaminated and reused. Temporary probes are probably the most commonly used method of gas collection in scil-gas surveys at waste disposal sites.

- <u>Semipermanent probes</u> Small diameter tubes driven or augered into the ground and sealed with a cement or clay grout. These probes can be used for time-series sampling for a period of as much as several months and are usually sampled with a portable instrument. Because they can be resampled, semipermanent probes can provide more quantitative results than can temporary probes or surface readings.
- <u>Sorptive collectors</u> A special type of temporary probe that uses a sorbant (activated charcoal) in a glass tube that is temporarily buried at a location. After a specified time period, the collector is exhumed and the sorbant analyzed in a laboratory.
- <u>Vapor wells</u> Permanently installed small diameter tubes. These probes are designed for long-term monitoring of a location such as around an underground storage tank.

Analytical approaches used for soil gas surveys fall into three types:

- <u>On-site qualitative instruments</u> Include such devices as photoionization or flame ionization detectors. These generally give a yes-or-no response during a survey for contaminants.
- On-site semiqualitative or qualitative instruments Include devices such as portable or mobile gas chromatographs or combination mass spectrometers/gas chromatographs. These devices usually give semigualitative results during a soil gas survey but, if used carefully, can produce qualitative results.
- Laboratory-based instruments Include the full range of available analytical laboratory equipment such as GC or GC/MS. Samples of soil gas collected in the field are brought back to the laboratory for analysis. This method is the most quantitative of the analytical techniques.

The use of soil gas surveys to determine the presence or quantity of contaminants located on or near a site is a very useful technique due to its flexibility and versatility. Because the data can be collected and reduced on-site, a flexible field program in which decisions are made to maximize data coverage while pinpointing source areas was possible. This technique is particularly useful because it can quickly screen a site and locate possible source areas. Some of the limitations of soil gas surveys include:

- Limitations on the detection capabilities of on-site analytical instrumentation (usually not below 1 ppm).
- False positive readings due to naturally occurring organic compounds (such as swamp gas).
- Barometric pressure fluctuation that may purge existing vapor probes of contaminant vapors, giving false negative readings.
- A lack of understanding of factors that influence the movement of soil gas and the effects of different soil gas sampling and analysis methods.

SECTION 2

DIRECT METHODS

A number of direct methods are available for the characterization of subsurface migration of contaminants. These methods can be broadly grouped into three categories:

- Soil and rock sampling.
- Hydrologic measurements.
- Aquifer testing.

Each of these categories is examined in detail in the following subsections.

2.1 SOIL AND ROCK SAMPLING

There are five techniques commonly utilized for the sampling of soil and rock at a site. These are:

- Grab sampling.
- Split-spoon sampling.
- Shelby tube sampling.
- Soil-core sampling.
- Rock-core sampling.

The advantages and disadvantages of these techniques are summarized in Table 2-1.

2.2 HYDROLOGIC MEASUREMENT

Hydrologic data required as part of a groundwater monitoring program include measurements of depth to groundwater, the nature of water in the unsaturated (vadose) zone, and the interaction of groundwater and surface water.

2.2.1 Depth to Groundwater

There are a variety of methods for measuring depth to groundwater that are acceptable under different site conditions. Table 2-2 summarizes the accuracy, ease of use, and cost of six types of devices. Methods of Soil and Rock Sampling

Sampling Technique	Principle of Operation	Advantage	Disadvantage
Grab Sampling	Sampling is performed by removing a soil or rock sample by hand, usually with a small trowel, shovel, or hand auger. While samples are usually removed at or just below the surface, Grab samples can be collected from test pits dug with a backhoe to depths of 15 feet or more below grade.	Surface samples - quick, inexpensive, visually confirmable for contami- nants; usually a one-per- son operation with simple equipment; large sample available. <u>Backhoe</u> <u>Samples</u> - Visually con- firmable; moderately ex- pensive; good strati- graphic exposure; large sample available.	Limitations on depth of sampling; some surfaces are difficult to penetrate. May require extra people; large equipment may present decontamination problems; test pits may require shoring if below 3 to 4 feet. May require "clean fill" to fill excavation.
Split-Spoon Sampling	A 1.5-2.0-foot-long (2-in diameter) hollow split tube is advanced by soils pounding it into the ground with a large drill-rig-operated "hammer." Auger drilling is required to advance the hole to the next level to be sampled.	Can sample as deep as 200+ feet. Can use spoon penetration rate for calculating beaming strength. Can penetrate moderately hard surface.	Expensive and moderately time consuming; pounding distorts stratigraphic relationships; only small sample available; efficient decontamination of multiple split spoons may present problems.
Shelby Tube Sampling	A 2.0-foot-long, 3-inch- diameter thin-walled hollow tube is hydraulic- cally pressed into the layer to be sampled.	Sampling minimizes disturbance to stratigraphic relation- ships. Laboratory con- ducted hydraulic tests can be performed on sam- ple. Larger sample avail- able than from split spoon.	More expensive than split spoon sampling. Low re- covery in hard or granular soils.

Table 2-1	
(continued))

Sampling Technique	Principle of Operation	Advantage	Disadvantage
Soil-Core Sampling (Vibracoring)	Sampler is a 40-foot- long, 3-inch-diameter aluminum tube advanced by mechanical vibrations.	Yields long, continuous relatively undisturbed soil cores; easy to perform; relatively inexpensive.	Requires saturated or nearly saturated soil. Cannot penetrate gravel or cobbled layer.
Rock-Core Sampling	Rock-core sample is obtained by using diamond or carbide-tipped, hollow drill bit advanced by a rotary drill rig.	Only way to obtain whole, subsurface, consolidated rock sample. Can see existing fabric and texture of rock sample. Depths to 1,500 feet are possible.	Very expensive, slow operation. At depth may lose correct orientation of core.

Table	2-2
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Device	Typical Accuracy (feet)	Relative Ease of Use	Approximate Purchase Cost	Recording Capabilities
Tape/Popper	0.1	Easy	\$ 15	No
Tape/Marker	0.05	Easy	20	No
Electrical	0.05	Easy	200	No
Mechanical	0.1	Difficult	1,000	Yes
Sonic	1.0	Moderate	500	Yes
Pressure Transducer	0.03	Moderate	1,500	Yes

Devices for Measuring Depth to Water

2.2.1 Vadose Zone Monitoring

Many techniques are available for collecting vadose zone information. These techniques can be divided into five different categories:

- Soil moisture potential.
- Soil moisture content.
- Soil salinity.
- Temperature.
- Soil pore water sampling.

Soil moisture potential is defined as the energy status of a soil water system, including both osmotic and matrix forces. These include such measurable forces as surface water tension, associated with osmotic forces dissolved components, ion molecular cohesion and adhesive forces to soil grams, and electrical forces. Since soil moisture potential is inversely proportional to the amount of water found in a soil, measuring the soil moisture potential will give indirect data about soil moisture content. Measurements of soil moisture potential are usually made with various types of tensiometers or thermocouple psychrometers.

Soil moisture content is defined as the weight of the water to the weight of solid particles in a soil mass. Soil moisture content data are critical to allow the correct method of soil pore water sampling to be employed. Soil moisture content can be measured in a variety of ways, including: laboratory drying methods; electromagnetic methods; capacitance sensors; electrothermal methods; and nuclear methods such as neutron flux, gamma ray attenuation, and nuclear magnetic resonance. The laboratory drying technique is most commonly used.

The soluble salt concentration, or soil salinity, can be a valuable pollution indication. то measure this parameter, laboratory and field techniques usually rely on the relationship between electrical conductivity/resistance and ionic strength of the salt. Laboratory techniques involve an extraction method and resultant conductivity measurements. Field methods employ different types of sensors that can be emplaced temporarily or permanently or noncontact EM techniques electromagnetic conductivity techniques (EM). will allow a rapid survey of a large area with qualitative or semiguantitative đata collection while the laboratory and sensor-based techniques will be more quantitative but more labor intensive.
Soil temperature is a basic soil property that can be measured in a variety of ways. Most soils show rapid and strong gradient changes with increasing depth along a soil profile. Accurate soil temperature data can be used to help predict geochemical reaction kinetics and may be used to determine soil permeability differences.

Techniques used for soil pore water sampling have generated a great deal of interest among environmental geologists. In areas with a shallow water table, in situ soil pore water sampling to determine the existence of pollution problems is usually not conducted, but many parts of the country have deep water tables (100's of feet below grade). It is in these areas that soil pore water sampling is often used with varying degrees of success.

Soil water pore samples are obtained either by laboratory extraction methods from grab samples or with in situ samplers. Laboratory extraction techniques can include displacement, compaction, centrifugation, or suction methods.

In situ techniques are generally based on a vacuum-induced suction method that causes the soil pore water to flow into a collection vessel and is then analyzed in a laboratory setting. Sampling devices developed for this purpose include vacuum plates and tubes, vacuum pressure lysimeters, membrane filter samples, and absorbent material based devices. Each of these types of sampling devices comes in a variety of configurations. Each type of device has its advantages and disadvantages, including installation techniques, operating characteristics, maintenance, and operating lifetime. Morrison (1980) describes many of the commonly used devices for this program. The EPA draft document, Unsaturated Zone Monitoring Techniques (1986), is an excellent reference for these methods. Continued interest in vadose zone monitoring will undoubtedly help to spawn new methods of monitoring this important zone for pollution problems.

2.3 AQUIFER TESTING

Individuals who design and construct wells must have a thorough understanding of well hydraulics. Most of the real-life conditions found in well hydraulics are quite complicated; therefore, it has been difficult to develop the complex mathematical solutions necessary to solve all of the geologic and hydrologic uncertainties that are present in an aquifer. Given this complexity, only the most fundamental hydraulic theories can be applied successfully in everyday well design and construction. Remarkably, these basic methods regularly yield accurate results in most cases without laborious calculations. This subsection briefly examines the various aquifer tests and their mathematical solutions. For additional information on the subject, see Driscoll (1986), Freeze and Cherry (1979), Lohman (1979) Bear (1972, 1979), and Walton (1970).

2.3.1 Types of Tests

2.3.1.1 Laboratory Tests

These tests are most commonly performed on a small, undisturbed sample of the rock or sediment in question. The sample is obtained from a Shelby tube sampler, and laboratory measurements are made on the sample. Because of the way in which the test is performed, the results are generally reported for vertical permeability only. Since only a small area is tested, heterogeneity in the aquifer cannot be considered except with the use of an extensive sampling program. Additionally, data on horizontal permeability are more important than vertical permeability when investigating pollutant migration.

2.3.1.2 Slug Tests

Slug tests offer a quick and inexpensive field method of obtaining in situ permeability values. These generally give a good approximation of horizontal permeability values for the localized zone surrounding a well with hydraulic conductivities less than or equal to 10^{-2} cm/sec.

The following general sequence of events is necessary to conduct a slug test:

- The static groundwater level is determined.
- A slug is injected into or withdrawn from the groundwater. Note that the analysis assumes an instantaneous change in volume with this event recorded at elapsed time equal to zero.
- Groundwater levels (depths) are measured and recorded with corresponding elapsed times. A number of measurements are required over time to adequately represent the test. Typically, a high density of measurements is necessary during the early stages of the test with the number of measurements decreasing over time.

• Measurements continue until the groundwater level approaches equilibrium.

The time required for a slug test to provide sufficient data is related to the volume of the slug, the hydraulic conductivity of the subsurface strata being tested, and the construction of the well. These factors must be such that several incremental changes in groundwater level can be practically measured during the test interval.

2.3.1.3 Constant-Rate Pump Tests

The major purpose of pumping tests is to provide data from which the principal factors of aquifer performance -- transmissivity and storage coefficient -- can be calculated. Pump tests will allow the hydrologist to predict:

- The rate of groundwater migration.
- The effect of new withdrawals on existing wells.
- The drawdowns in a well at future times and different discharges.
- The radius of the cone of influence for individual or multiple wells.

A pump test consists of pumping a well at a certain rate and recording the drawdown in the pumping well and in nearby observation wells at specific times. There are two primary types of aquifer tests: constant-rate tests and step-drawdown tests. In the constant-rate test, the well is pumped for a significant length of time at one rate, whereas in a step-drawdown test the well is pumped at successively greater discharges for relatively short periods. The results obtained from properly performed pump tests are one of the most important tools in groundwater investigations.

Measurements required for pump tests include the static water levels just before the test is started, time since the pump was started, pumping rate, pumping levels or dynamic water levels at various intervals during the pumping period, time of any change discharge rate, and time the pump stopped. in Measurements of water levels after the pump is stopped (recovery) are extremely valuable in verifying the aquifer coefficients calculated during the pumping phase of the test. In areas where nearby wells being pumped may have an effect on the well to be tested, data should be collected for a day or before the start of the test to determine water table two fluctuation patterns. Pump tests are usually run for a minimum period of 12 hours. Many pump tests are conducted for a period of up to 96 hours. High labor costs and disposal of a large quantity of contaminated water are two major problems that must be considered during the pump test design.

2.3.1.4 Step-Drawdown Pump_Tests

Conventional well hydraulics theory is based on the assumption that laminar flow conditions exist in the aquifer during pumping. If the flow is laminar, drawdown is directly proportional to the pumping rate. Turbulent flow occurs in some wells, however, when they are pumped at a sufficiently high rate. Under turbulent conditions, the linear relationship between drawdown and pumping rate no longer holds, and part of the drawdown is generally related to the pumping rate raised to some power greater than 1.

When turbulent flow occurs, the specific capacity will decline, often dramatically, as the discharge rate is increased. When this happens, it is useful to have a means of computing the turbulent and laminar drawdown components in order to make proper judgments concerning the optimum pumping rate and pump-setting depth.

The step-drawdown test was developed to examine the performance of wells having turbulent flow (Jacob, 1946b). In a step-drawdown test, the well is pumped at several successively higher pumping rates and the drawdown for each rate, or step, is recorded. The entire test is usually conducted during one day, and calculations are simplified if all the pumping times are the same for each discharge rate. Usually five to eight pumping steps are used, each lasting 1 to 2 hours. The data from a step test can be used to determine the relative proportion of laminar and turbulent flow occurring at any pumping rate. It can also be used to determine the discharge rate at which a full-scale pump test should be conducted. The step-drawdown test is usually conducted at least 24 hours before the pump test is to be started. This allows the well time to recover fully.

2.3.1.5 Packer Tests

occasionally be necessary to It determine aquifer may characteristics for discrete zones either in open boreholes or in a screened well. In these cases, pressure permeability tests can be run using one or two packers to isolate various screened zones or lengths of drill hole in stable rock. While hole diameters usually do not exceed 3-1/2 inches, larger holes can also be tested if suitable equipment is available. The tests may be run in vertical, angled, or horizontal holes and analyzed if the head and zone relationships can be determined. Pressure tests are often the only practical tests to use when it is necessary to determine permeability of stream beds or lake beds below water.

Compression packers, inflatable packers, leather cups, and similar types of packers have been used for pressure testing. Inflatable packers are usually more economical because they reduce testing time and ensure a tighter seal, particularly in rough-walled or out-of-round holes. The packers are inflated through tubes extending to a cylinder of air or nitrogen at the surface. If a pressure-sensing instrument is included, pressure in the test section is sensed by the instrument and is transmitted to the surface by an electrical circuit where it either is read from a register at the surface or is recorded on This double packer arrangement permits a chart. successive tests at different depths in a completed hole without having to remove the packer between each test. The pressure sensor can also be adapted where a single packer is used.

2.3.1.6 Tracer Tests

In principle, the tracer method of studying groundwater movement corresponds to placing a float in a river and timing its travel between two points. Although the velocity of a float is readily determinable, the relationship between its movement and the mean water velocity is not fixed. A tracer, injected as a slug into a groundwater body, depicts the movement of groundwater with accuracy, but it is subject to diffusion, dispersion, dilution, and adsorption. Therefore, the tracer must be carefully selected.

The ideal tracer:

- Is detectable at low concentration.
- Is absent, or nearly absent, from the water of the aquifer.
- Must not react within the aquifer to form a precipitate.
- Must not be absorbed or adsorbed.
- Has a low toxicity.
- Is cheap and readily available.

There is no substance that meets these requirements for every aquifer, although reasonably satisfactory tracers may be found for particular sets of circumstances. Tracers may be classified by method of detection: color, chemical determination, electrical conductivity, nuclear radiation, mass spectrography, and flame spectrophotometry. Organic dyes, the most common of which is sodium fluorescein, be detected in very low concentrations. Fluorescein, may however, is readily adsorbed by the clay fractions of the geological matrix. The chloride ion in sodium or calcium chloride 'also been used successfully has as tracer. а Radioactive substances provide convenient and very sensitive tracers since they can be measured by their nuclear radiations at mass concentrations as low as 10^{-17} . They are, however, affected by base-exchange and adsorption phenomena. Certain radioisotopes, tritium in particular, can be used as tracers without danger of contaminating the aquifer or of being absorbed.

In some groundwater systems, such as those in Karst Terrane, tracer tests may be the only way to determine direction and travel time. For a more detailed discussion of tracer test procedures, see Davis et al (1985), Smart and Laidlaw (1977) and Jones (1984).

2.3.2 Aquifer Test Data Analysis

Aquifer characteristics exert primary control over well performance in terms of yield versus drawdown. Accordingly, determination of the effects of well geometry on the flow and head distribution in aquifers and on the yield and drawdown of wells has been the goal of most research on well hydraulics. Mathematical analyses have been made on the basis of steady state flows according to Darcy's law, and Dupuit's assumption of horizontal radial flow and mixed radii of influence, as well unsteady state conditions in ideal aquifers which as are isotropic, homogeneous, infinite of uniform thickness, and areal extent. The conclusions are generally adequate for estimating the performance of wells in confined aquifers, as well as in unconfined aquifers where the drawdown is a small percentage of the aquifer thickness and the discharging well is fully penetrating. Corrections for partial penetration of the discharging well, large drawdowns in unconfined aquifers, and anisotropy have been derived, but adequate data for application of the corrections are often not readily available. Much research has also been done on analogs and other models of various types, but too often the geometry of the test apparatus has not duplicated field conditions.

Analyses of results of systematic observations of water level changes and of other test data yield values of aquifer characteristics. The extent and reliability of these analyses are dependent on features of the test including duration of test, number of observation wells, and method of analysis. Two general types of analyses are available for determination of aquifer characteristics: (1) steady state or equilibrium methods which yield values of transmissivity and hydraulic conductivity, and (2) transient or nonequilibrium methods which also yield storativity and boundary conditions. The principal difference between the two methods is that the transient method permits analysis of groundwater conditions which change with time and involve storage, whereas the steady state method does not.

Test analyses also require an understanding and appreciation of the hydrologic and geologic setting of the aquifer. Conditions that should be known include: location, character, and distance of nearby bodies of surface water; depth, thickness, and stratigraphic conditions of the aquifer; and construction details of the test well and of observation wells, if used.

The following subsections describe commonly used analytical models for aquifer pump test data analysis. Also included is a summary of analytical models used to solve for slug testing. For further information on any of these analytical solutions, see the listed papers and Freeze and Cherry (1979), Fetter (1980), and Driscoll (1986).

2.3.2.1 Analytical Techniques for Slug Test Data

Four analytical techniques used in the analysis of slug test data are discussed below. These techniques constitute empirical relationships that are used to solve for the hydraulic conductivity in an aquifer immediate to the test well. Both confined and unconfined aquifer conditions are addressed with two different approaches to solve for conductivity for each condition. The applicability of each analytical technique is contingent upon collected data meeting specified validity criteria as described below.

• Ferris-Knowles Method

In general, this method is applied to wells completed in confined aquifers with hydraulic conductivities than 0.05 cm/sec. The analysis of the data less involves an arithmetic plot of residual drawdown versus the reciprocal of time. Validity of the analysis is determined by fitting a straight line through the plot of the data points, in which the line intersects the origin (0,0). The equation used to solve for hydraulic conductivity, K, using this method is as follows:

$$K = \frac{q(1/t)}{4 \pi H(t)L}$$

Where:

q = Volume Discharged (Slug Volume)
H(t) = Residual Drawdown at Time = t
t = Time
L = Screen Length

The values of 1/t and H(t) are obtained from a straight line fit through the plot of slug test data.

Hvorslev Method

associated The research with this method was originally performed in near-surface saturated soils. As a result, this method is applied to wells completed unconfined aquifers. Analysis of in this method involves а **semilogarithmic** plot of the residual drawdown divided by the instantaneous drawdown versus time. Validity of the analysis is ascertained by fitting a straight line through the plot of the data points so that the line intercepts the coordinate 1,0. Basic equations applied for different are configurations of soil. In general, permeability is a "shape factor" proportional to and inversely proportional to a "time lag." The shape factor is determined from the test well characteristics and dimensions, while the time lag is determined from the semilogarithmic plot. The equation used to solve for hydraulic conductivity, K, using this method is as follows:

$$K = \frac{r^2 \ln(L/R_w)}{2LT_o}$$

Where:

r = Well Casing Radius
L = Screen Length
Rw = Borehole Radius
To = Time Lag When Residual Drawdown/Instantaneous
Drawdown = 10^{-0.4343}

Bouwer-Rice Method

The solution for hydraulic conductivity using this method is more involved than the other methods, resulting from empirical derivations. This method is applied to either partially or completely penetrating wells in unconfined aquifers. Analysis involves a semilogarithmic plot of residual drawdown versus time. A straight line is fitted to the early-time data for use in calculating conductivity. The equation used to solve for hydraulic conductivity, K, using this method is as follows:

$$K = \frac{r^2 \ln(R_e/R_w)}{2L(t)} \ln \frac{H_o}{H(t)}$$

Where:

r = Well Radius R_e = Effective Radius R_w = Borehole Radius L = Screen Length t = Time at Residual Drawdown Measurement H_o = Instantaneous Drawdown at Time, t = 0 H(t) = Residual Drawdown at Time = t

The term $[\ln (R_e/R_w)]$ is determined with one of two empirical relationships. These relationships use one or two empirical coefficients derived from curves based on the value of L_e/R_w .

• Cooper-Bredehoeft-Papadopulos Method

This method applies to wells completed in confined aquifers with hydraulic conductivities less than 0.05 cm/sec. The analysis of the data involves a semilogarithmic plot of residual drawdown divided by the initial residual drawdown versus time. The plot is then matched to a set of type curves. Resulting match points are substituted into an equation as time values for derivation of hydraulic conductivity. The equation used to solve for hydraulic conductivity, K, using this method is as follows:

$$K = \frac{r^2}{tL}$$

Where:

r = Well Casing Radius
t = Time Corresponding to a Metch Point on a Type Curve
L = Screen Length

2.3.2.2 Analytical Techniques for Pump Test Data

Table 2-3 summarizes several of the more commonly used techniques for analyzing pump test data. Details of these sources can be found in Kruseman and DeRidder (1976).

Table 2-3

Analytical Models for Aquifer Test Data Analysis (after Kruseman and DeRidder, 1976)

Aquifer Type	Type of Solution	Method Name*	Туре	Comments
Confined	Steady state	Thiem (1906)	Calculation	
Semiconfined		DeGlee (1930)	Curve fitting	
		Hantush-Jacob (1955)	Straight line	
Unconfined		Theim-Dupuit (1906)	Calculation	
Confined	Unsteady state	Theis (1935)	Curve matching	
		Chow (1952)	Nanograph	
		Jacob (1946)	Straight line	
		Theis Recovery (1935)	Straight line	
Semiconfined	Unsteady state	Walton (1962)	Curve matching	
		Hantush I, II (1956)	Inflection point	
		Hantush III (1956)	Curve matching	
Unconfined with delayed yield	Unsteady state	Bolton (1963)	Curve matching	

Table 2-3 (continued)

Aquifer Type	Type of Solut	of ion	Method	Name*	Туре	Comments
Any	Unsteady	state	Stallma (Ferris 1962)	n et al	Curve matching	Aquifer crossed by fully penetrating recharge or discharge boundary
			Hantush (1959)	Image	Straight line	l recharge boundary only
Any	Unsteady	state	Hantush	(1966)	Calculation	Anisotropic aquifer
Confined			Hantush	(1964)	Curve matching	Variable thickness
Confined	Unsteady	state	Hantush	(1962)	Curve matching or straight line	Partial penetration
Confined			Papadop Copper	ulos & (1967)	Curve fitting	Casing storage
Any	Unsteady	state	Aron & (1965)	Scott	Straight line	Variable discharge
			Sternbe (1967,	rg 1968)	Straight line	Rate-decreasing discharge
			Cooper (1946)	Jacob		Step-pumping

*Descriptions of method and reference are available in Kruseman and DeRidder, 1976.

SECTION 3

MONITORING SYSTEM DESIGN

Designing systems for monitoring groundwater contamination is as much an art as a science because of the numerous factors that should be considered. As a consequence, there may be many technically acceptable system designs for a given set of site conditions, and practically speaking, no one perfect system.

Specifying a groundwater monitoring system requires addressing a variety of elements, as illustrated in Figure 3-1. The focus of this paper is system design, which involves planning the number and locations of wells in the system, as well as the depth (i.e., screen setting) and configuration (Figure 3-2) of each well. Table 3-1 summarizes some of the technical considerations and sources of data for specifying well numbers, locations, and depths. Table 3-2 summarizes the advantages and disadvantages of the five well configurations shown in Figure 3-2.

Figures 3-3 and 3-4 illustrate some of the factors that should be considered in selecting well locations, depths, and configurations. In Figure 3-3, the site is underlain by strata of substantially different hydraulic conductivities. In this situation, the depth and location of each well must be closely coordinated if each hydrogeologic unit is to be monitored adequately. In Figure 3-4, the site is located on a drainage divide and is underlain by sands and clays. In this situation, shallow monitor wells should be placed around the perimeter of the site boundaries on the assumption that groundwater will flow in all directions from the site. Provisions would also have to be made to identify an appropriate off-site location for one or more "background" wells. Furthermore, it would be prudent to also monitor deeper sand zones given that very few geologic units are truly impermeable. In both of these cases, information from geophysical surveys and soil boring samples would be needed to support the design of the monitoring systems.

through 3-12 Figures 3-5 illustrate how а groundwater monitoring system can evolve as additional studies are undertaken on a site. Figure 3-5 is a map view of a hypothetical site located between a forest and a lake. An environmental survey of the site recorded the presence of areas of dead vegetation, a contaminated spring, and contaminated lake sediments (Figure 3-5). Based on this survey and a review of the geology of the area that indicated bedrock sequences of sandstones and shales, a monitoring system was designed to assess groundwater quality. Each of the five wells in the monitoring system, shown in Figure 3-6, were screened in silty



Assess Groundwater Quality; Delineate Horizontal and Vertical Rate And Extent of Contamination; Evaluate Effectiveness of Corrective Actions; Monitor Long-Term Groundwater Quality



Figure 3-1 Elements of Groundwater Monitoring

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Technical Considerations and Data Sources for Monitoring System Design

System Design Parameter	Technical Considerations		Primary Data Sources
Well Locations	 Objectives of monitoring system, waste types and locations, con- taminant geochemistry, access, and clearance 	•]	Background information review
	 Stressed vegetation, fracture traces Contamination of surface waters, springs, or existing wells 	• / •]	Aerial photographs Environmental surveys
	 EM, GPR and other geophysical anomalies 	•	Geophysical surveys
	 Soil-gas anomalies Soil or rock samples, hydrologic measurements 	•	Soil-gas survey Direct field surveys
Well Depths	 Objectives of monitoring system, waste types and locations, con- taminant geochemistry 	•	Background information review
	 Elevations of surface waters, springs, and water in existing wolls 	•	Environmental surveys
	 Stratigraphic information from GPR, seismic, or resistivity 	•	Geophysical surveys
	 surveys Soil or rock samples, hydrologic measurements 	•	Direct field surveys
Well Configura- tions	 Objectives of monitoring system, waste types and locations, con- 	•	Background information review
	 Stratigraphic information from GPR, seismic, or resistivity 	•	Geophysical surveys
	 surveys Soil or rock samples, hydrologic measurements 	•	Direct field surveys



Figure 3-2 Well Configurations Used for Groundwater Monitoring

Table 3-2

Advantages and Disadvantages of Monitoring Well Configurations Shown in Figure 3-2

Well Configurations	Advantages	Disadvantages
Single Zone Well	 Relatively simple to install by a variety of methods Can provide discrete samples from a precise interval thus aiding data interpretation Easy to prevent interaquifer contamination if designed and installed properly 	 Vertical distributions of contaminants or hydraulic gradients cannot be determined Many wells are needed to delineate a plume increasing costs and the time required to install and sample the system
Fully Screened Well	 Relatively simple to install by a variety of methods Can provide composite samples of large intervals thus reducing the number of samples Produces relatively higher yields and thus is useful for pump testing 	 Results are biased if highly contaminated waters are diluted by less contaminated waters during sampling Vertical distributions of contaminants or hydraulic gradients cannot be determined Vertical migration of contaminants may occur over the screened interval spreading contaminants to clean zones Impossible to prevent interaquifer mixing if screened over more than one aquifer
Multiple Sampling Point Well	 Can provide information on the vertical distribution of contaminants and hydraulic gradients Installation is relatively simple although construction takes longer than for wells with a single screen Can be used to obtain composite samples Fewer wells are needed in a monitoring system thus reducing costs 	 Preventing interaquifer contamination is difficult if not impossible Sampling is complicated, time consuming, and requires specialized equipment Cost per well is relatively high

Table 3-2 (continued)

Well Configurations	Advantages	Disadvantages	
Single- Borehole Well Nest	 Provides information on the vertical distribution of contaminants and hydraulic gradients Sampling is not difficult but may require specialized equipment depending on well diameters 	 Requires suitable installation methods Improper construction can reduce effectiveness and allow vertical movement of of contaminants Installation is time consuming Cost per nest is relatively high although cost per well is relatively low 	
Multiple- Borehole Well Nest	 Provides information on hydraulic gradients and the vertical distribution of contaminants Simple to install by a variety of methods Preventing aquifer cross contamination is not difficult Sampling is simple and usually does not require specialized equipment 	 Installation is time consuming but not difficult Cost per nest is relatively high 	



Source. Repa and Kufs, 1985

Figure 3-3 Example of a Situation in Which Geologic Units of Different Hydraulic Conductivities Can Influence the Design of a Monitoring System



Source: Repa and Kufs, 1985

Figure 3-4 Example of a Situation in Which Different Groundwater Flow Directions and Geologic Heterogeneities Can Influence the Monitoring System Design

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After: Repa and Kufs, 1985

Figure 3-5 Result of an Environmental Survey at a Hypothetical Site



After: Repa and Kufs, 1985

Figure 3-6 Monitoring System for Assessing Groundwater Quality



After: Repa and Kufs, 1985

Figure 3-7 Result of a Fracture-Trace Analysis

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After: Repa and Kufs, 1985

Figure 3-8 Result of a GPR Survey

Superimposed on a Cross Section of the Site



After: Repa and Kufs, 1985

Figure 3-9 Result of a Soil-Gas Survey



After: Repa and Kufs, 1985



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Source: Repa and Kufs, 1985

Figure 3-11 Example of the Effects of Site Geology on Leachate Plume Movement (Map View)



Source: Repa and Kufs, 1985

Figure 3-12 Example of the Effects of Site Geology on Leachate Plume Movement

(Cross Sectional View)

sands which overlie shale bedrock. Contamination in the four downgradient wells prompted the site operator to conduct additional studies, including a fracture-trace evaluation (Figure 3-7), a GPR survey (shown in cross section in Figure 3-8), a soil-gas survey (Figure 3-9), and a soil-boring program (Figure 3-9). These studies revealed the presence of a sandstone unit underlying the site and the potential for both bedrock and overburden contamination. Based on these studies, the monitoring system was expanded to assess the directions, extents, and rates of contaminate migration, as shown in Figure 3-10.

Actual site conditions are illustrated in Figures 3-11 (map view) and 3-12 (cross sections). By comparing Figures 3-5 through 3-10 with Figures 3-11 and 3-12, it is easy to understand how even a carefully designed monitoring system could fail to detect a zone of contamination, in this case in the sandstone unit under the lake.

The failures of the hypothetical system described above and many actual systems are frequently the result of presumptions that are made about the extent of contamination based on the contamination observed in wells. Figures 3-13 pattern of through 3-19 illustrate this point further. Figure 3-13 is a hypothetical site located near a small lake and the confluence of two small rivers. Some of the domestic and industrial wells in the vicinity of the site are contaminated while others are not. Figures 3-14 through 3-19 are cross sections of the site a variety of hydrogeologic illustrating and geochemical conditions that could cause similar contamination patterns. Figures 3-14 and 3-15 illustrate simple geologic settings in which the contamination pattern is caused by differences in well depths or improper well construction. In Figure 3-14, the uncontaminated wells are shallow while in Figure 3-15 they are deep. Figure 3-16 illustrates a somewhat more complex geologic situation in which the uncontaminated wells are set within a perched water table. Figure 3-17 shows how complex rock structures can account for the contamination pattern. In Figure 3-17, all the wells are screened at the bottom of sandstone units above shales, and there is a second source of contamination. In Figure 3-18, all the wells are installed in unconsolidated materials above fractured and faulted bedrock. Finally, Figure 3-19 illustrates how two sources of nonaqueous phase liquids (NAPL's), one high density and the other low density, can account for the observed contamination.



Source. Repa and Kufs, 1985

Figure 3-13 Result of Sampling Existing Wells at a Hypothetical Site



After: Repa and Kufs, 1985

Figure 3-14 Example of a Situation in Which Well Construction and Depth Influence the Pattern of Contamination



After: Repa and Kufs, 1985

Figure 3-15 Example of a Situation in Which Well Depth Influences the Pattern of Contamination



After: Repa and Kufs, 1985

Figure 3-16 Example of a Situation in Which Different Water-Bearing Zones Influence the Pattern of Contamination



After: Repa and Kufs, 1985

Figure 3-17 Example of a Situation in Which Rock Structure and Well Depth Influence the Pattern of Contamination



After: Repa and Kufs, 1985

Figure 3-18 Example of a Situation in Which Rock Faults and Fractures Influence the Pattern of Contamination



After: Repa and Kufs, 1985

Figure 3-19 Example of a Situation in Which Contaminant Solubility and Density Influence the Pattern of Contamination

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SECTION 4

PROBLEMS IN MONITORING SYSTEM DESIGN

Because there are so many variables to consider in planning and implementing a monitoring system, it is understandable that most systems do not function as designed. Typical problems found in groundwater monitoring systems can be categorized as: planning problems, implementation problems, site-condition problems, and "special" problems.

Planning problems are commonly the result of using incorrect background information or failing to consider one of the many factors in system design. Examples of planning problems include:

- 0 Wells not positioned appropriately - Usually the an inadequate result of understanding of the hydrogeology of the site and the contaminant's geochemistry or a failure to consider how the system will be used to collect data for the intended purpose.
- <u>Screen lengths not correctly selected</u> Usually for the same reasons as well positions.
- <u>Periodic flow changes not addressed</u> Usually the result of a failure to consider interactions between surface water and groundwater.

Even the most carefully designed monitoring system can fail to achieve its objectives under certain conditions. Two types of problems that can occur even in well-planned systems are associated with the installation of the system and with unanticipated conditions.

Problems that can occur as a result of implementing the system include:

- Screen setting not correct Usually the result 0 of poor judgment in the field or fractionated leachate cannot be monitored easily. Dense nonaqueous that liquids (NAPL'S) phase are good examples of contaminants for which it is difficult to select optimal screen settings.
- <u>Well silts up after installation</u> Usually the result of a broken screen or joint, an inappropriate selection of screen and sandpack for the aquifer material, or inadequate development.

- <u>Gravel pack clogged</u> May be the result of a poorly specified gravel pack or the presence of NAPL's or bacteria that can fill void areas, thus inhibiting flow.
- <u>Well seal leaks</u> Usually the result of improper installation but may be caused by degradation of the seal by contaminants or aggressive groundwater.

Other implementation problems include inappropriate choice of drilling technique, poor selection of well materials, inadequate decontamination, inadequate documentation of well installation, inadequate development, lack of well top identification and security, and poor sampling and analysis techniques.

Problems that can occur as a result of unanticipated site conditions include:

- <u>Well does not produce</u> Usually the result of trying to monitor low-yield zones but may also be caused by inadequate development or poor screen/sandpack design.
- Water table fluctuates greatly Can involve short-term fluctuation such as those caused by tides or seasonal trends in precipitation and evapotranspiration or long-term fluctuations such as those associated with aquifer depletion.
- <u>Pumping wells disrupt flow patterns</u> Usually involves high-capacity supply wells screened in the same zone as the monitoring system and having a large zone of influence or wells screened in adjacent zones that induce recharge from the zone being monitored.
- <u>Undocumented waste sources confound results</u> Usually attributable to inconspicuous waste sources such as buried tanks, sewers, or pipelines, especially when associated with commercial establishments such as gas stations, dry cleaners, beauty salons, photofinishers, and analytical laboratories.

Figure 4-1 illustrates a situation in which the proximity of two sources of contamination could lead to uninterpretable results from a monitoring system. It would also be difficult in this situation to determine "background" water quality conditions given that the upgradient groundwater of the site is contaminated. Confounded results from a monitoring system may also be attributed to degradation of contaminants downgradient of the primary contaminant source.



Source. Repa and Kufs, 1985

Figure 4-1 Example of a Situation in Which Multiple Waste Sources Can Influence Monitoring System Results The last category of problems with monitoring systems includes problems "special" site conditions caused by those or Site contaminant properties. conditions that complicate monitoring system design include the presence of irregularly water-bearing zones and hiqh shaped zones of secondary permeability (i.e., units with fractures or solution cavities). Irregularly shaped aquifers include perched zones, shoestring or fluvial aquifers, interfingered glacial layers, and structurally altered zones (i.e., rock units that have been folded, faulted, or intruded). Fractured units could include almost any rock type, as well as unconsolidated deposits having a high clay content. Solution cavities are most commonly found in carbonate rocks (e.g., limestones and dolomites) although other types may also be dissolved. Figure 4-2 illustrates some of the difficulties of trying to monitor zones of secondary permeability.

Contaminants can also cause problems with monitoring systems because of the transformations and other interactions they undergo in the environment (e.g., sorption, biodegradation, chemical reactions) and because of the way their solubility and influence flow. NAPL's density can can 🕔 be especially troublesome to monitor. Low-density NAPL's will float on top of the water table and depress it somewhat requiring that wells be screened above and below the top of the seasonal high water table. The top of the screen must also be set far enough above the top of the seasonal high water table so that the well will intercept the full thickness of floating NAPL. Furthermore, because of the different properties of water and low-density NAPL's, special equipment is required to determine their depth and thickness. High-density NAPL's will tend not to migrate in the direction of groundwater flow, but rather to sink in an aquifer and follow the topography of a relatively impermeable unit. Figure 4-3 illustrates this concept.

A summary of some of the more common problems with monitoring systems and approaches to prevent or correct the problems is presented in Table 4-1.

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Source: Repa and Kufs, 1985

Figure 4-3 Example of a Situation in Which High-Density NAPLs Could Migrate Against the Direction of Groundwater Flow

Table 4-1

Selected Problems in Monitoring System Design

E	Description of Problems	Approach to Prevention	Approach to Correction
		PLANNING PROBLEMS	
1.	Wells not positioned for triangulating ground- water flow directions.	Use basic hydrogeologic assumptions to estimate flow directions. Use GPR to evaluate validity of assumptions.	Install additional wells or find existing wells screened in the same water-bearing zone.
2.	Wells not positioned for evaluating extent of contamination.	Estimate the distance the plume may have migrated from the site based on site history and hydro- geology and contaminant geochemistry (See Repa and Kufs, 1985). Use aerial image or EM and soil gas surveys to check estimation.	Install additional wells or find existing wells screened in the same water-bearing zone.
3.	Screen length or settings not correctly selected.	Use background geologic and geochemical infor- mational to anticipate contaminant flow. Compare information to on-site soil samples collected from boreholes.	Install additional wells or find existing wells screened in the same water-bearing zone.
4.	Periodic flow changes not addressed.	Use basic hydrogeologic assumptions and back- ground data to anticipate possible flow changes.	Install additional wells or find existing wells screened in the same water-bearing zone.

Table 4-1 (continued)

D	escription of Problems	Approach to Prevention	Approach to Correction
		IMPLEMENTATION PROBLEMS	
1.	Well seals leak.	Design seals to be com- patible with anticipated use of well and site hydrogeology and geochem- istry. Monitor installa- tion of seals closely by repetitive measurements of depth to seal.	Abandon leaking wells to prevent interaquifer leakage and replace well.
2.	Well silts up after installation or sand pack clogs.	Select screen opening size and sand pack gradation to be compatible with geologic materials to be screened.	Redevelop well or replace.
3.	Well construction not documented.	Require contractors to produce as-built diagrams of each well installed.	Use downhole TV and geo- physical logs to approximate well construction details.
		SITE CONDITION PROBLEMS	

1.	Water table fluctuates too far above or below screened portion of well.	Estimate water table fluctuations from historical precipitation recorded and regional water levels in lakes and existing wells.	Schedule sampling to correspond with appropriate water level or replace well.
2.	Pumping wells period- ically disrupt flow patterns.	Identify presence and schedule of any high- capacity wells and estimate their zones of influence. Position monitor wells to assess the effects of inter- mittent pumping.	Collect water level data at regular intervals over time and attempt to model site. Add additional wells as needed.

Table 4-1 (continued)

Description of Problems		Approach to Prevention	Approach to Correction
3.	Undocumented waste sources confound results.	Identify presence of potential contaminant sources and position wells appropriately.	Develop chemical profiles for each well to try to correlate contaminant geo- chemistry. Add additional wells if necessary.
	· · · · · · · · · · · · · · · · · · ·	SPECIAL PROBLEMS	
1.	Presence of irregularly shaped aquifers.	Use background geologic information; GPR, seismic, and resistivity surveys; and soil borings to evaluate aquifer geomet- rically. Install monitor wells in phases to optimize effectiveness.	Conduct geophysical surveys and install additional wells as necessary.
2.	Contaminant migration follows complex fracture patterns.	Evaluate possible fracture patterns using background geologic literature, aerial photographs, measurements of outcrops, oriented cores, downhole flowmeters, packer tests, and appropriate borehole geophysical techniques (Thomas and McGlew, 1986). Install wells in phases to optimize effectiveness.	Conduct additional surveys, such as packer tests and tracer studies, and install wells as necessary.
3.	Aquifer-contaminant interactions confound results.	Identify contaminants of concern and potential environmental transfor- mations. Conduct labora- tory tests if appropriate.	Use statistical models or other advanced techniques to evaluate data inter- relationships. Install additional wells as needed.

Table 4-1 (continued)

	Description of Problems	Approach to Prevention	Approach to Correction
4.	Nonaqueous phase liquids (NAPL's) do not follow expected patterns.	Low-density NAPL's: use soil borings, soil-gas surveys, and geophysical techniques for mapping water tables to approxi- mate contaminant movement patterns. <u>High-density</u> <u>NAPL's</u> : use GPR, seismic, and resistance surveys and soil borings to evaluate stratigraphy relative to movement patterns.	Conduct additional surveys such as packer tests and trace studies and install wells as necessary.

SECTION 5

REFERENCES

Bear, J. Dynamics of Fluids in Porous Media, American Elsevier, NY, NY. 1972.

Bear, J. Hydraulics of Groundwater 2nd ed. McGraw Hill, Inc., NY, NY. 1979.

Benson, R.C. Geophysical Techniques for Sensing Buried Wastes and Waste Migration: An Update. Seminar Presented at the 7th National Conference on the Management of Uncontrolled Hazardous Waste Sites. December 1-3, 1986. Washington, DC. 1986.

Bisque, R.E. Migration Rates of Volatiles from Buried Hydrocarbon Sources in: Petroleum Hydrocarbons and Organic Chemicals in Groundwater Prevention, Detection and Restoration, NWWA/API, pp.267-271. 1984.

Davis, S.N., D.J. Campbell, H.W. Bentley and T.J. Flynn, 1985. Groundwater Tracers. National Well Water Association, Worthington, OH.

Driscoll, F.G. Groundwater and Wells 2nd ed. Johnson Division, St. Paul, MN. 1986.

Fetter, C.W. Applied Hydrogeology. Charles E. Merrill Publishing Co., Columbus, OH. 1980.

Freeze; R.A. and J.A. Cherry. Groundwater. Prentice-Hall, Inc. Englewood Cliffs, NJ. 604 pp. 1979.

Jacob, C.E. Radial Flow in a Leaky Artesian Aquifer. Trans. American Geophysical Union, V. 27, no. 2, pp. 198-205. 1946.

Johnson, W.J. and D.W. Johnson. Pitfalls of Geophysics in Characterizing Underground Hazardous Waste. pp. 227-232 in Proceedings of the 7th National Conference on Management of Uncontrolled Hazardous Waste Sites. Hazardous Materials Control Research Institute (HMCRI), Silver Spring, MD. 1986.

Kelley, D.R. A Summary of Major Geophysical Logging Methods, Pennsylvania Geological Survey M. R. Report 61. 1969.

Keys, W.S. and L.M. MacCary. Applications of Borehole Geophysics to Water Resources Investigations. U.S. Geological Survey Techniques of Water Resources Investigation. Book 2, Chapter E-1. U.S.G.S. Reston, VA. Krauss, E.V., J.G. Oster, and K.O. Thomsen. Processes Affecting the Interpretation of Trichloroethylene Data from Soil Gas Analysis. pp.138-142 in Proceedings of the 7th National Conference on Management of Uncontrolled Hazardous Waste Sites. HMCRI, Silver Spring, MD. 1986.

Kruseman, G.P. and N.A. DeRidder. Analysis and Evaluation of Pumping Test Data. International Institute for Land Reclamation and Improvement. Wageningen, Netherlands. 1976.

Kufs, C.T., D.J. Messinger and S. DelRe. Statistical Modeling of Geophyscal Data. pp. 110-114 in Proceedings of the 7th National Conference on the Management of Uncontrolled Hazardous Waste Sites. HMCRI, Silver Spring, MD. 1986.

Levine, J.D. Capabilities of Soil Sentry Underground Tank Leak Detection System Under Field Conditions. Report for Genelco, Inc., Levine and Fricke, Inc. Consulting Engineers and Hydrologists, Walnut Knoll, CA 1985.

Lohman, S.W. Ground Water Hydraulics. U.S. Geological Survey Professional Paper 708. Washington, D.C. 1979.

Lord, A.E. and R.M. Koerner. Nondestructive Testing Location of Containers Buried in Soil. pp. 161-169 in Proceedings of the 12th Annual Research Symposium on Land Disposal, Remedial Action, Incineration and Treatment of Hazardous Waste. U.S. EPA, ORD, HWERL, Cincinnati, OH. 1986.

Mardia, K.V. Statistics of Orientation Data. Academic Press, Inc., London. 1972.

Morrison, R.D. Ground Water Monitoring Technology: Procedures, Equipment and Applications. Timco Mfg., Inc. Prairie DuSac, WI. 1980.

National Water Well Association. Remote Sensing: Applications to Hydrogeology. NWWA Short Course. October 1-3, 1986. Spring-field, MA. 1986.

Repa, E. and C. Kufs. Leachate Plume Management. EPA/540/2-85/004. U.S. EPA, ORD, HWERL, Cincinnati, OH. 1985.

Sangrey, D.A. and W.R. Philipson. Detecting Landfill Leachate Contamination Using Remote Sensors. EPA/600/4-79/060. U.S. EPA, ORD, EMSL. Las Vegas, NV. 1979.

Scheinfeld, R.A., J.B. Robertson and T.B. Schwendeman. Underground Storage Tank Monitoring: Observation Well Systems. Groundwater Monitoring Review, V. 6, no. 4, pp.49-55. 1986. Smart, P.L. and I.M.S. Laidlaw. An evaluation of Some Flourescent Dyes for Water Tracing. Water Resources Research, V. 13, no. 1, pp. 15-33. 1977.

Stanfill, D.F. and K.S. McMillan. Radar-Mapping of Gasoline and Other Hydrocarbons in the Ground. pp. 269-274 in Proceedings of the 6th National Conference on the Manageement of Uncontrolled Hazardous Waste Sites. HMCRI, Silver Spring, MD. 1985.

U.S. Environmental Protection Agency. Unsaturated Zone Monitoring Techniques (DRAFT). 1986.

U.S. Department of the Interior. Ground Water Manual. U.S. DOI, Water and Power Resources Service, Water Resources Technical Publication. 1981.

Walton, W.C. Groundwater Resource Evaluation. McGraw-Hill Book Co, NY, NY. 1970.

MONITORING SYSTEM

DESIGN AND CONSTRUCTION

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1.0 INTRODUCTION

Monitoring systems are installed to obtain direct information on the physical and chemical characteristics of the ground-water environment. The monitoring well permits determination of hydrologic properties (e.g., nydraulic conductivity and transmissivity), water levels from which flow nets and hydraulic gradients are calculated, and water quality. Well design may significiantly affect the quality of the data produced by the well. The well should therefore be designed to maximize the quality of the data produced.

Well design is affected by many integral factors. any of which may dominate the ultimate monitoring well consuctruction specifications. These tactors include monitoring plan objectives (i.e., which specific types of data will be collected), regulatory criteria (i.e., regulatory guidance or philosophy on preferred design), geologic environment, containment characteristics, and drilling method. The successful well design integrates all of the above factors to maximize the utility and quality of data obtained trom the monitoring well.

Well design and installation involves several physical components including the drilling equipment, well case, well screen (or open hole), filter packs, annulus sealers (plugs and grouts), well development, and above-grade appurtenances. This paper presents an overview of the components of the well system emphasizing interrelationships with other well components and advantages and disadvantages of each.

2.0 DRILLING METHODS

The choice of drilling method is dependent upon the hydrogeology of the site, intended use of the well, depth of the zone to be monitored, and other site-specific factors.

In this section, the mechanics of several drilling methods are discussed. Section 3 details the controlling factors to consider when selecting a drilling method, Section 4 describes well construction materials, and Section 5 discusses well development techniques.

Drilling methods discussed below include: o Cable Tool o Solid-Stem Continuous Flight Auger o Hollow-Stem Auger o Water Rotary o Mud Rotary o Air Rotary o Reverse Circulation Rotary Techniques

Cable Tool Drilling

Cable tool drilling machines operate by repeatedly lifting and dropping a heavy string of drilling tools suspended at the end of a cable. The tools consist of five components: a drill bit, a drill stem, drilling jars, a swivel socket, and a cable as shown in Figures 1 and 2. In consolidated rock, the drill bit breaks the rock into small fragments; in unconsolidated rock, the bit primarily loosens the material. The reciprocating action of the tools mixes the crushed and loosened particles with water (added or naturally occurring) to form a slurry at the bottom of the borehole. The slurried cuttings are bailed from the well periodically prior to advancement of the borehole.

The drill stem adds additional length and weight to the bit to maintain a straight borehole during drilling. Drilling jars consist of a pair of linked. neat-treated steel bars, whose primary function is to free the bit when it becomes stuck. The swivel socket connects the string of tools to the cable, and the socket's weight supplies upward energy to the drilling jars when the bit becomes stuck.

The drill line is a wire cable that carries and rotates the drilling tools. It twists the tool joint on each upstroke to prevent it from unscrewing.

Cable tool drilling rates are affected by the resistance of the rock, the weight of the drill tools, the diameter of the bit, the length of the stroke, the number of strokes per minute, and the thickness and depth of accumulated cuttings in the borehole. As depth increases, more time is needed to remove the drilling tools, bail out the slurry, and reinsert the tools.



Figure 1. Cable Tool Drilling Components (Johnson Division, UOP, 1975)



Figure 2. Cable Tool Operation

Advantages in using the cable tool method include:

- o Drill rigs are relatively inexpensive
- o Drill rigs are simple in design and require little sophisticated maintenance
- o Borehole is stabilized during entire drilling operation
- Collection of excellent undisturbed formation samples is possible
- o This method is amendable to most geologic conditions

Disadvantages of the cable tool method include:

- Relatively slow penetration rates result in relatively high costs
- o The use of water during drilling may dilute formation water

Solid-Stem Continuous-Flight Auger

Solid-stem augers consist of auger flights welded to a solid core as shown in Figure 3. Drilling is performed by rotating the augers, which convey material to the surface. The solid-stem auger uses either a single flight (one section) or continuous flights (several sections). Augers with one flight can have diameters as large as 54 inches, but average diameters range from 6 to 24 inches. Special hardened teeth or cutters are attached when drilling through hard ground, cobbles, or soft rock. Single flight augers are not effective in loose ground or below the water table. However, single-flight augers are sometimes used to bore a large diameter hole to the water table, and after casing is set, the well is completed using another drilling method.

Solid-stem continuous-flight augers are used to advance holes in stable formations. The auger sections are turned by means of a rotary drive head mounted on a hydraulic-feed mechanism. Auger lengths are usually 5 feet, and the usual well depth is 40 to 120 feet.

Advantages of using the solid-stem auger include: o Operating cost is low o Drilling rigs are highly mobile

Disadvantages include: o Sample recovery is poor o Use is limited to unconsolidated materials o Depth is usually limited to 150 feet o Borehole tends to cave in

Hollow-Stem Continuous-Flight Auger

This method is commonly used when drilling in unconsolidated material. Figure 4 shows a hollow-stem auger. Flights are welded onto larger diameter pipe with a cutter head mounted at the bottom. Unlike the solid-stem auger, a drill stem can be passed through the center of the hollow-stem auger. A plug with an attached bit may be inserted into the cutter head to prevent soil from entering the inside of the auger. The bit aids in advancing the hole. A drill rod and plug, which rotate with the flights, connect through the auger to the top-head drive unit by small diameter rods. The most common outside



Figure 3. Solid-Stem Continuous-Flight Auger



Figure 4. Hollow-Stem Auger (Johnson Division, UOP, 1986)

diameters are 6 1/4 to 22 inches (inside diameter of 2 1/2 to 13 inches). Auger lengths average approximately 5 feet. Holes as deep as 300 feet have been drilled with hollow-stem augers with outside diameters of 6 1/4-inches. More commonly, the hollow-stem auger can drill to about 120 feet in stable formations with a 6 1/4-inch outside diameter and to about 40 feet with a 120-inch diameter.

Advantages of using the hollow-stem auger include:

- o Relatively low operating cost
- No drilling fluids are introduced into the borehole; no possibility of diluting formation water
- Formation waters can be sampled during drilling by using a screened auger or by advancing a well point ahead of the augers
- It is more effective than solid-stem augers because hollow-stems can be used as temporary casing to prevent the borehole from caving
- o Drilling is fast and efficient
- o Undisturbed samples can be easily obtained

Disadvantages of using the hollow stem auger include:

- o It normally cannot drill deeper than 150 feet
- o It can be used only in unconsolidated sediments

Water Rotary

in water rotary drilling, water is introduced into the borehole through the drill pipe and circulates back up the borehole to remove drill cuttings as shown in Figure 5. Roller-type rock bits consisting of two, three, or four cones with teeth are mounted on a bit body by means of roller or ball bearings. The bit is rotated by the drill rod, and the teeth on the bit strike the formation to break it into smaller pieces. Great care must be taken to ensure that water used in the drilling process does not contain contaminants.

Advantages of water rotary drilling include:

- o It can drill in both consolidated and unconsolidated formations
- o It can drill to any depth
- o Drilling is relatively fast

Disadvantages of water rotary drilling include:

- Water-bearing zones are difficult to recognize because of the addition of water to the system
- Caving of the borehole is a problem in poorly consolidated sediments
- Water circulation is difficult to maintain in highly fractured material
- o Drilling fluid may affect quality of water in formations



Figure 5. Components of Rotary Drilling Operation (Geraghty & Miller; Booz, Allen, and Hamilton, 1982)

Mud Rotary

The mud rotary drilling method operates the same way as water rotary drilling except that various types of muds are circulated instead of air or water. The use of mud helps to stabilize the borehole. Figure 6 shows a mud rotary drilling operation.

Muds used include bentonite, barium sulfate, and organic polymers. Care must be taken to ensure that the muds do not affect ground-water chemistry, borehole samples, or well operations. For example, bentonite muds often tighten the formation around the annulus making it difficult to assess aquifer characteristics.

Advantages of using the mud rotary method include:

- o It can drill in both consolidated and unconsolidated material
- o It can drill to any depth
- o Drilling is fast
- o Mud stabilizes the borehole

Disadvantages of the mud rotary method include:

- o Undisturbed samples are difficult to obtain
- o Bentonite fluids can interfere with well operations
- o Organic fluids can sometimes affect monitoring parameters
- o Water bearing zones are difficult to locate

Air Rotary Method

In air rotary drilling, air is forced down the drill pipe and back up the borehole to remove the drill cuttings. Compressed air is directed into the drill pipe and through the bit as it rotates. The air strikes the rock as it is cut and blows it away from the bottom of the bit. The velocity of the air is great enough to carry the cuttings to the surface.

Advantages of using the air rotary method include:

- Orilling does not affect the quality of ground water from monitoring wells in hard rock formations
- o Can drill in both consolidated and unconsolidated material
- o Can drill to any depth
- o Because formation water is blown out of the borehole, it is easy to determine where water-bearing zones exist
- o Drilling is fast

Disadvantages of this method include:

- o It is relatively more expensive than other drilling method
- Casing or additives may be required to keep borehole open in soft formations below the water table
- o Undisturbed samples are somewhat difficult to obtain
- o It may not be economical for small jobs
- o Drilling rig is not very mobile



Figure 6. Mud Rotary Drilling

Reverse Circulation Rotary Drilling

The drilling methods described for air, water, and mud rotary drilling are generally effective in removing drill cuttings from the borehole. If cuttings are not removed, drilling cannot continue. The reverse circulation technique is designed to remove drill cuttings more efficiently than other drilling methods.

Drilling is accomplished by using gravity to run drilling fluid down the annulus around the drill pipe as shown in Figure 7. The fluid picks up cuttings and is pumped back up through holes in the drill bit. The fluid and cuttings move upward inside the drill-string assembly and are pumped to a settling pit. The drilling fluid usually consists of a muddy water rather than bentonite or mud.

The equipment consists of a rotary table, and two engines: one to run the rotary table and one to run the pump. A drill rod is used and may range in diameter from 3 to 8 inches with lengths ranging from 10 to 30 feet. Several types of bits are used, depending upon the type of material drilled. All bits have open bottoms to allow cuttings to enter.

Advantages of using the reverse-circulation technique include: o It is favorable for drilling in sand, silt, or clay o It is favorable for drilling in areas where the static water level depth is 10 feet or more

Disadvantages of this method include: o It is less effective in hard rock formations o It requires a large water supply

o Rigs can be expensive



Figure 7. Principles of Reverse Circulation (Johnson Divison, UOP, 1975)

3.0 CONTROLLING FACTORS IN SELECTING A DRILLING METHOD

Several factors should be considered before a drilling method is selected. The chief factors to consider are:

- o Geologic formation to be drilled
- o Depth of the well to be drilled
- o Size of well

Because the objective of a ground-water monitoring well is to obtain representative ground-water data that will yield reliable information, an accurate description of the site geology should be obtained. This should include a definition of the geology beneath the site and identification of ground-water flow paths and rates. Table 1 lists drilling methods for various geologic conditions.

In addition to considering hydrogeologic conditions at the site, it is important that the intended well use be considered, since this will, to some extent, dictate well diameter and well depth. The diameter of a monitoring well is predicated on the size of the sampling device or pump to be used. The smaller the diameter, the less the cost for drilling and construction. Large diameter wells are necessary with a well depth of over 200 feet, or if the well will be used to recover contaminated water for remedial purposes. Certain drilling methods are most effective when drilling to certain depths. fable 2 presents well drilling methods and their most effective diameters and depths.

The cable tool method is used to drill in a variety of hydrogeologic conditions. It is usually the preferred method when drilling in cavernous rock or other highly permeable material. Although boulder beds and glacial material are both difficult to drill through by any method, the cable tool usually does best since boulders or cobbles can be cracked or chipped by hard blows of the bit. An advantage of the cable tool method is that it can drill wells to a depth of 400 feet, and it has no borehole diameter restrictions.

The hollow-stem auger method is most often used when drilling in unconsolidated sediments. Using this method, wells can be constructed in tirm, non-caving environments. When the borehole will not stand open by itself, the hollow-stem auger can be used as a temporary casing. Because no arilling fluids are involved, there is minimal disturbance to the acuifer. The hollow-stem auger is less effective in saturated material and below the water table. The maximum drilling depth is approximately 100 feet, and the borehole diameter range is limited to 9 to 12 inches. If vertical leakage of water through the borehole is a concern, the hollow-stem auger method should not be used.

Use of the solid-stem auger is limited to fine-grained unconsolidated materials that will maintain an open borehole or in consolidated sediments. Its use below the potentiometric surface is limited, and maximum drilling depth is about 200 feet.

TABLE 1

DRILLING METHODS FOR VARIOUS TYPES OF GEOLOGIC SETTINGS

	Drilling Methods				
Geologic Environment	Air Rotary	Water/Mud Rotary	Cable Tool	Hollow-Stem Continous Auger	Solid-Stem Continuous Auger*
Glaciated or unconsolidated materials less than 150 feet deep	9	۲	9	9	Ø
Glaciated or unconsolidated materials more than 150 feet deep	Ð	÷	۲		
Consolidated rock formations less than 500 feet deep (minimal or no fractured formations)	9	9	۲		
Consolidated rock formations iess than 500 feet deep (highly fractured formations)	٠	ø	Ċ		
Consolidated rock formations more than 500 feet deep (minimal formations)	۲	Û	9		
Consolidated rock formations more than 500 feet deep (highly fractured formations)	@	9	œ		

* Above potentiometric surface.

NOTE:

Although several methods are suggested as appropriate for similar conditions, one method may be more suitable than the others.

(From Draft RCRA Ground-Water Monitoring Technical Enforcement Guidance Document, U.S. EPA.)

TABLE 2

	Cable Tool	Hollow- Stem Auger	Solid- Stem Auger	Air Mud Rotary Rotary
Depth Restrictions	up to 400'	<u>+</u> 100'	+ 200'	none none
Hole Diameter	unlimited	9-12"	18-20"	none none

DRILLING METHOD VS WELL DEPTH AND WELL DIAMETER

Rotary drilling can generally be used to drill holes in all types of geologic conditions, but it is best suited for drilling in hard rock formations. In soft rock formations, casing is driven to keep the formations from caving. The use of drilling fluids provide a much more stable borehole than the auger method. When contamination from drilling fluids is a concern, air rotary drilling can be used without affecting ground-water quality. The air rotary method should not be used when drilling in areas where the upper soil horizons are contaminated because the sloughing off of sidewalls can contaminate the well. Also, care should be taken when using the air rotary technique in a highly contaminated environment. Contaminated solids and water blown out of the hole are difficult to contain at the surface. The rotary drilling method is capable of drilling to any depth, with any size diameter.

4.0 WELL CONSTRUCTION MATERIALS

In this section, the following specific components of well completion are aiscussed:

- o Drilling fluids
- o Casing
- o Grouting
- o Screens

Drilling Fluids

As discussed in Section 2.0, drilling fluids are essential in the rotary drilling method. Drilling fluids include air, water, or specially-prepared mixtures of materials. Drilling fluids perform several functions:

- o They remove drill cuttings from the borehole
- o They support the borehole and prevent it from caving
- o They seal the borehole to prevent fluid loss
- o They cool, lubricate, and clean the bit

Drilling fluids used to construct ground-water monitoring wells are either water-based or air-based. Table 3 outlines some of the more common drilling fluids used today. Water-based drilling fluids consist of a liquid phase, colloidal phase, and cuttings from the drilling process. Air-based fluids usually consist of a dry air phase and a water phase to which a surfactant is added to produce a foam.

The type of drilling fluid used depends on the porosity of the material being drilled. When drilling in unconsolidated material, a water-based drilling fluid system with clay or polymeric additives are typically used. In well-consolidated or semi-consolidated materials, air is generally used.

A great variety of additives are available to modify the chemical and physical properties of air and water so that drilling can be performed more satisfactorily. Table 4 lists some of the more common commercial additives and their uses.

Casing Installation

A well is cased to prevent collapse of the borehole wall and to prevent surface drainage or polluted water from contaminating the well. Casing typically extends at least 1 foot above the ground.

A variety of materials have been used to construct casing including virgin fluorocarbons, resins, stainless steel, cast iron, galvanized steel, polyvinyl chloride (PVC), polyethylene, epoxy biphenyl, and polypropylene. Many of these materials can affect ground-water quality. For example, steel casing deteriorates in corrosive environments, and PVC deteriorates in the presence of ketones, esters, and aromatic hydrocarbons as discussed in Table 5. Therefore, selection of a casing material should be made with consideration to geochemistry, well depth, and chemical parameters to be monitored for, among others.

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MAJOR TYPES OF DRILLING FLUIDS USED IN THE WATER WELL INDUSTRY

	Water Based		Air Based
1.	Clean fresh water	1.	Dry air
2.	Water with clay additives	۷.	Mist: Droplets of water entrained in the airstream
3.	Water with Polymeric additives	3.	Foam: air bubbles surrounded by a film of water containing a foam-stabilizing surfactant
4.	Water with clay and polymeric additives	4.	Stiff foam: Foam containing tilm-strenghtening materials such as polymers and bentonite

Source: Fletcher Driscoll, <u>Groundwater and Wells</u>, Second Edition

FABLE 4

TYPICAL ADDITIVE CONCENTRATIONS, RESULTING VISCOSITIES, AND REQUIRED UPHOLE VELOCITIES FOR MAJOR TYPES OF DRILLING FLUIDS IN VARIOUS AQUIFER MATERIALS

Base Fluid	Additive/ Concentration	Observations
Water	None	For normal drilling (sand, silt, and clay).
Water	Clay (High-Grade Bentonite)	Increases viscosity (lifting ca- pacity) of water significantly.
	15-25 lb/100 gal	For normal drilling conditions (sand, silt, and clay).
	25-40 lb/100 gal	For gravel and other course- grained, poorly consolidated formations.
	35-45 lb/100 gal	For excessive fluid losses.
Water	Polymer (Natural	Increases viscosity (lifting capacity) of water siginificantly.
	4.0 lb/100 gal	For normal drilling conditions (sand, silt, and clay).
	6.1 lb/100 gal	For gravel and other course- grained, poorly consolidated formations.
	6.5 lb/100 gal	For excessive fluid losses.
		Cuttings should be removed from the annulus before the pump is shut down, because polymeric drilling fluids have very little gel strength.
Air	None	Fast drilling and adequate cleaning of medium to fine cut- tings, but may be dust problems at the surface.
		This range of annular uphole velocities is required for the dual-wall method of drilling.

TABLE 4 (Continued)

Base Fluid	Additive/ Concentration	Ubservations
Air	Water (Air Mist) 0.25-2 gpm	Controls dust at the surface and is suitable for formations that have limited entry of water.
Air	Surfactant/Water (Air-Foam)	Extends the lifting capacity of the compressor.
	1-2 qt/100 gal (0.25-0.5% surfactant)	For light drilling; small water inflow: also for sticky clay, wet sand, fine gravel, hard rock; few drilling problems.
	2-3 qt/100 gal (0.5-0.75% surfactant)	For average drilling conditions; larger diameter, deeper holes; large cuttings; increasing volumes of water inflow; excellent hole cleaning.
	3-4 qt/100 gal (0.75-1% surfactant)	For difficult drilling; deep, Targe-diameter holes; large, heavy cuttings; sticky and incompetent Formations; large water inflows.
		Injection rates of surfactant/water mixture: Unconsolidated Formations 3-10 gpm Fractured rock 3-7 gpm Solid rock 3-5 gpm
Air	Surfactant/Colloids/ Water (Stiff Foam)	Greatly extends lifting capacity of the compressor.
	3-4 qt/100 gal (0.75-1% surfac- tant plus 3-6 lb polymer/100 gal or 30-50 lb bentonite/100 gal	For difficult drilling; deep, large-diameter holes; large, heavy cuttings; sticky and incompetent formations; large water inflows.
	4-9 qt/100 gal (1-2% surfactant) plus 3-6 lb polymer/100 gal or 30-50 lb bentonite/100 gal	For extremely difficult drilling; iarge, deep holes; lost circula- tion; incompetent formations; excessive water inflows.

⁽Compiled partly from information presented in Imco Services, 1975; Magcobar, 1977; and Baroid, 1980.)
TABLE 5 WELL CASING AND SCREEN MATERIAL

Туре	Advantages	Disadvantages
PVC (Polyvinyl- chloride)	 o Lightweight o Excellent chemical resistance to weak alkalies, alcohols, alipha- tic hydrocarbons, and oils o Good chemcial resistance to strong mineral acids, concentrated oxidi- zing acids, and strong alkalies o Readily available o Low priced compared to stainless o steel and Teflon 	 o Weaker, less rigid, and more temperature sensi- tive than metallic mate- rials o May absorb some constitu- ents from ground water o May react with and leach some constituents from ground water o Poor chemical resistance to ketones, esters, and hydrocarbons
Polypropylene	 Lightweight Excellent chemical resistance to mineral acids Good to excellent chemical resist- ance to mineral acids Good to excellent chemical resist- ance to alkalies, alcohols, ketones and esters Good chemical resistance to oils Fair chemical resistance to con- centrated oxidizing acids, ali- phatic hydrocarbons, and aromatic hydrocarbons Low priced compared to stainless steel and Teflon 	 o Weaker, less rigid, and more temperature sensi- tive than metallic mate- rials o May react with and leach some constituents into ground water o Poor machinability-it cannot be slotted be- cause it melts rather than cuts
Teflon	 o Lightweight o High impact strength o Outstanding resitance to chemical attack; insoluble in all organics except a few exotic fluorinated solvents 	 Tensile strength and wear resistance low compared to other engineering plastics Expensive relative to other plastics and stain- less steel
Kynar	o Greater strength and water resist- ance than Teflon o Resistant to most chemicals and solvents o Lower priced than Teflon	o Not readily available o Poor chemical resistance to ketones, acetone

(Continued)

Туре	Advantages	Disadvantages	
Mild steel	o Strong, rigid; temperature sensi- tivity not a problem o Readily available o Low priced relative to stainless steel and Teflon	 o Heavier than plastics o May react with and leach o some constituents into ground water o Not as chemically resist- 	
Stainless Steel	 o High strength at a great range of temperatures o Excellent resistance to corrosion and oxidation o Readily available o Moderate price for casing 	 ant as stainless steel o Heavier than plastics o May corrode and leach some chromium in highly acidic waters o May act as a catalyst in some organic reactions o Screens are higher priced than plastic screens 	

TABLE 5 (Continued)

Source: Fletcher Driscoll, Groundwater and Wells, Second Edition

Screens

Screens provide formation support and sand control. Common screening materials include stainless steel, bronze, galvanized steel, and plastic. Screens have openings of varying sizes to fit the size of the surrounding water-bearing sands. Well screens should have the following characteristics:

- o They should be constructed of a material that is inert in the water-bearing strata
- Open area should be maximized to facilitate rapid sample recovery
- o Slot openings should be a nonplugging design

Care should be taken in selecting a screen material because many common screen materials can react with ground water and produce erroneous waterauality data. When selecting a screen material, consider the following factors:

- o The contaminants to be sampled
- o Chemical reactiveness
- o Material strength
- o Ease of installation
- o Material cost

Table 5 lists some common screening materials and their advantages and disadvantages.

Typical screen lengths are 2 to 5 feet for wells used to collect water samples. Screens monitoring ground-water quality are generally 10 to 20 feet iong, depending upon anticipated variations in ground-water elevation. Part of the screen is always above the ground-water table in the vadose zone to monitor for hydrocarbons or other volatiles that might have reached the ground-water table.

Grouting

Grouting well casing involves filling the annular space between the casing and the drilled hole to secure the casing in place and exclude water and other materials from entering the borehole. Grouting is standard practice in all monitoring well installations.

Most grout consists of cement or bentonite. Table 6 lists these two grouting materials and their advantages and disadvantages.

One concern with grouting is that the seal is inadequate due to premature hydration of the clay in a bentonite grout. Another potential grouting problem is that if the volume of material necessary to seal the annular space is overestimated, the grout may be forced into the formation. This tends to elevate the pH level of water samples.

Selection of grouting material should be made in consideration of the formation groundwater. Refer to Table 6 for specific considerations.

Гуре	Advantages	Disadvantages
dentonite	o Readily Available o Inexpensive	<pre>o May produce chemical interfer- ence with water-quality analysis o May not provide a complete seal because: -There is a limit (14 percent) to the amount of solids that can be pumped in a slurry. Thus, there are few solids in the seal; should wait for liq- uid to bleed off so solids will settle -During installation, bentonite pellets may hydrate before reaching proper depth, thereby sticking to formation or casing and causing bridging -Cannot determine how effec- tively material has been placed -Cannot assure complete bond to caning</pre>
Cement	 Readily available Inexpensive Can use sand and/or gravel tilter Possible to determine how well the cement has been placed by temperature logs or acoustic bond logs 	 May cause chemical interferences with water-quality analysis Requires mixer, pump, and tremie line; generally more cleanup than with bentonite Shrinks when it sets; complete bond to formation and casing not assured

TABLE 6 GROUTING MATERIALS FOR MONITORING WELLS

Source: Fletcher Driscoll. Groundwater and Wells, Second Edition

5.0 Well Development

Well development involves those steps necessary to provide the aquifer the easiest possible path into the well. In unconsolidated formations, the coarsest sands and gravels should be concentrated next to the well screen, with the degree of fineness increasing as distance from the well increases until it roughly equals that of the aquifer. As a result, water moves more freely as it approaches the well. In consolidated formations, wells are developed by assuring free flow from fractures or by increasing the fractures by artificial means.

There are several methods of developing wells, either by natural means or by gravel-packing. These include overpumping; backwashing; surging, either with a plunger or by air; jetting; or using chemicals and explosives.

Overpumping is considered the simplest method of removing fines from water-bearing formations. This procedure involves pumping at a higher rate than the well will normally be pumped. Ordinarily, a test pump is used for overpumping.

Backwashing development procedures cause a reversal of flow through the screen openings that will agitate the sediment, remove the finer fraction, and then rearrange the remaining particles. By reversing the flow, the bridging between large particles across screen openings is broken down. The backwash portion of the procedure breaks down the bridging, and the inflow moves the fine material toward the screen and into the well.

Mechanical surging is the process of operating a plunger to force water into and out of a screen. The downstroke of the plunger forces water out of the well and into the surrounding formation. The upstroke pulls water back into the well, bringing with it sand, silt, and other material fine enough to pass through the screen. By forcing water out of the well, the surge breaks up the bridges of sand particles.

Air compressers are sometimes used to develop wells in consolidated and unconsolidated formations. The well is alternately surged and pumped with air by injecting the well with air to lift the water to the surface. As it reaches the top of the casing, the air supply is cut off to allow the aerated column of water to fall. This helps move sediment away from the screen.

Development by high velocity jetting can be performed with either water or air. Jetting with water almost always involves simultaneous air-lift pumping so that the formation does not clog. Water is pumped through small nozzles at high velocity. This allows a small area of the well to be treated, concentrating on areas with the greatest problems, until the entire well is developed.

Development using explosives, chemicals, and acids is useful when a "skin" of caked clay and drilling mud is left on the borehole. Dispensing agents added to water work well in clay formations to help break up the skin. In hard rock, explosives are used to develop wells in fractured or faulted areas. Acids work well when developing wells in limestone, since limestone dissolves in acid. With fractures around the borehole opened, particles can be removed from openings and water can flow more freely to the well.

REFERENCES

- Departments of the Army and the Air Force, 1965. <u>Well Drilling Operations</u>. Washington, D.C.
- Freeze, R.A., and J.A. Cherry, 1979. <u>Groundwater</u>. Prentice-Hall, Inc. Englewood Cliffs, N.J.
- Geraghty & Miller, Inc., and Booz, Allen, & Hamilton, Inc., 1982. <u>Injection</u> <u>Well Construction Practices and Technology</u>. Prepared for U.S. EPA, Uffice of Drinking Water, Washington, D.C.
- Johnson Division, 1986. <u>Groundwater and Wells</u>. Johnson Division. St. Paul, MN.
- U.S. EPA, 1980. <u>Procedures Manual for Ground-Water Monitoring at Solid Waste</u> <u>Disposal Facilities</u>, U.S. EPA, Office of Water and Waste Management, Washington, D.C.
- U.S. EPA, 1985. <u>Leachate Plume Management</u>. U.S. EPA, Office of Solid Waste. Cincinnati, OH.
- U.S. EPA, 1986. Draft RCRA Ground-Water Monitoring Technical Enforcement Guidance Document. U.S. EPA, Office of Waste Programs Enforcement.
- Wehrman, H.A., 1983. "Monitoring Well Design and Construction." <u>Ground Water</u> <u>Age</u>. April, 1983.

The following articles and tables were selected to provide additional information on Monitoring System Design and Construction (Articles are reprinted courtesy of the National Water Well Association.) They can be found in Appendix A.

- 1. Table: Monitoring Well Design Rating System
- 2. Table: Drilling Method Rating System
- 3. Selection of Drilling Method, Well Design and Sampling Equipment for Wells to Monitor Organic Contamination
- 4. Small vs Large Diameter Monitoring Wells
- 5. An Evaluation of Nested Monitoring Wells
- 6. Custom Designing of Monitoring Wells for Specific Pollútants and Hydrogeological Conditions
- 7. Method to Avoid Ground-Water Mixing Between Two Aquifers During Drilling and Well Completion Procedures
- 8. Will My Monitoring Wells Survive Down There? Design and Installation Techniques for Hazardous Waste Studies
- 9. A Technique for Renovating Clogged Monitor Wells

CHAPTER IV PROBLEM AREAS IN GROUNDWATER SAMPLING

PROBLEM AREAS IN GROUNDWATER SAMPLING

INTRODUCTION

This paper is essentially an essay, in all senses of the word, on groundwater sampling for waste management facilities. It is not intended to provide exhaustive prescriptions for sampling strategies, devices, or procedures. These subjects are capably and voluminously addressed by many other authors (see the attached reference list) and in any number of other seminars and courses. Rather, the purpose of this paper is to try opinions, to provoke thoughtful or heated discourse about some difficult aspects of groundwater sampling.

NEGOTIATED TECHNOLOGY, NOT SCIENCE

Some preliminary axioms regarding the monitoring of waste management facilities:

- The fundamental objective is to assure that a facility has no (or, at least, no unacceptable) deleterious affects.
- Therefore, samples representative of adjacent, potentially affected environments are obtained and analyzed chemically.
- The representativeness of samples is assured by forestalling or removing errors associated with sampling.
- Analyses of the samples are then used to evaluate the deleterious effects of the facility.

Every single sample taken in this context, then, begs the following questions:

- How is representativeness¹ defined?
- What are the sources of error associated with sampling?
- o What defines deleterious effects?

These three questions are clearly motivated by a concern for the truth of the matter, by a scientific spirit. However, they are extremely difficult to address, even in a

In response to a comment on an earlier draft: "representativeness" is indeed a word, albeit an awkward

one. See Webster's New Collegiate Dictionary, 1974.

rigorously scientific, experimental context. And they are raised here in an engineering context: a large number of facilities must be monitored, even-handedly, at reasonable cost and in reasonable time. In fact, they are currently answered, either explicitly or implicitly, in this same context. In other words, the practical answers to these questions are always negotiated. It is useful to think of these negotiated, practical answers as an evolving "state of the practice". The state of the practice is, by definition, distinct from the "state of the art," which is avowedly scientific and free of political concerns.

Representativeness

Every definition of representativeness incorporates, whether explicitly or not, a definition of representative spatial and temporal scales. Put very simply, every groundwater sample has a finite volume and, prior to its withdrawal, occupied a finite volume of pore space(s) in the ground. Furthermore, the sample was withdrawn over a finite period of time. What must the size of the sample volume be, where and when exactly must it derive from, in order to represent the medium being sampled? Representative scale is a fundamental issue of groundwater sampling, one which underlies many arguments (negotiations) about appropriate monitoring procedures for waste management facilities.

It is natural to think of a representative sample as one for which an accuracy can be defined. In the purest statistical sense, however, it is not clear how to define the accuracy of an analysis of a groundwater sample. As Barcelona et al. (1985, p. 11) said it, "...sampling accuracy cannot be verified in the field since the 'true' or in situ value is unknown and it is most unlikely that any single (or average) value for a particular chemical constituent could be considered as the 'true' one except for very localized sites."

In part because of the complexity and difficulty of these two issues--issues of scale and accuracy--there is a tendency to identify representativeness with standard sampling protocols, and to assume that reproducible analytical results indicate that the protocols were implemented in an acceptable manner. As a matter of logic only, this approach is seriously flawed. As a practical matter, however, standardization does have value, even though standard protocols do not and cannot address fundamental issues of representativeness. Standard protocols remove or control some sources of error, and they therefore give some bounds to our ignorance.

Sources of Error

Many potential sources of error in groundwater sampling are obvious, have been the subject of fruitful study, and can therefore be controlled. Obvious potential sources of error can be seen as falling into three categories: those involving the improper choice or use of sampling (1) materials, (2) mechanisms, and/or (3) procedures. If number of publications is any index, the definition of the state of the practice currently revolves around the minutia of protocols intended to address these obvious sources of error.

Appendices A through C present examples of the lengths to which the prescription of sampling protocols may be taken. Appendix A is a portion of an example groundwater sampling plan for use by relatively inexperienced field personnel at a site which does not have free-phase contaminants. Appendix B excerpts a portion of the RCRA Ground-Water Monitoring Technical Enforcement Guidance Document (TEGD), and Appendix C excerpts a portion of the RCRA Ground-Water Monitoring Compliance Order Guidance. Both excerpts are exhaustive checklists of the technical details involved in obtaining "error-free" groundwater samples.

The Definition of Deleterious

Monitoring protocols and concentration standards are explicit or implied in all definitions of "deleterious." Obviously, those constituents of a sample which may be harmful (or may indicate harm) must be identified before the sample is taken and analyzed. Just as obviously, the results of analyses of representative samples will be used in some way; the results must at least be compared to concentration standards. Extant standards range from those which are practically simple because they have already been negotiated (e.g., maximum contaminant levels) to those which are so complex or poorly defined that they explicitly require further negotiation (e.g., alternate concentration limits). The methods of comparison of analyses to standards also range from simple and direct (e.g., is one concentration greater than the other?) to complex and under development or negotiation (e.g., statistical tests or risk calculations).

The definition of deleterious becomes increasingly difficult as issues of temporal and spatial scale are drawn into the definition. Logically, the definition of the risks posed by a facility requires prediction of the concentrations of contaminants at all points of possible exposure over the entire period during which the facility may have harmful effects. In other words, the definition of deleterious logically requires definition of the spatial and temporal scales which characterize a facility and its environs. Consequently, if the preliminary axioms of this essay (p. IV-1) hold true, then the definitions of representativeness and deleterious are not independent. In short, the preliminary axioms are circular: we must take representative samples in order to determine deleterious effects, but we cannot really define what a representative sample is until we know what those effects might be. This explains why the establishment of an "acceptable" groundwater sampling program must invariably be an iterative process, one which can proceed only through judgment and negotiation. In this process, definitions of representativeness and deleterious are approached through successive approximation; "final" definitions are never attained.

EXAMPLES FROM THE PRACTICE

The issues raised above are manifested directly and concretely in the daily discourse of hydrogeologists; they are addressed in the evolving state of the practice.

What is Being Sampled?

There is, of course, general agreement that a representative sample of groundwater should consist of "undisturbed" pore water. Whether undisturbed pore water should contain sediment (colloidal or suspended) or not is sometimes debated; the practical solution involves filtration. There is no debate over drilling materials: everyone agrees that they should not be part of the sample, because they may contain foreign substances (Figure IV-1). However, there is evidence that, even after purging and long after development by standard procedures, the chemistry of water from some monitoring wells may be affected by drilling fluid additives which remain in the formation or gravel pack (Figure IV-2).

There is also general agreement that a representative groundwater sample should not show the effects of materials used in the well or the sampling equipment. Consequently, there is a general preference for relatively inert (and more costly) materials, i.e., materials which neither release (leach) nor adsorb contaminants (Figure IV-3). However, because leaching and adsorption are generally not instantaneous, because samples are taken over a finite period of time, and because only a fraction of any sample actually contacts these materials, there is still debate as to the wisdom of legislated Teflon® or stainless steel. Although Barcelona et al. (1985) approach a resolution of the issue (Figure IV-4), it has not yet been finally settled through research.

Where and When is the Sample From?

For reasons of geochemistry discussed below, it is generally agreed that, in order to be representative, the sample should spend as little time as possible (consistent with good sampling practices) in the well. Consequently, monitoring wells are 'purged' prior to sampling, to draw in 'fresh' pore water from the formation. Gibb et al. (1981) used equations

CHEMICAL COMPOSITIONS OF DRILLING ADDITIVES

(From Brobst and Bubka, 1986)

۲	Bentonite	Approximate Percent
	-Montmorillonite	85
	$-SiO_2$	7
	-K.Na.Ca-Aluminosilicates	5
	-Illite	2
	-CaCO2	0.5
	-CaSO4 · 2H2O	0.5
	-Sodium Polyacrylate	0.01
۲	Guar Bean	
	-Galactomannan	80.4
	-Water	11
	-Protein	4
	-Fiber	3
	-Ash	1
	-Fat	0.5
	-Methyl Blue	0.1



(From Groundwater and Wells, 1986)



RECOMMENDED MATERIALS

(From Barcelona et. al., 1984)

- 1) Fluorocarbon Resins (e.g., Teflon TM)
- 2) Stainless Steel (316, 304)
- 3) Polypropylene
- 4) Polyethylene
- **5) Linear Polyethylene**
- 6) Viton TM
- 7) Conventional Polyethylene
- 8) PVC

SAMPLE CONTACT RATES (0.4 GPM)

(From Barcelona et. al., 1985)

MATERIAL	AQUIFER SOLIDS (SAND)	WELL (2")	TUBING (1/4")
CONTACT Rate (m ² /hr)	66	0.72	4.0
RELATIVE % CONTACT	92	1	6

developed by Papadopulos and Cooper (1967) to determine the amount of fresh formation water in a monitoring well over a range of purge times and transmissivities (Figure IV-5). Their analysis suggests that very long purge times are necessary before representative water may be obtained from formations having low transmissivities, and that representative water may be obtained almost instantaneously from highly transmissive formations. This analysis appears to overlook the geometry of the well; for example, the same equations suggest that acceptably long purge times would dry out many wells in poorly transmissive formations (Figure IV-6). In any event, the entire problem may be circumvented by the simple expedient of a packer (Figure IV-7).

The question of the spatial and temporal origin of a sample has important dimensions beyond the issue of 'stale' well water. In the current state of the practice, control over the spatial scale of samples is typically exerted through the design and location of monitoring wells (i.e., the spacing of wells and the lengths and depths of screens); control over temporal scale is exerted through sampling frequency. Implicit in this practice is the assumption that one sample represents a single point in space and time.

In fact, it is obvious that any one sample represents a range of points and times, depending in part upon the volume of water purged from the well prior to sampling. A very simple analysis (Figure IV-8)--which assumes a fully penetrating well, a formation porosity of 30 percent, and radial 'plug' flow--indicates the radial distance from which a sample might originate for a range of total pumpages and three ratios of purge rate to transmissivity. For example, after a total pumpage of 100 gallons at a purge rate/ transmissivity ratio of 0.5 feet, the water entering the well effectively originates from points 3 feet distant from the well screen. Depending upon the hydrodynamics of the natural flow system encompassed within that radius, the entire sample could, in effect, be a composite of 'subsamples' which have had very different histories.

More complex methods may be used to analyze this problem, and the scale of interest may be expanded. For example, it is common practice to employ digital modeling to define wellhead protection areas by determining the travel times of contaminants which could enter an aquifer in the vicinity of a well field (Figure IV-9). In effect, this approach defines the times and locations represented by any sample taken from the well(s) over the period of concern. In this example, it is abundantly clear that a single sample from one of the wells could contain subsamples having completely different histories.

PERCENT OF AQUIFER WATER VERSUS TIME FOR DIFFERENT TRANSMISSIVITIES

(From Gibb et. al., 1981)



4-11

CRITICAL PURGE TIMES (2")



4-12

PACKER ISOLATION OF PUMP

A 11 1 1 1 1 1 1 1







Figure

1V-8



Figure IV-9

This point is of more than academic interest, because numbers and kinds of wells, and frequency of sampling, are typically major issues of negotiation (heated argument). The natural bias of regulatory authorities (as evidenced in the defunct 1985 version of the TEGD) is toward more wells, shorter screens, and higher frequency--in short, toward the increasing subdivision of the monitored volume. Because increasing subdivision increases cost, the natural bias of the regulated community is contrary. The state of the practice offers no easy solutions; methods of defining representative scales are poorly defined and/or too complex to be employed widely.

What Happens as the Sample is Taken?

There is general agreement that, at least in permeable formations, some minimum number of well volumes should be purged prior to obtaining the sample; the magic number generally ranges from three to five. As noted above, the purpose of purging is to obtain fresh, representative formation water. In this instance, "representative" means representative of geochemical conditions in undisturbed parts of the formation.

It is known that the partial pressures of certain gases (particularly carbon dioxide, oxygen, and volatile organics) which often are significant constituents of groundwater may change dramatically as the water is exposed to the atmosphere. These changes may be significant in and of themselves (e.g., loss of volatile organics), or may produce other, equally significant changes. For example, the stability of iron species in solution is strongly dependent on pH and Eh (Figure IV-10), which are in turn strongly dependent upon the partial pressures of carbon dioxide and oxygen. Some organic contaminants are readily adsorbed by iron precipitates. Consequently, exposure of groundwaters to the atmosphere can cause changes in pH and Eh, consequent precipitation of iron species from solution, and consequent loss of organics from solution through adsorption on the precipitates.

Considerations of this kind have lead to the use of easily measured "field parameters" (pH, Eh², conductivity, and temperature) as indices of the representativeness of a sample (Figure 4-11). These parameters are measured as a function of well volumes purged; when they remain stable over a few consecutive volumes, the water is considered to be representative. Of course, there is no reason a priori to suppose that unstable readings always indicate a bad sample; such readings could simply indicate that the chemistry of the water shows considerable natural variation.

²Calibrated measurements (absolute values) of Eh are extremely difficult to obtain in the field.

STABILITY OF IRON SPECIES

(After Garrels and Christ, 1965)



PURGE PARAMETERS



. . .

How are Analytical Results Evaluated?

Beyond the simple comparison of a concentration to a standard, beyond a cookbook risk assessment, the methods for defining the risks posed by a facility can become highly complex.

The end result of one such highly complex evaluation is exemplified in Figure IV-12. In brief, the figure represents the output of a digital contaminant transport model. The basic purpose of the model was to determine the maximum permissible concentrations (trigger levels) of contaminants (in this case, 1,2-DCE) in a source zone. The model provided the analytical linkage between the trigger levels and the maximum permissible concentrations (in this case, 10 ppb, a cancer risk level of 10^{-5}) at offsite receptors.

To use the figure, one simply divides the area of the contaminated zone (indicated on the abscissa of the figure) into the trigger $(10^{\circ} \text{ ft}^2 \text{-ppm})$; the result is a concentration, in ppm, which must not be exceeded in the source zone. Note that the orientation of the source zone with respect to the flow system affects the trigger level; the solid lines within the figure represent widths of source zones parallel to the gradient of the flow system.

An important feature of the procedure is that it involves assignment of areas to a series of monitoring wells in the source zone. Each well is taken to represent a given area, not just the point at which it is situated; the concentration of a contaminant in that well is assigned to the entire area. The monitoring protocol allows for the installation of additional wells if any one source zone causes the trigger to be exceeded.

Clearly, this method of evaluating risks, of determining the significance and meaning of samples, involves very complex, rigorously defined notions of representative scales. It was produced through an equally complex and rigorous series of investigations and negotiations.

WDR223/008



REFERENCES

Barcelona, M. J., J. P. Gibb, J. A. Helfrich, and E. E. Garske. Practical Guide for Ground-Water Sampling. Illinois State Water Survey Contract Report 374. 1985. 94 pp.

Barcelona, M. J., J. A. Helfrich, and E. E. Garske. Sampling Tubing Effects on Ground Water Samples. <u>Analytical</u> Chemistry. V. 57, No. 2. 1985. Pp. 460-464.

Barcelona, M. J., J. A. Helfrich, E. E. Garske, and J. P. Gibb. A Guide to the Selection of Materials for Monitoring Well Construction and Ground-Water Sampling. Illinois State Water Survey Contract Report 327. 1983. 78 pp.

Brobst, R. B. and P. M. Buszka. The Effect of Three Drilling Fluids on Ground Water Sample Chemistry. <u>Ground</u> Water Monitoring Review. Winter 1986. Pp. 62-70.

Driscoll, F. G., ed. Groundwater and Wells. 2nd ed. Johnson Division, St. Paul. 1986. 1089 pp.

Garrels, R. M. and C. L. Christ. Solutions, Minerals, and Equilibria. San Francisco: Freeman, Cooper, and Company. 1965. 450 pp.

Gibb, J. P., R. M. Schuller, and R. A. Griffin. Procedures for the Collection of Representative Water Quality Data from Monitoring Wells. Cooperative Groundwater Report 7. Illinois State Water and Geological Surveys. 1981.

Gillham, R. W., M. J. L. Robin, J. F. Barker, and J. A. Cherry. Groundwater Monitoring and Sample Bias. Environmental Affairs Department, American Petroleum Institute. 1983. 206 pp.

Holden, P. W. Primer on Water Well Sampling for Volatile Organic Compounds. Water Resources Research Center, University of Arizona. Undated. 44 pp.

Papadopulos, I. S. and H. H. Cooper. Drawdown in a Well of Large Diameter. <u>Water Resources Research</u>. V. 3, No. 1. 1967. Pp. 241-244.

Scalf, M. R., J. F. McNabb, W. J. Dunlop, R. L. Cosby, and J. S. Fryberger. Manual of Ground-Water Quality Sampling Procedures. National Water Well Association. 1981. 93 pp. Sisk, S. W. NEIC Manual for Groundwater/Subsurface Investigations at Hazardous Waste Sites. National Enforcement Investigations Center. 1981. 72 pp. and Appendices.

Wood, W. W. Guidelines for Collection and Field Analysis of Ground-Water Samples for Selected Unstable Constituents. Chapter D2, Techniques of Water Resources Investigators of the United States Geological Survey. 1976. 24 pp.

WDR223/021

SAMPLE ANALYSIS AND QUALITY ASSURANCE

by

Pat Esposito, Thomas Wagner, and William Thompson PEI Associates, Inc. Once a ground-water monitoring system has been properly designed and installed and the samples have been collected, it becomes necessary to perform a number of prescribed chemical analyses. As with other aspects of groundwater monitoring, it is necessary to ensure that all data generated in the analytical process are valid and capable of withstanding the most rigorous of challenges. To assure the highest quality results, these key topics must be effectively addressed. First, good lines of communication must be established with the analytical laboratory before any samples are delivered as well as during and after analysis is complete. Second, proper analytical protocols must be selected. And third, a specified quality assurance program must be developed. Each of these three key topics is discussed below.

COMMUNICATIONS WITH LABORATORY

As early as possible in the project planning stages and prior to sample collection, the investigation team should meet with the analytical laboratory staff to discuss a number of specific items relative to the collection and analysis of samples. Key subjects that should be thoroughly discussed, explored, and mutually understood include:

- 1. The laboratory should clearly understand the overall project goals, including the anticipated sampling strategy and schedule, sampling methodologies (including QA/QC) that will be used, constituents of concern for analysis, and anticipated levels (concentrations) to be encountered.
- 2. The most reliable and appropriate analytical methods available for the constituents of interest should be identified. Particular attention must be given to potential interferences, the need for special field or laboratory preparation and preservation methods, if any, and detection limits.
- 3. Steps for determining the true concentration of difficult-to-measure constituents should be explored. This includes decisions on the fraction of samples, if any, that should be spiked with standards, either in the lab or in the field, for purposes of determining recovery factors.
- 4. The number of split samples or replicate samples that should be prepared in the field and in the laboratory as quality control checks on precision and accuracy should be established.
- 5. The volume of sample that must be collected and made available for analytical purposes, as well as the type, size, and number of individual sample containers must be determined. Careful attention must be given to the methods to be used for prewashing sample containers and sampling equipment in order to avoid interferences during analysis.

- 6. Sample shipping and arrival schedules and priorities for analytical determinations on each sample must be addressed. Sample shelf life, and overall laboratory workload and turn-around times must be predetermined and used to set schedules for sample collection intervals and analysis by the laboratory.
- 7. Both field and laboratory personnel should be made aware of any potential health and safety hazards that may be associated with specific samples and the precautions that should be taken to avoid exposures.
- 8. The frequency with which blanks and controls will be integrated into the analytical process for each constituent and each set of samples should be established.
- 9. Costs per sample, on an individual sample and on a lot basis, should be documented. Costs will vary significantly, depending on the type of analysis, the level of QA/QC involved, the number of samples to be analyzed, and on priority/schedule demands.

Adequate consideration of these areas will help to minimize discovery of "suprising" results, which cause project delays, including resampling and analysis and increased project cost. Well defined lines of communication will also allow development of a confident presentation of results that all investigation parties (i.e., regulator and regulated community) can defend.

SELECTION OF ANALYTICAL METHODS

Ground-water samples collected at Superfund sites or for CERCLA programs tend to be analyzed for different parameters and by different methods than those collected for RCRA purposes. Current RCRA and CERCLA practices relative to ground-water sample analysis are discussed below.

RCRA

One of the fundamental building blocks of the RCRA regulatory program is the list of hazardous constituents found in 40 CFR Part 261, known commonly as Appendix VIII. If any constituent on the Appendix VIII list is found in a waste, the waste can be listed as a hazardous waste, unless it can be otherwise demonstrated that the waste poses little or no danger to man or the environment. (See 40 CFR 261.10 for more details.) The constituents found in Appendix VIII number more than 350. Each has been shown to possess some type of toxic, carcinogenic, mutagenic, or teratogenic property. Table 1 presents a complete list of Appendix VIII constituents.

Ground-water protection provisions of Parts 264 and 265 currently require testing for evidence of contamination by analyzing for Appendix VIII constituents and certain other parameters indicative of contamination including total organic carbon (TOC), total organic halogen (TOX), pH, specific conductance, iron, manganese, chloride, sodium, sulfate, phenols, fluoride, radiation, and coliform bacteria. However, to analyze ground-water samples for <u>all</u> Appendix VIII constituents is now considered to be unrealistic and unnecessary.

In an effort to be responsive to both these regulatory requirements and analytical limitations, EPA proposed in July of 1986 an alternate list of chemicals for ground-water monitoring which is referred to as the Appendix IX list. This list, which contains a somewhat more limited core of 250 specific chemicals, was largely derived from Appendix VIII by adding 25 chemicals routinely analyzed in ground water under the CERCLA program, by deleting those chemicals that are unstable in water or not amenable to EPA's standard analytical methods for screening (i.e., gas chromatography [GC] or gas chromatography/mass spectrometry [GC/MS] for organics, and atomic absorption [AA] or inductively coupled plasma spectrometry [ICAP] for metals), and by selecting appropriate representatives for ionic compounds and categories. Table 2 lists the constituents of Appendix IX.

The analytical reference methods currently preferred by EPA for analyzing RCRA ground-water samples are those contained in EPA's publication, "Test Methods for Evaluating Solid Waste, Physical/Chemical Methods," which is most commonly referred to by its publication number EPA SW-846 (Second Edition, 1982, as amended by Update I issued April 1984, and Update II issued April 1985 (see 40 CFR Part 261, Appendix III). This publication, SW-846, was first published in 1980 and has been revised and updated to improve on the prescribed methodologies. The document does not contain methods for analyzing all of the constituents in either Appendix VIII or Appendix IX and does not contain reference methods for measuring other required ground-water parameters such as sulfate, phosphate, chloride, TOC, specific conductance, To augment SW-846, other analytical methods, such as those contained in etc. "Methods for Chemical Analysis of Water and Waste" (EPA 600/7-79-020), "Methods for Organic Chemical Analysis of Municipal and Industrial Waste Water" (EPA 600/4-82-057), "Standard Methods for the Examination of Water and Wastewater," (Sixteenth Edition, American Public Health Association, Washington, D.C., 1985), and the EPA Contract Laboratory Program (CLP) methods are all potential alternatives that RCRA permittees may wish to propose for monitoring certain constituents and parameters in their ground-water samples.

Through laboratory certification programs have not been developed for analyses conducted by SW-846 methods, the methods are readily available and in use by many analytical laboratories throughout the country.

CERCLA

Ground-water and soil/sediment samples from Superfund sites are analyzed under the EPA Contract Laboratory Program (CLP) for a specified list of constituents known as the Hazardous Substances List (HSL). This list, which is shown in Table 3, consists of 136 organic compounds, and 24 inorganics including cyanide. A special set of CLP analytical procedures are used, and only certain laboratories are approved by EPA to conduct the analyses for the Agency. At the present time, 31 labs are authorized to analyze for HSL organics, 11 are authorized to analyze for the HSL inorganics, and 13 are authorized to analyze for dioxins, using the CLP methods. CLP laboratories must utilize specific QA/QC procedures for all CLP analyses, and they are audited by EPA every three months. The results of the audits are used to update, modify, or otherwise revise the analytical methods. Only CLP laboratories get the updates, which are frequently issued. Hence the system is underlain by a large and ever expanding data base which is used to control data ouality by continually improving the accuracy, precision, and detection capabilities of each lab in the program.

The CLP methods, which are not published, are only available through CLP contract personnel. Other parties wishing to utilize CLP analytical procedures should contact the authorized EPA Contacts in their Region for details.

QUALITY ASSURANCE PROGRAMS

Quality assurance programs are developed and used by analytical laboratories to guarantee delivery of valid and reliable data. Quality assurance consists of two distinct and equally important functions. One is the assessment of the quality of the data by establishing their precision and accuracy [referred to collectively as Quality Assessment (QA)]. The other function is the control, and improvement by corrective action, of the quality of the data by implementation of specific policies and procedures [referred to collectively as Quality Control (QC)]. The two functions form a control loop--the QA/QC plan.

QA involves analytical accuracy and precision. Accuracy is maintained through rigorous instrument calibration and reagent standardization procedures using standards specified in the analytical methods. Methods are followed strictly and method accuracy is checked routinely with appropriate control samples, standard reference solutions, spikes (individual compounds and/or surrogates), internal standards, and audits (both performance and system audits). Performance audits are external evaluations comparing laboratory results on blind samples against standard values. System audits are random on-site qualitative inspections and review. Analytical precision is maintained by adherence to methods and is evaluated by comparison of results between replicate measurements. While replicate analyses may be precise (i.e., little deviation between results) they may not necessarily be accurate; hence the need for utilization of accuracy evaluations.

QC involves those functions within the laboratory which control the quality and completeness of the data collected. Functions involved include but are not limited to:

- Analytical methods utilization of published and standardized procedures.
- Reagent control utilization of analytical reagents conforming to specifications of the Committee in Analytical Reagents of the American Chemical Society.
- Volumetric glassware high quality measuring devices.

- Calibration standards specially prepared, known quality reagents for system checks.
- ^o Blanks both batch and method blanks should be used.
- Calibration procedures and frequency defined program to conduct calibration tests.
- ° Control samples known reference standards.
- Duplicate analyses replicate analyses on a defined percentage (usually 10 percent) of samples.
- Spiked samples used to verify presence or absence of matrix interference.
- Corrective measures defined procedures to handle accuracy and precision problems.
- ^o Data validation review of results by supervisory personnel.
- Glassware cleaning housekeeping procedures to return equipment to "clean" conditions.
- [°] Equipment maintenance routine servicing of equipment.
- Training utilizing technicians and staff who are qualified by experience.

Too frequently, the staff involved with the design and operation of the ground-water monitoring program know little about what happens to a sample once it goes to the laboratory. Familiarity with laboratory QA/QC procedures will help "investigators" understand and interpret the analytical results that are ultimately produced.

Acetic acid, 2,4,5-trichlorophenoxy-, salts and esters (2,4,5-T, salts and esters) Acetonitrile (Ethanenitrile) Acetophenone (Ethanone, 1-phenyl) 3-(alpha-Acetonylbenzyl)-4hydroxycoumarin and saits (Warfarin) 2-Acetylaminofluorene (Acetamide, N-(9Hfluoren-2-yl)-) Acetyl chloride (Ethanoyl chloride) 1-Acetyl-2-thiourea (Acetamide, N-(aminothioxomethyl)-) Acrolein (2-Propenal) Acrylamide (2-Propenamide) Acrylonitrile (2-Propenenitrile) Aflatoxins Aldrin (1.2.3,4.10,10-Hexachloro-1,4,4a,5,8,8a-hexahydro-endo,exo-1.4:5.8-dimethanonaphthalene) Allyl alcohol (2-Propen-1-ol) Aluminum phosphide 4-Aminobiphenyl ([1,1'-Biphenyl]-4-amine) 6-Amino-1,18,2,8,88,8b-hexahydro-8-(hydroxymethyl)-8a-methoxy-5-methylcarbamate azirino[2',3':3,4]pyrrolo[1,2-a]indole-4,7-dione, (ester) (Mitomycin C) (Azirino[2'3':3,4)pyrrolo(1,2-a)indole-4,7dione. 6-amino-8-((aminocarbonyl)oxy)methyl)-1,1a,2,8,8a,8b-hexahydro-8amethoxy-3-methy-) 5-(Aminomethyl)-3-isoxazolo] (3(2H)-Isoxasolone, 5-(aminomethyl)-) 4-Aminopyridine (4-Pyridinamine) Amitrole (1H-1,2,4-Triazol-3-amine) Aniline (Bensenamine) Antimony and compounds, N.O.S.* Aramite (Sulfurous acid, 2-chloroethyl-, 2-[4-(1,1-dimethylethyl)phenoxy]-1methylethyl ester) Arsenic and compounds, N.O.S.* Arsenic acid (Orthoarsenic acid) Arsenic pentoxide (Arsenic (V) oxide) Arsenic trioxide (Arsenic (III) oxide) Auramine (Benzenamine, 4.4'carbonimidoylbis[N.N.Dimethyl-, monohydrochloride) Azaserine (L-Serine, diazoacetate (ester)) Barlum and compounds, N.O.S.* Barium cyanide Benz[c]acridine (3,4-Benzacridine) Benz[a]anthracene (1,2-Benzanthracene) Benzene, 2-amino-1-methyl (o-Toluidine) Benzene, 4-amino-1-methyl (P Toluidine) Benzene (Cyclohexatriene) Benzenearsonic acid (Arsonic acid, phenyl-) Benzene, dichloromethyl- (Benzal chloride) Benzenethiol (Thiophenol) Benzidine ([1,1'-Biphenyl]-4,4'diamine) Benzo[b]fluoranthene (2,3-Benzofluoranthene) Benzo[j]fluoranthene (7,8-Benzofluoranthene) Benzo[a]pyrene (3,4-Benzopyrene) p-Benzoquinone (1,4-Cyclohexadienedione) Benzotrichloride (Benzene, trichloromethyl-Benzyl chloride (Benzene, (chloromethyl)-) Beryllium and compounds, N.O.S.*

Bis(2-chloroethoxy)methane (Ethane, 1,1'-(methylenebis(oxy)]bis[2-chloro-]) Bis(2-chloroethyl) ether (Ethane, 1,1'oxybis[2-chloro-]) N.N-Bis(2-chloroethyl)-2-naphthylamine (Chlornaphazine) Bis(2-chloroisopropyl) ether (Propane, 2,2oxybis(2-chloro-1) Bis(chloromethyl) ether (Methane. oxybis[chloro-]) Bis(2-ethylhexyl) phthalate (1.2-**B**enzenedicarboxylic acid. bis(2-ethylhexyl) ester) Bromoacetone (2-Propanone, 1-bromo-) Bromomethane (Methyl bromide) 4-Bromophenyl phenyl ether (Benzene, 1bromo-4-phenoxy-) Brucine (Strychnidin-10-one, 2,3-dimethoxy-2-Butanone peroxide (Methyl ethyl ketone, peroxide) Butyl benzyl phthalate (1.2. Benzenedicarboxylic acid, butyl phenylmethyl ester) 2-sec-Butyl-4.6-dinitrophenol (DNRP) (Phenol, 2,4-dinitro-6-(1-methylpropyl)-) Cadmium and compounds, N.O.S. Calcium chromate (Chromic acid, calcium salt) **Calcium** cyanide Carbamic acid, ethyl ester Carbon disulfide (Carbon bisulfide) Carbon oxyfluoride (Carbonyl fluoride) Chloral (Acetaldehyde, trichloro-) Chlorambucil (Butanoic acid, chloroethyl)amino]benzene-) 4-[bis(2-Chlordane (alpha and gamma isomers) (4,7-Methanoindan, 1,2,4,5,6,7,8,8-octachloro-3,4,7,7a-tetrahydro-) (alpha and gamma isomers) Chlorinated benzenes, N.O.S.* Chlorinated ethane, N.O.S. Chlorinated fluorocarbons, N.O.S.* Chlorinated naphthalene, N.O.S.* Chlorinated phenol, N.O.S. Chloroscetaldehyde (Acetaldehyde, chloro-) Chloroalkyl ethers, N.O.S.* p-Chloroaniline (Benzenamine, 4-chloro-) Chlorobenzene (Benzene, chloro-) Chlorobenzilate (Benzeneacetic acid chloro-alpha-(4-chlorophenyl)-alphaacid. hydroxy-, ethyl ester) 2-Chloro-1,3-butadiene (chloroprene) p-Chloro-m-cresol (Phenol, 4-chioro-3methyl) 1-Chloro-2,3-epoxypropane (Oxirane, 2-(chloromethyl)-) 2-Chloroethyl vinyl ether (Ethene, (2-chloroethoxy).) Chloroform (Methane, trichloro-) Chloromethane (Methyl chloride) Chloromethyl methyl ether (Methane, chloromethoxy-) 2-Chioronaphthalene (Naphthalene, betachloro-) 2-Chlorophenol (Phenol, o-chloro-) 1-(o-Chlorophenyl)thiourea (Thiourea, (2chlorophenyl)-)

• The abbreviation N.O.S. (not otherwise specified) signifies those members of the general class not specifically listed by name in this appendix.
TABLE 1 (continued)

3-Chloropropene (allyl chloride) 3-Chloropropionitrile (Propanenitrile, 3chloro-) Chromium and compounds, N.O.S * Chrysene (1,2-Benzphenanthrene) Citrus red No 2 (2-Naphthol, 1-1(2,5dimethoxyphenyl)azo].) Coal tars Copper cyanide Creosote (Creosote, wood) Cresols (Cresylic acid) (Phenol, methyl-) Crotonaldehyde (2-Butenal) Cyanides (soluble salts and complexes), N O.S.* Cyanogen (Ethanedinitrile) Cyanogen bromide (Bromine cyanide) Cyanogen chloride (Chlorine cyanide) Cycasin (beta-D-Glucopyranoside, (methyl-ONN-azoxy)methyl-) 2.Cyclohexyl-4,6.dinitrophenol (Phenol, 2cyclohexyl-4.6-dinitro-) (2H-1,3,2,-Oxazaphos-Cyclophosphamide phorine. {bis(2-chloroethyl)amino]-tetrahydro, 2 oxide) Daunomycin (5,12-Naphthacenedione, (8Scis)-8-acetyl-10-[(3-amino-2,3,6-trideoxy)alpha-L-lyxo-hexopyranosyl)oxy]-7,8,9,10tetrahydro-6,8,11-trihydroxy-1-methoxy-) (Dichlorodiphenyldichloroethane) DDD 1,1-dichloro-2,2-bis(p-chloro-(Ethane, phenyl)-) DDE (Ethylene, 1.1-dichloro-2,2-bis(4-chlorophenyl)-) DDT (Dichlorodiphenyltrichloroethane) (Ethane, 1,1,1-trichloro-2,2-bis(p-chlorophenyl)-) (S-(2,3-dichloroallyl) Dialiate dusopropylthiocarbamate) Dibenz[a,h]acridine (1,2,5,6-Dibenzacridine) Dibenz[a,]]acridine (1,2,7,8-Dibenzacridine) Dibenz[a,h]anthracene (1,2,5,6-Dibenzanthracene) 7H-Dibenzo(c,g]carbazole (3,4,5,6-Dibenzcarbázole) Dibenzo(a,e]pyrene (1 2,4,5-Dibenzpyrene) Dibenzola,h)pyrene (1,2,5,6-Dibenzpyrene) Dibenzo(a,i)pyrene (1.2.7.8-Dibenzpyrene) 1.2-Dibromo-3-chloropropane (Propane, 1,2dibromo-3-chloro-) 1.2-Dibromoethane (Ethylene dibromide) Dibromomethane (Methylene bromide) Di-n-butyl phthalate (1.2.Benzenedicarboxylic acid, dibutyl ester) o-Dichlorobenzene (Benzene, 1,2-dichloro-) m-Dichlorobenzene (Benzene, 1,3-dichloro-) p-Dichlorobenzene (Benzene, 1,4-dichloro-) Dichlorobenzene, NO.S * (Benzene, dichloro , NO.S •) 3.3 -Dichlorobenzidine ([1,1'-Biphenyl]-4,4'diamine, 3,3'-dichloro-) 1.4-Dichloro-2-butene (2-Butene, 1,4-dichloro-) Dichlorodifluoromethane (Methane, dich-In-odifluoro.) 1.1-Dichloroethane (Ethylidene dichloride) 1 2-Dichloroethane (Ethylene dichloride) trans-1,2-Dichloroethene (1,2-Dichloroethylene) Dichloroethylene, N.O.S.* (Ethene, dichloro-, N O.S *) 1,1-Dichloroethylene (Ethene, 1,1-dichloro-) Dichloromethane (Methylene chloride) 2,4-Dichlorophenol (Phenol, 2,4-dichloro-) 2.6-Dichlorophenol (Phenol, 2,6-dichloro-) 2.4-Dichlorophenoxyacetic acid (2,4-D), salts

- and esters (Acetic acid, 2.4-dichlorophenoxy., salts and esters)
- Dichlorophenylarsine (Phenyl dichloroarsine)

Dichloropropane, NO.S.* (Propane, dichloro-, N.O.S *) 1,2-Dichloropropane (Propylene dichloride) Dichloropropanol, N.O.S.* (Propanol, dichloro-, NO.S *) Dichloropropene, N.O.S.* (Propene, dichloro, N.O.S.*) 1,3 Dichloropropene (1 Propene, 1,3 dichloro-) Dieldrin (1,2,3,4,10,10-hexachloro-6,7-epoxy-1,4,4a,5,6.7,8,8a-octa-hydro-endo,exo-1,4:5,8-Dimethanonaphthalene) 1,2:3,4-Diepoxybutane (2,2'-Bioxirane) Diethylarsine (Arsine, diethyl-) N,N'-Diethylhydrazine (Hydrazine, 1,2diethvl) O.O.Diethyl S-methyl ester of phosphorodithioic acid (Phosphorodithioic acid, O.O-diethyl S-methyl ester acid. O.O-Diethylphosphoric O-p-nitrophenyl ester (Phosphoric acid, diethyl pnitrophenyl ester) Diethyl phthalate (1,2-Benzenedicarboxylic acid diethyl ester) O.O-Diethyl O-2-pyrazinyl phosphorothioate (Phosphorothioic acid, O.O-diethyl O-pyrazinyl ester Diethylstilbesterol (4.4'-Stilbenediol, alpha.alpha-diethyl, bis(dihydrogen phosphate, (E)-) Dihydrosafrole (Benzene, 1,2-methylenedioxy-4-propyl-) 3.4 Dihydroxy-alpha-(methylamino)methyl benzyl alcohol (1,2-Benzenediol, 4-[1-hydroxy-2-(methylamino)ethyl]-) Dusopropylfluorophosphate (DFP) (Phosphorofluoridic acid, bis(1-methylethyl) ester) Dimethoate (Phosphorodithioic acid, O,Odimethyl S-[2-(methylamino)-2-oxoethyl] ester 3.3 -Dimethoxybenzidine ([1.1'Biphenyl]-4.4 diamine, 3-3'-dimethoxy-) p.Dimethylaminoazobenzene (Benzenamine, N,N-dimethyl-4-(phenylazo)-) 7,12-Dimethylbenz[a]anthracene (1,2-Benzanthracene, 7,12-dimethyl-) 3.3'-Dimethylbenzidine ([1.1'-Biphenyl]-4,4'diamine, 3.3'-dimethyl-) Dimethylcarbamoyl chloride (Carbamoyl chloride, dimethyl-) 1.1-Dimethylhydrazine (Hydrazine, 1.1-dimethyl-) 1,2-Dimethylhydrazine (Hydrazine, 1,2-dimethyl.) 3.3-Dimethyl-1-(methylthio)-2-butanone, O-[(methylamino) carbonyl]oxime (Thiofanox) alpha.alpha.Dimethylphenethylamine (Ethanamine, 1,1-dimethyl-2-phenyl-) 2,4-Dimethylphenol (Phenol, 2,4-dimethyl-) phthalate Dimethyl (1.2) Benzenedicarboxylic acid, dimethyl ester) Dimethyl sulfate (Sulfuric acid, dimethyl ester) Dinitrobenzene, N.O.S.* (Benzene, dinitro-, N.O.S.*) 4,6-Dinitro-o-cresol and salts (Phenol, 2,4dinitro-6-methyl-, and salts) 2.4-Dinitrophenol (Phenol, 2,4-dinitro-) 2.4-Dinitrotoluene (Benzene, 1-methyl-2,4dinitro-) 2,6-Dinitrotoluene (Benzene, 1-methyl-2,6dinitro-) Di-n-octyl phthalate (1.2-Benzenedicarboxylic acid, dioctyl ester) 1,4-Dioxane (1,4-Diethylene oxide) Diphenylamine (Benzenamine, N-phenyl-)

1,2-Diphenylhydrazine (Hydrazine, 1,2-diphenyl-) Di-n-propylnitrosamine (N-Nitroso-di-n-propylamine) Disulfoton (O.O.diethy) S-12-(ethylthio)ethyl] phosphorodithioate) 2.4-Dithiobiuret (Thioimidodicarbonic diamide) Endosulfan (5-Norbornene, 2,3-dimethanol, 1.4,5.6,7,7-hexachloro-, cyclic sulfite) Endrin and metabolites (1,2,3,4,10,10-hexachloro-6.7-epoxy-1 4,4a,5,6,7,8,8aoctahydro-endo,enou-1,4.5,8dimethanonaphthalene, and metabolites) Ethyl cyanide (propanenitrile) Ethylenebisdithiocarbamic acid, salts and esters (1.2-Ethanediylbiscarbamodithioic acid, salts and esters Ethylene glycol monoethyl ether (Exthanol, 2-ethoxy) Ethyleneimine (Aziridine) Ethylene oxide (Oxirane) Ethylenethiourea (2-Imidazolidinethione) Ethyl methacrylate (2-Propenoic acid, 2methyl-, ethyl ester) Ethyl methanesulfonate (Methanesulfonic acid, ethyl ester) Fluoranthene (Benzo[j.k]fluorene) Fluorine 2-Fluoroacetamide (Acetamide, 2-fluoro-) Fluoroacetic acid, sodium salt (Acetic acid, fluoro-, sodium salt) Formaldehyde (Methylene oxide) Formic acid (Methanoic acid) Glycidylaldehyde (1-propanol-2,3-exoxy) Halomethane, NOS* Heptachlor (4.7-Methano-1H-indene, 1,4,5.6,7,8.8-heptachloro-3a,4,7,7atetrahydro-) Heptachlor epoxide (alpha, beta, and gamma isomers) (4,7-Methano-1H-indene, 1,4,5,6,7,8,8-heptachloro-2,3-epoxy-3a,4,7,7tetrahydro-, alpha, beta, and gamma isomers) Hexachlorobenzene (Benzene, hexachloro-) Hexachlorobutadiene (1,3-Butadiene, hexachloro-) Hexachlorocyclohexane (all isomers) (Lindane and isomers) Hexachlorocyclopentadiene (1,3-Cyclopentadiene, 1.2.3,4,5,5-hexachloro-) Hexachlorodibenzo-p-dioxins Hexachlorodibenzofurans Hexachloroethane (Ethane, hexachloro-) 1,2,3,4,10,10-Hexachloro-1,4,4a,5,8,8ahexahydro-1,4.5,8-endo,endodimethanonaphthalene (Hexachlorohexahydro-endo.endodimethanonaphthalene) Hexachlorophene (2,2'-Methylenebis(3,4,8-trichlorophengl)) Hexachloropropene (Propene, hexachloro-)

Hexaethyl tetraphosphate (Tetraphosphoric acid, hexaethyl ester)

Hydrazine (Diamine) Hydrocyanic acid (Hydrogen cyanide) Hydrofluoric acid (Hydrogen fluoride) Hydrogen sulfide (Sulfur hydride) Hydroxydimethylarsine oxide (Cacodylic acid) Indeno(1.2,3-cd)pyrene (1,10-(1,2phenylene)pyrene) Iodomethane (Methyl iodide) Iron dextran (Ferric dextran) Isocyanic acid, methyl ester (Methyl isocvanate) Isobutyl alcohol (1-Propanol, 2-methyl-) Isosafrole (Benzene, 1,2-methylenedioxy-4allyl.) Kepone (Decachlorooctahydro-1,3,4-methano-2H-cyclobuta[cd]-pentalene-2-one) Lasiocarpine (2-Butenoic acid, 2-methyl-, 7-[(2,3-dihydroxy-2-(1-methoxyethyl)-3methyl-1-oxobutoxy)methyl]-2.3,5.7atetrahydro-1H-pyrrolizin-1-yl ester) Lead and compounds, N.O.S * Lead acetate (Acetic acid, lead salt) Lead phosphate (Phosphoric acid, lead salt) Lead subacetate (Lead, bis(acetato-O)tetrahydroxytri-) Maleic anhydride (2,5-Furandione) Maleic hydrazide (1,2-Dihydro-3,6-pyridazinedione) Malononitrile (Propanedinitrile) Melphalan (Alanine, 3-[p-bis(2chloroethyl)aminolphenyl-, L-) Mercury fulminate (Fulminic acid, mercury salt) Mercury and compounds, NOS.* Methacrylonitrile 12-Propenenitrile, 2methyl-) Methanethiol (Thiomethanol) 2-{(2-Methapyrilene (Pyridine. dimethylamino)ethyl]-2-thenylamino-) Metholmyl (Acetimidic acid, N-[(methylcarbamoyl)oxy]thio-, methyl ester Methoxychlor (Ethane, 1.1.1-trichloro-2.2'bis(p-methoxyphenyl)) 2-Methylaziridine (1,2-Propylenimine) 3 Methylcholanthrene (Benz[j]aceanthrylene, 1.2-dihydro-3methvl-) Methyl chlorocarbonate (Carbonochloridic acid. methyl ester) 4.4'-Methylenebis(2-chloroaniline) (Benzenamine, 4,4'-methylenebis-(2-chloro-) Methyl ethyl ketone (MEK) (2-Butanone) Methyl hydrazine (Hydrazine, methyl-) 2-Methyllactonitrile (Propanenitrile, 2-hydroxy-2-methyl-) Methyl methacrylate (2-Propenoic acid, 2methyl-, methyl ester) Methyl methanesulfonate (Methanesulfonic acid, methyl ester) 2-Methyl-2-(methylthio)propionaldehyde-o-(methylcarbonyl) oxime (Propanal, 2methyl-2-(methylthio)-,

((methylamino)carbonyl]oxime)

5-9

TABLE 1 (continued)

N-Methyl-N'-nitro-N-nitrosoguanidine (Guanidine, N-nitroso-N-methyl-N'-nitro-) Methyl parathion (O.O-dimethyl O-(4nitrophenyl) phosphorothioate) Methylthiouracil (4-1H-Pyrimidinone, 2.3dihydro-6-methyl-2-thioxo-) Mustard gas (Sulfide, bis(2-chloroethyl)-) Naphthalene 1.4-Naphthoguinone (1.4-Naphthalenedione) 1-Naphthylamine (alpha-Naphthylamine) 2-Naphthylamine (beta-Naphthylamine) 1-Naphthyl-2-thiourea (Thiourea, 1naphthalenyl-) Nickel and compounds, NO.S.* Nickel carbonyl (Nickel tetracarbonyl) Nickel cyanide (Nickel (II) cyanide) Nicotine and salts (Pyridine, (S)-3-(1-methyl-2-pyrrolidinyl)-, and salts) Nitric oxide (Nitrogen (II) oxide) p-Nitroaniline (Benzenamine, 4-nitro-) Nitrobenzine (Benzene, nitro-) Nitrogen dioxide (Nitrogen (IV) oxide) Nitrogen mustard and hydrochloride salt (Ethanamine, 2-chloro-, N-(2-chloroethyl)-N-methyl-, and hydrochloride salt) Nitrogen mustard N-oxide and hydrochloride salt (Ethanamine, 2-chloro-, N-(2-chlor-oethyl)-N-methyl-N-oxide, and hydrochloride salt) Nitroglycerine (1.2.3-Propanetriol, trinitrate) 4-Nitrophenol (Phenol, 4-nitro-) 2-Nitropropane (Propane, 2-nitro) 4-Nitroquinoline-1-oxide (Quinoline, 4-nitro-1oxide-) Nitrosamine, N.O.S. N-Nitrosodi-n-butylamine (1-Butanamine, Nbutyl-N-nitroso-) N-Nitrosodiethanolamine (Ethanol, 2.2'-(nitrosoimino)bis-) N-Nitrosodiethylamine (Ethanamine, N-ethyl-N-nitroso-) N-Nitrosodimethylamine (Dimethylnitrosamine) N-Nitroso N-ethylurea (Carbamide, N-ethyl-N-nitroso-) N-Nitrosomethylethylamine (Ethanamine, Nmethyl-N-nitroso-) N-Nitroso-N-methylurea (Carbamide, Nmethyl-N-nitroso-) N-Nitroso-N-methylurethane (Carbamic acid, methylnitroso-, ethyl ester} N-Nitrosomethylvinylamine (Ethenamine, Nmethyl-N-nitroso-) N-Nitrosomorpholine (Morpholine, N-nitroso-N-Nitrosonomicotine (Nornicotine, Nnitroso-) N-Nitrosopiperidine (Pyridine, hexahydro-, Nnitroso-) Nitrosopyrrolidine (Pyrrole, tetrahydro-, Nnitroso-)

N-Nitrososarcc sine (Sarcosine, N-nitroso-) 5-Nitro-o-toluidine (Benzenamine, 2-methyl-5nitro-Octamethylpyrophosphoramide (Diphosphoramide, octamethyl-) Osmium tetroxide (Osmium (VIII) oxide) 7-Oxabicyclo[2.2.1]heptane-2.3-dicarboxylic acid (Endothal) Paraldehyde (1 3.5-Trioxane, 2.4.6-trimethyl-) Parathion (Phosphorotmone a tid, O.O-diethyl O-(p-nitrophenyl) ester Pentachlorobenzene (Benzella, pentachloro-) Pentachlorodibenzo-p-dioxins Pentachlorodibenzofurans Pentachloroethane (Ethane, pentachloro-) Pentachloronitrobenzene (PCNB) (Benzene. pentachloronitro-) Pentachlorophenol (Phenol, pentachloro-) Perchioromethyl mercaptan (Methanesultenvi chloride, trichloro-) Phenacetin (Acetamide. N-(4-ethoxyphenyl)-) Phenol (Benzene, hydroxy-) Phenylenediamine (Benzenediamine) Phenylmercury acetate (Mercury, acetatophenyl-) N-Phenylthiourea (Thiourea, phenyl-) Phosgene (Carbonyl chloride) Phosphine (Hydrogen phosphide) Phosphorodithioic acid, O.O-diethyl S-[(ethylthio)methyl] ester (Phorate) Phosphorothioic acid, O.O-dimethyl O-[p-((dimethylamino)sulfonyl)phenyl] ester (Famphur) Phthalic acid esters, N.O.S.* (Benzene, 1.2dicarboxylic acid. esters, NO.S *) Phthalic anhydride (1.2-Benzenedicarboxylic acid anhydride) 2-Picoline (Pyridine, 2-methyl-) Polychlorinated biphenyl, N.O.S.* Potassium cyanide Potassium silver cyanide (Argentate(1-), dicyano-, potassium) Pronamide (3.5-Dichloro-N-(1,1-dimethyl-2propynyl)benzamide) 1.3-Propane sultone (1.2-Oxathiolane, 2.2dioxide) Propionic acid. 2- (2,4,5-trichlorophenoxy salts and esters (2.4.5-TP, Silvex, salts and esters. n-Propylamine (1-Propanamine) Propylthiouracil (2,3-dihydro-6-propyl-2thioxo-4(H)-pyrimidinone) 2-Propyn-1-ol (Propargyl alcohol) Pyridine Reserpine (Yohimban-16-carboxylic acid, 11.17-dimethoxy-18-[[3.4.5trimethoxybenzoyl)oxy]-, methyl ester) Resorcinol (1,3-Benzenediol) Saccharin and salts (1.2-Benzoisothiazolin-3one. 1.1-dioxide, and salts)

TABLE 1 (continued)

Salrole (Benzene, 1,2-methylenedioxy-4-al-1/1-1 Selemous acid (Selemum dioxide) Selemum and compounds, N.O.S. Selenium sulfide (Sulfur selenide) Selenourea (Carbamimidoselenoic acid) Silver and compounds, NO.S.* Silver cyanide Sodium cyanide Streptozotocin (D-Glucopyranose, 2-deoxy-2-(3-methyl-3-nitrosoureido]-) Strontium sulfide Strychnine and salts (Strychnidin-10-one, and salts} 1.2.4,5-Tetrachlorobenzene (Benzene, 1,2,4,5tetrachloro-) 2.3.7.8-Tetrachlorodibenzo-p-dioxin (TCDD) (Dibenzo-p-dioxin, 2.3,7.8-tetrachloro-) Tetrachlorodibenzo-p-dioxins Tetrachlorodibenzofurans Tetrachloroethane, N.O.S.* (Ethane, tetrachloro-, N.O.S.*) 1,1.1,2-Tetrachlorethane (Ethane, 1,1,1,2-(etrachloro-) 1.1.2.2-Tetrachlorethane (Ethane, 1.1,2,2tetrachloro-) Tetrachloroethane (Ethene, tetrachloco-) Tetrachloromethane (Carbon tetrachloride) 2.3 4.6.-Tetrachlorophenol (Phenol. 2.3.4.6tetrachloro-) Tetraethyldithiopyrophosphate (Dithiopyrophosphoric acid, tetraethylester) Tetraethyl lead (Plumbane, tetraethyl-) Tetraethylpyrophosphate (Pyrophosphoric acide, tetraethyl ester) Tetranitrumethane (Methane, tetranitro-) Thallium and compounds. N.O.S Thallic oxide (Thallium (III) oxide) Thallium (I) acetate (Acetic acid, thallium (I) salt) Thallium (I) carbonate (Carbonic acid. dithallium (I) salt) Thallium (I) chloride Thallium (I) nitrate (Nitric acid. thallium (I) salt) Thallium selenite Thallium (I) sulfate (Sulfuric acid, thallium (I) salt) Thioacetamide (Ethanethioamide) Thiosemicarbazide (Hydrazinecarbothioamide)

Thiourea (Carbamide thio-) Thiuram (Bis(dimethylthiocarbamoyl) disulfide) Toluene (Benzene, methyl-) Toluenediamine (Toluene, 2,5-diamine-) 2,4-Toluenediamine 2,6-Toluenediamine 3.4-Toluenediamine Toluenediamine, NOS. o-Toluidine hydrochloride (Benzenamine, 2methyl-, hydrochloride) Tolylene diisocyanate (Benzene, 2.4-and 2.6disocyanatomethyl-) Toxaphene (Camphene, octachloro-) fribromomethane (Bromotorm) 1.2.4-Trichlorobenzene (Benzene, 1.2.4 trichloro-) 1.1.1-Trichloroethane (Methyl chloroform) 1.1.2-Trichloroethane (Ethane, 1.1.2-trichloro-) Trichloroethene (Trichloroethylene) Trichloromethanethiol (Methanethiol. trichloro-) Trichloromonofluoromethane (Methane, trichlorofluoro-} 2.4,5-Trichlorophenol (Phenol, 2.4,5-trichloro-) 2.4.6-Trichlorophenol (Phenol, 2.4.6-trichloro-) Trichloropropane, N.O.S.* (Propane, trichloro, N.O.S.*) 1.2,3-Trichloropropane (Propane, 1.2,3trichloro-) O.O.O-Triethyl phosphorothioate (Phosphorothioic acid, O,O,O-triethyl ester) sym-Trinitrobenzene (Benzene, 1,3.5 trinitro-) Tris(1-azridinyl) phosphine sulfide (Phosphine sulfide, tris(1-aziridinyl-) Tris(2.3-dibromopropyl) phosphate (1-Propanol, 2,3-dibromo-, phosphate) Trypan blue (2.7-Naphthalenedisulfonic acid, 3,3'-[(3.3'-dimethy](1.1'-bipheny])-4.3'diyl)bis(azo)]bis(5-amino-4-hydroxy-, tetrasodium salt) Undecamethylenediamine, N,N'-bis-2-chlorobenzyl)-, dihydrochloride (N,N'-Undecamethylenebis (2-chlorobenzylamine, dihydrochloride) Uracil mustard (Uracil 5-Ibis(2chloroethyl)amino]-) Vanadic acid, ammonium salt (ammonium vanadate) Vanadium pentoxide (Vanadium (V) oxide)

Vinyl chloride (Ethene. chloro-) Zinc cyanide

Zinc phosphide

Source: 40 CFR Part 261, Appendix VIII. July 1, 1986, as amended by 51FR28297, August 6, 1986.

TABLE 2. APPENDIX IX CONSTITUENTS

Group Volatile organics	Constituen	ts
Volatile organics	Chloromethane	1;2-dichloropropane
	Bromomethane	Trans-1,3-dichloropropene
	Vinyi chloride Chlorosthano	Irichloroethene
	Chioroethane Methylene chloride	Ulbromoch/oromethane
	Acetone	Benzene
	Carbon disulfide	Cis-1.3-dichloropropene
	1,1-Dichloroethene	2-Chloroethylvinylether
	1,1-Dichloroethane	Bromoform
	Trans-1,2-dichloroethene	4-Methy1-2-pentanone
	Chloroform	2-Hexanone
	2 Puterono	letrachioroethene
-	2-Butanone 1 1 1-Trichloroathana	I,I,2,2+letrachioroethane Toluene
	Carbon tetrachloride	Chlorobenzene
	Vinvl acetate	Ethylbenzene
	Bromodichloromethane	Styrene
	Acetonitrile	Total xylenes
	Acrylonitrile	Ethylene oxide
	Acrolein	Iodomethane
	3-Chloropropene	Methacrylonitrile
	1,2-Dibromoethane	Methyl methacrylate
	Ulbromomethane	1,1,1,2-letrachloroethane
	1,2-010romo-3-chioropropane Dichlorodifluoromethane	1 2 3-Trichloropropage
	1.4-Dioxane	Bromomethane
	Ethyl methacrylate	
Semivolatile organics	Pheno 1	Acenaphthene
	Bis(2-chloroethyl)ether	2,4-Dinitrophenol
	2-Uniorophenoi 1 3 Dichlorobonzono	4-Nitrophenol Dibonzofuman
	1,4-Dichlorobenzene	2 A-Dinitrotoluene
	Benzyl alcohol	2.6-Dinitrotoluene
	1.2-Dichlorobenzene	Diethyl phthalate
	2-Methylphenol	4-Chlorophenylphenyl ether
	Bis(2-chloroisopropyl)ether	Fluorene
	4-Methylphenol	4-Nitroaniline
	N-nitroso-di-n-propylamine	4.6-Dinitro-2-methylphenol
	Hexachloroethane	N-Nitrosodiphenylamine
	ki Lrobenzene	4-Bromopneny Ipneny letner
	2-Nitrophenol	Pentachlorophano]
	2.4-Dimethylphenol	Phenanthrene
	Benzoic acid	Anthracene
	Bis(2-chlorethoxy)methane	Di-n-butyl phthalate
	2,4-Dichlorophenol	Fluoranthene
	1,2,4-Trichlorobenzene	Pyrene
	Naphinalene A Chloroppiline	Buty Ibenzy Iphthalate
	4-chlorobutadiene Hexachlorobutadiene	Benzo(a)anthracene
	4-Chloro-3-methylphenol	Bis-(2-ethylhexyl)nhthalat
	2-Methylnapthalene	Chrysene
	Hexachlorocyclopentadiene	Di-n-octyl phthalate
	2,4,6-Trichlorophenol	Benzo(b)fluoranthene
	2,4,5-Trichlorophenol	Benzo(k)fluoranthene
	2-Chloronaphthalene	Benzo(a)pyrene
	2-Nitroaniline	Indeno(1,2,3-cd)pyrene
	Acenanthylene	Dibenzo(a,n)anthracene Benzo(a,b,f)convlore
	3-Nitroaniline	Methanyrilene
	Aramite	1-Naphthylamine
	2-Acetylaminofluorene	2-Naphthylamie
	4-Aminobiphenyl	N-Nitrosodiethylamine
	Aniline	N-Nitrosodimethylamine
	Benzidine	N-Nitosodi-n-butylamine
	4-Benzoquinone	N-Nitrosomethylathylamine
	2-Sec-buty1-4,6-dinitrophenol	N-Nitrosomorphoiine
	UNIORODENZILATE 3_Chlomonionit=il=	N-Nitrosopiperidine
	Diberto(a e) pymana	N-NICTOSOPYTOIICINE
	n mentola 'e hauene	3-N1010-2-001010108

(continued)

Group	Constituents	
Semivolatile organics (continued)	Dibenzo(a,h)pyrene Dibenzo(a,1)pyrene 2,6-Dichlorophenol 3,3'-Dimethoxybenzidine	Pentachlorobenzene Pentachloroethane Pentachloronitrobenzene Phenacetin
	7,12-Dimethylbenz-(a,h)-anthracene	2-Picoline
	a,a-Dimethylphenethylamine	Pronamide
	1,3-U1nitrobenzene	Resorcinol
	Diphenylbydrazine	1.2.4.5-Tetrachlorobenzene
	Hexachlorophene	2.3.4.6-Tetrachlorophenol
	Hexachloropropene	Methylmethanesulfonate
	Isosafrole	Pyridine
	3-Methylcholanthrene	Benzenethiol
	1.4-Nanhthooninone	Acetophenone
	4-Dimethylaminoazobenzene	Ethyl cyanide
	3,3'-Dimethylbenzidine	Isobutyl alcohol
	2-Chloro-1,3-butadiene	2-Propyn-1-ol
	Allyl alcohol	Trichloromethanethiol
	1-1,4-D1CN10r0-2-Dutene	
'estisides,	Alpha-BHC	Methoxychlor
nerbicides,	Beta-BHC	Endrin ketone
PCB'S	Delta-BHC (lindana)	Lalordane
	Heptachlor	Arochlor-1016
	Aldrin	Arochlor-1221
	Heptachlor epoxide	Arochlor-1232
	Endosulfan I	Arochlor-1242
	U1010110 4 4 - DD5	Arochior-1248
	4,4 -DUC Endrin	Arochlor-1254 Arochlor-1260
	Endosulfan 11	Endrin aldehvde
	4,4'-DDD	Isodrin
	Endosulfan sulfate 4,4'-DDT	Kepone
	2,4,5-T 2,4,5-TP (Silvex) 2,4-D	
	0.0-diethvl-0-2-pyrazinvl-	Parathion
	phosphrothioate	Phorate
	Disulfoton	Tetraethyldithiopyrophospha
	Famphur Methyl parathion	Tris(2,3-dibromopropyl)-pho phate
	Dioxin/dibenzofuran	Tris(2,3-dibromopropyl)-pho phate
Inorganics	Fluoride	
	Cyanide	
	Su}fide	
	Aluminum	Magnesium
	Antimony	Nanganese
	Barium Rervilium	N1CKel Ocmium
	Cadmium	Potassium
	Calcium	Silver
	Chromium	Sodium
	Cobalt	Thallium
	Lopper Iron	lin Vərədium
	Lead	Zinc
	Arsenic	C-lonium
	Mercury	26160100

TABLE 2 (continued)

Source: 51 FR 26632, July 24, 1986.

TABLE 3. THE CONTRACT LABORATORY PROGRAM HAZARDOUS SUBSTANCES LIST

Substance	CAS number
Volatiles	
1. Chloromethane	74-87-3
2. Bromomethane	74-83-9
3. Vinyl chloride	75-01-4
4. Chloroethane	75-00-3
5. Hethylene chloride	15-09-2 67 64 1
7 Carbon disulfide	75-15-0
B. 1.1-Dichloroethene	75-35-4
9. 1,1-Dichloroethane	75-35-3
10. Trans-1,2-dichloroethene	156-60-5
11. Chloroform	67-66-3
12. 1,2-Dichloroethane	107-06-2
13. 2-Butanone	78-93-3
14. 1,1,1-ificnioroethane 15. Carbon tetrachlaride	56 27 6
15. Carbon Lectachtoride	108-05-4
17. Bromodichloromethane	75-27-4
18. 1,1,2,2-Tetrachloroethane	79-34-5
19. 1,2-Dichloropropane	78-87-5
20. Trans-1,3-dichloropropene	10061-02-6
21. Trichloroethene	79-01-6
22. Dibromochioromethane	124-48-1
23. I,1,2-ITICHIDTOEthane 24. Benzene	79-00-5
25. Cis-1.3-dichloropropene	10061-01-5
26. 2-Chloroethyl vinyl ether	110-75-8
27. Bromoform	75-25-2
28. 2-Hexanone	591-78-6
29. 4-Methyl-2-pentanone	108-10-1
30. Tetrachloroethene	127-18-4
31. IDIUENE 32. Eblandensee	108-88-3
33 Ethul henzene	100-41-4
34. Styrene	100-42-5
35. Total xylenes	
Semivolatiles	
36. Phenol	108-95-2
37. Bis(2-chloroethyl)ether	111-44-4
38. 2-Chlorophenol	95-57-8
39. 1,3-Dichlorobenzene	541-73-1
4U. 1,4-DICHIOTODENZENE	100-40-/
42 1 2-Dichlorobenzene	95-50-1
43. 2-Methylphenol	95-48-7
44. Bis(2-chloroisopropyl)ether	39638-32-9
45. 4-Methylphenol	106-44-5
46. N-nitroso-dipropylamine	621-64-7
47. Hexachloroethane	67-72-1
48. Witrobenzene	98-95-3
<pre>system = sopport = so</pre>	10-59-1 89 75 E
51. 2.4-Dimethylahenal	105-67-9
52. Benzoic acid	65-85-0
53. Bis(2-chloroethoxy)methane	111-91-1
54. 2,4-Dichlorophenol	120-83-2
55. 1,2,4-Trichlorobenzene	120-82-1
56. Naphthalene	91-20-3
D/. 4-LNIOFDANIIINE KD. Havarbianabusadiana	105-4/-8
50. mexachiorodutagiene 59. 4-[h]oro-3-methy]obeno][nara_ch]oro-meta-creso]	59-50-7
60. 2-Methylnaphthalene	91-57-6
ees a manifrinkinkinking	1 77 47 4
61. Mexachlorocylcopentadiene	1/-4/-4
61. Mexachlorocylcopentadiene 62. 2,4,6-Trichlorophenol	88-06-2

(continued)

Substance	CAS number
Semivolatiles (continued)	
64. 2-Chloronaphthalene	91-58-7
55. 2-Nitroaniline 55. Dimethyl obthalate	B8-74-4
67. Acenaphthylene	208-96-B
68. 3-Nitroaniline	99-09-2
59. Acenaphthene	83-32-9
70. 2,4-Dinitrophenol	51-28-5
71. 4-ATTrophendi 72. Dibenzofuran	100-02-7
73. 2.4-Dinitrotoluene	121-14-2
74. 2,6-Dinitrotoluene	606-20-2
75. Diethylphthalate	84-66-2
76. 4-Chlorophenyl phenyl ether	7005-72-3
77. riuorene 78. A-Nitroaniline	100-01-6
79. 4.6-Dinitro-2-methylphenol	534-52-1
80. N-nitrosodiphenylamine	86-30-6
81. 4-Bromophenyl phenyl ether	101-55-3
82. Mexachiorobenzene 83. Pentischiorobenal	118-74-1
84 Phenanthrene	85-01-8
85. Anthracene	120-12-7
86. Di-n-butylphthalate	84-74-2
87. Fluoranthene	206-44-0
88. Pyréne 89. Butul banaul abthalata	120-00-0
90 3.3'-Dichlorohenzidine	91-94-1
91. Benzo(a)anthracene	56-55-3
92. Bis(2-ethylhexyl)phthalate	117-81-7
93. Chrysene	218-01-9
94. Ul-n-Octyl phthalate 05. Benzo(b)fluoranthann	11/-84-0
96. Benzo(k)fluoranthene	207-08-9
97. Benzo(a)pyrene	50-32-8
98. Indeno(1,2,3-cd)pyrene	193-39-5
99. Dibenzo(a,h)anthracene	53-70-3
100. benzo(g,n,1)perytene	191-24-2
Pesticides/PCB	
101. Alpha-BHC	319-84-6
107. Beta-EHC	319-85-7
104 Gamma-BHC (lindane)	58-89-9
105. Heptachlor	76-44-8
106. Aldrin	309-00-2
107. Heptachlor epoxide	1024-57-3
108, Endosultan I 109 Dialdrin	959-98-8
110. 4.4'-DDE	72-55-9
111. Endrin	72-20-B
112. Endosulfan 11	33213-65-9
113. 4,4'-DDD	72-54-B
114. ENGOSUITAN SUITALE 115. A. A'-DNT	50-20-2
116. Endrin ketone	53494-70-5
117. Methoxychlor	72-43-5
118. Chlorodane	57-74-9
119. Toxaphene 120. Apoci 09.1016	8001-35-2
121. AROCI 0R-1221	11104-28-2
122. AROCL OP-1232	11141-16-5
123. AROCLOR-1242	53469-21-9
124. AROCL OR-1248	12672-29-6
125. ARUCLUR-1254	11097-69-1
120. ANULLUK-1200	111030-85-2

(continued)

TABLE 3 (continued)

Substance	CAS number
Hetals	
127. Aluminum	
128. Antimony	
129. Arsenic	1
130. Barium	
131. Beryllium	
132. Cadmium	
133. Calcium	
134. Chromium	
135. Cobalt	
136. Copper	
137. Iron	
138. Lead	1
139. Magnesium	i
140, Manganese	
141. Mercury	
142. Nickel	1
143. Potassium	
144. Selenium	
145. Silver	
146. Sodium	
147. Thallium	
148. Vanadium	
149. Zinc	1
150. Cyanide	1

APPENDIX A

1511

	Design Requirements	Cable Tool	Direct Mud Rotary	Reverse Rotary	Dual Tube-Air Rotary	Top Casing Drive Air/Mud	-Air rotary	Hollow Stem Auger
1	Piezometer single (1")							
	A. consolidated	1	5	1	2	1-4	4	4
	B unconsolidated	1	5	1	2	1-4	1	4
	Multiple piezometer in a single borehole							
	A. consolidated	1	5	4	0	1-4	3	0
	B unconsolidated	1	5	4	0	1-4	1	0
2.	Water samples single (2″)							
	A. consolidated	1	5	1	2	1-4	4	3
	B. unconsolidated	1	5	1	2	1-4	1	3
3.	Aquifer testing single casing (6")							
	A consolidated	3	5	4	0	4	4	0
	B unconsolidated	3	5	4	0	4	2	0
	Multiple casings in a single borehole							
	A consolidated	1	5	4	0	0	1	0
	B unconsolidated	1	5	4	0	0	0	0

Monitoring Well Design Rating System

From: Eugene E. Luhdorff and Joseph C. Scalmanini, Consulting Engineers

Drilling Method Rating System

_	Objectives	Cable Tool	Direct Mud Rotary	Reverse Rotary	Dual Tube-Air Rotary	Top Casing Drive Air/Mud	Air Rotary	Hollow Stem Auger
1.	Identification of lithology A. consolidated formations B. unconsolidated formations	3-5 3-5	1-4 1-4	1-4 1-4	3-5 3-4	3-5 3-5	2-3 2-3	3-5 3-5
2.	Sampling of aquifer fluid A. non-volatile B. volatile	3-5 3-5	1-2 1-2	0-2 0-2	2-5 0-1	3-5 3-5	1-2 0-1	2-4 2-4
3.	Rate of penetration A. consolidated formations hard soft B. unconsolidated formations max size > 20mm max size \$ 20mm	1-2 1-2 1-2 1-2	1-3 2-5 1-3 2-5	1-3 2-5 2-4 2-5	2-4 1-3 0-2 0-2	1-4 1-4 1-3 1-3	2-4 2-3 0-2 0-2	1-2 2-4 0-2 0-3
4.	Ability to perform geophysical logging A. consolidated formations B. unconsolidated formations	0-2 0	5 5	3-4 3-4	0-1 0-1	0-5 0-5	0-3 0-2	0-2 0
5.	Ability to complete borehole into monitoring well during construction A. consolidated formations B. unconsolidated formations	3-4 3-4	3-5 3-5	3-5 3-5	1-3 0-2	3-4 0-3	1-3 0-3	0-3 0-3
6.	Ability to complete borehole into well following time lapse for log review A. consolidated formations B. unconsolidated formations	0-3 0-2	3-5 3-5	1-3 1-3	0-2 0-2	2-5 2-5	2-3 1-2	0-1 0-1
7.	Ability to obtain cores or sidewall samples	3-4	2-4	1-2	3-4	2-4	0-2	2-4
8	Ability to contain formation fluid and drill cuttings	3-5	3-5	0-3	3-5	2-4	0-2	3-5
9	Special site conditions A. lost circulation B. high formation pressure	4	2	1	5	4	3	1
	(exceeding surface elevation) C. flammable or explosive materials D. toxic materials E. other site-specific problems	0 3 3	5 5 5	0 3 3	2 1 1	4 4 4	0 1 1	0 1 1

From: Eugene E. Luhdorff and Joseph C. Scalmanini, Consulting Engineers

Selection of Drilling Method, Well Design and Sampling Equipment for Wells to Monitor Organic Contamination

by Eugene E. Luhdorff, Jr. and Joseph C. Scalmanini, Luhdorff & Scalmanini, Consulting Engineers

In the course of ground-water investigations, including those designed to identify and correct or control ground-water contamination problems, some of the most important components are the drilling of boreholes for exploratory purposes, the completion of those or other boreholes into wells and the design and ultimate operation of wells for various purposes. Yet the attention paid to these components often seems cursory, thus allowing an element of question to enter regarding the accuracy of geologic or geophysical data, piezometric measurements and water quality samples. Equally as important, the cost effectiveness or, in certain extreme cases, the pure ability to accomplish the desired tasks become subject to serious question. This paper investigates improvements and innovations in drilling technology in the ground-water industry during the past decade which make available a vast assortment of techniques which, if properly selected, will provide efficient means to initially investigate ground-water quality and aquifer characteristics and to ultimately complete and operate monitoring or other wells. The paper further presents a methodology for rating several drilling methods based on their ability to achieve typical tasks in a ground-water quality investigation, and it illustrates the application of the rating system to two ground-water contamination problems in California.

Selection of Drilling Method

Objectives of a Drilling Program

After completion of the preliminary phases of a ground-water investigation, which might include review of existing data, surface geologic and geophysical exploration and collection of water-level and waterquality data from existing wells, subsurface exploration and investigation follow. The selection of a drilling method for this phase of work should be based on the ability and cost effectiveness of a particular method to accomplish the desired objectives of the drilling program. The objectives should be carefully defined prior to drilling in order to avoid costly and timeconsuming frustrations resulting from the inability of a drilling method to penetrate the geologic conditions at the site or to attain the necessary information from the boreholes.

The objectives of a drilling program, or the tasks to be accomplished by a drilling program at any given site can include some or all of the following:

• The ability to physically penetrate all anticipated formations and materials at the particular site, to penetrate at a desired rate and to construct a borehole of desired diameter

• Identification of lithology, or development of a geologic log of all formations and materials penetrated to the desired depth

 Collection of samples of aquifer fluid during the drilling process and prior to well construction

• Geophysical logging of the borehole, ranging from electrical surveys to measurements of natural radiation, to determination of formation characteristics using sonic or radioactive tools

• Collection of "undisturbed" formation samples from the center line or sidewall of the borehole

Containment of drill cuttings and fluids

• The ability to handle special conditions such as lost circulation, high pressure, flammable or toxic substances or other site-specific problems

• Completion of the borehole into a monitoring well during the initial construction process, i.e., constructing a well as the borehole is drilled or constructing a well in the borehole immediately after the drilling tools are removed

• Completion of a monitoring well in the borehole after a time lapse for interpretation of geologic and geophysical data collected from the borehole. Each ground-water investigation will have sitespecific objectives among those listed above which can be used to select the best method of drilling at that site. In some cases, one objective may predominate and thus dictate a particular drilling method; in others, all the desired objectives might not be achievable and some compromise might be required either to reduce the objectives or increase the number of boreholes.

Drilling Methodology

The advancement of drilling techniques over the past decade presents a wide range of choices to those responsible for the selection of a drilling method in a ground-water investigation. The selection of the drilling procedure to employ on a project should be based on an analysis of a rig's capability to develop the specific exploration and well-completion requirements of the project.

Seven drilling techniques have been reviewed and relative values assigned to a series of objectives for each type of drilling procedure.

A detailed review of each drilling procedure is beyond the scope of this paper; however, a brief description of each type of operation follows.

1. Cable Tool Drilling

This procedure is the oldest method of well construction still widely practiced in the water well industry. The cable tool or percussion drilling method has been used for centuries throughout the world. It involves the raising and lowering of a string of drilling tools suspended on a drilling line in the well bore, followed by the bailing of the drilled cuttings from the hole. Generally, the well bore is kept open by the installation of a casing string as the drilling operation proceeds to the completion depth.

This practice of construction is usually much slower than the more modern rotary drilling techniques; however, the procedure has application in certain monitoring well applications.

2. Direct Circulation Mud Rotary Drilling

The introduction of direct circulation rotary well construction made possible the development of much of the world's oil resources. Adapted to water well construction in the early part of the 20th century, this drilling method allowed for more rapid construction of deeper wells for the ground-water industry. The practice employs a drilling fluid—normally a viscous fluid, heavier than water—which is circulated down a rotating drill pipe, through the drilling bit, returning up the annulus of the borehole, removing the drill cuttings in a settling pit where the fluid is again recirculated through the fluid system via a pump. Hole stability is accomplished by the hydrostatic pressure of the drilling fluid.

3. Reverse Circulation Rotary Drilling

The first unique drilling procedure developed by the water well industry was the introduction of reverse circulation drilling. The procedure of reversing the direction of flow—allowing the circulation of fluid from the bit up the rotating drill pipe to the settling pit allowed for holes of larger diameters to be constructed. The integrity of the borehole is achieved by hydrostatic fluid pressures created by maintaining the hole full of water during drilling operations. The procedure reduced the need for specialized drilling mud control and reduced the development time required for normal mud rotary well construction completions.

4. Air Rotary Drilling

A second modification of conventional direct circulation rotary drilling is the use of compressed air as a drilling fluid instead of water or drilling mud. A high uphole velocity of air is used to remove cuttings from the borehole. While foaming agents and misting assist the driller in cleaning the hole, hole maintenance relies on the integrity of the formation to remain open during construction without the hydrostatic pressures present in conventional and reverse circulation drilling operations. This procedure is widely used throughout much of the northeastern United States and elsewhere in the country where consolidated formations exist, for domestic well construction.

5. Dual-Tube Rotary Construction

In order to obtain more precise control of the drill cuttings being returned up the hole, the air rotary drilling method has been refined by employment of a dual-tube drill pipe assembly. The drilling fluid (air) is sent down the drill pipe and the cuttings returned up the drill pipe in a second part of the "dual-tube." The practice is further refined by the use of a smooth outer drill pipe just slightly smaller than the hole diameter or bit diameter thus serving as a mechanical means of maintaining the integrity of the borehole. The drilling procedure has had wide application in the mining industry for material identification and for formation fluid sampling via air lift pumping.

6. Tophead Drive, Casing Hammer, Combination Rotary Rigs

Many rig manufacturers today provide drilling equipment which is capable of employing either air or drilling mud as the drilling fluid. In addition, some rigs are further refined to include tophead drive, casing hammer operations. Such a rig provides the ability to alter the method of construction to meet varving hole conditions encountered in the well. The use of a casing hammer allows casing to be installed through difficult drilling formations such as unconsolidated surface deposits and then returns to either air or mud circulation drilling for hole completion. The flexibility of the system does not provide the planner an endless freedom of choice in the random selection of drilling medium. Once committed to mud circulation, it is difficult to convert the system to air circulation in the same horehole. The rig flexibility allows the planner a first noice in drilling procedures.

7. Hollow Stem Auger Rig

While normally not considered a water well drilling rig, the hollow stem auger rig provides a means for construction of shallow piezometer wells commonly associated with monitoring projects. As the name implies, the rig configuration is normally a continuous rotary auger which is frequently used in soil foundation studies. The hollow stem in the auger drill string permits coring and water sampling during the drilling operation. In addition, small diameter casing can be installed through the hollow stem prior to removal of the drill string from the well.

Rating and Selection of Drilling Methods

To address the question of selection of the best drilling method for two recent ground-water contam-

Table 1Drilling Method Rating System

	Objectives	Cable Tool	Direct Mud Rotary	Reverse Rotary	Dual Tube-Air Rotary	Top Casing Drive Air/Mud	Air Rotary	Hollow Stem Auger
1.	Identification of lithology A. consolidated formations B. unconsolidated formations	3-5 3-5	1-4 1-4	1-4 1-4	3-5 3-4	3-5 3-5	2-3 2-3	3-5 3-5
2.	Sampling of aquifer fluid A. non-volatile B. volatile	3-5 3-5	1-2 1-2	0-2 0-2	2-5 0-1	3-5 3-5	1-2 0-1	2-4 2-4
3.	Rate of penetration A. consolidated formations hard - soft B. unconsolidated formations max size > 20mm max size * 20mm	1-2 1-2 1-2 1-2	1-3 2-5 1-3 2-5	1-3 2-5 2-4 2-5	2-4 1-3 0-2 0-2	1-4 1-4 1-3 1-3	2-4 2-3 0-2 0-2	1-2 2-4 0-2 0-3
4.	Ability to perform geophysical logging A. consolidated formations B. unconsolidated formations	0-2 0	5 5	3-4 3-4	0-1 0-1	0-5 0-5	0-3 0-2	0-2 0
5.	Ability to complete borehole into monitoring well during construction A. consolidated formations B. unconsolidated formations	3-4 3-4	3-5 3-5	3-5 3-5	1-3 0-2	3-4 0-3	1-3 0-3	0-3 0-3
6.	Ability to complete borehole into well following time lapse for log review A. consolidated formations B. unconsolidated formations	0-3 0-2	3-5 3-5	1-3 1-3	0-2 0-2	2-5 2-5	2-3 1-2	0-1 0-1
7.	Ability to obtain cores or sidewall samples	3-4	2-4	1-2	3-4	2-4	0-2	2-4
8.	Ability to contain formation fluid and drill cuttings	3-5	3-5	0-3	3-5	2-4	0-2	3-5
9.	 Special site conditions A. lost circulation B. high formation pressure (exceeding surface elevation) C. flammable or explosive materials D. toxic materials 	4 0 3 3	2 5 5 5	1 0 3 3	5 2 1 1	4 4 4	3 0 1 1	1 0 1 1
-	E. other site-specific problems			ر 	•	т 	•	•

ination investigations and other ground-water quality investigations in California, a simple and direct rating system was developed to evaluate all the above drilling methods and their abilities to accomplish the objectives. selected for each. For each objective or task, values from zero to five are assigned to each drilling method. A value of zero indicates the inability of the drilling method to accomplish a particular objective and, of course, precludes either that drilling method or that objective from further consideration. Other values are assigned as follows to qualitatively rate the drilling methods: 1-poor, 2-fair. 3-satisfactory, 4-good and 5- excellent After assignment of values for all the objectives, the respective totals for the various drilling methods provide an indication of the best method for the particular job.

In some cases, a particular investigation may have one or more essential objectives. In such a case, the values assigned for those particular objectives can be inflated to "weigh" the selection of drilling method toward that which will best accomplish the essential objectives.

The rating and selection system is illustrated in Table 1 with values assigned to each of the seven drilling methods described above for the various objectives potentially desired in any ground-water investigation. The values included in Table 1 are typical of ratings or ranges of ratings which would be applicable to drilling with these methods in various geologic environments.

Well Design

Design of wells for monitoring ground-water quality can differ from well design for ground-water development and production. As in the case of selecting the best drilling method, monitoring well design can also be considered in terms of a series of objectives which the wells might be expected to achieve.

Monitoring wells generally are constructed for one or more of three purposes:

• Measurement of water table or piezometric surface elevations

Collection of ground-water samples

• Determination of aquifer characteristics.

It can generally be concluded that all three of the above purposes require certain similarities to production wells: wells free of sand and turbidity, and wells properly sealed and developed to monitor formation fluids. Given those considerations, monitoring wells can be sized as a function of their purpose: a minimum of 1-inch in diameter for water level measurements: a minimum of 2 inches for water sample collection and a minimum of 6 inches for wells to be pumped for aquifer analysis.

If the initial drilling program, selected in a manner as described above, is to include well construction, a similar evaluation technique can be employed either to add the well construction requirements to those for drilling only (Table 1), or to consider the well construction objectives separately, which may result in more than one drilling method being employed on a project

-	Design Requirements	Cabie Tool	Direct Mud Rotary	Reverse Rotary	Dual Tube-Air Rotary	Top Casing Drive Air/Mud	Air rotary	Hollow Stem Auger
1.	Piezometer single (1")							
	A. consolidated	1	5	1	2	1-4	4	4
	B. unconsolidated	1	5	1	2	1-4	1	4
	Multiple piezometer in a single borehole							
	A. consolidated	1	5	4	0	1-4	3	0
	B. unconsolidated	1	5	4	0	1-4	1	0
2.	Water samples single (2")							
	A. consolidated	1	5	1	2	1-4	4	3
	B. unconsolidated	1	5	1	2	1-4	1	3
3.	Aquifer testing single casing (6")							
	A. consolidated	3	5	4	0	4	4	0
	B unconsolidated	3	5	4	0	4	2	0
	Multiple casings in a single borehole							
	A consolidated	1	5	4	0	0	1	0
	B. unconsolidated	1	5	4	0	0	0	0

Table 2 Monitoring Well Design Rating System

In the extreme, more than one drilling method may be employed on a single location: one method to satisfy exploratory objectives and a second to construct permanent monitoring wells

The rating and selection system for well design, similar to that described above for drilling methods, is illustrated in Table 2. In this case, the values have the same qualitative ratings as used earlier and again, after application to a certain set of objectives, would allow for selection of the best equipment for monitoring well construction.

Applications of Drilling Method Selection Criteria

The selection procedures described herein have been effectively applied to two ground-water contamination investigations in California during the last two years. Both are briefly summarized below.

Case 1—Eastern Sacramento County

In the spring of 1981, it was determined that ground water in eastern Sacramento County had become contaminated. Organic and inorganic pollutants, including chlorinated organic chemicals, phenol, perchlorate, arsenic and sulfates had been found in concentrations exceeding the State and Federal drinking water action levels.

The State of California Water Resources Control Board commenced a program to construct test holes and monitoring wells in the affected area to obtain geologic, hydrologic and water quality information in order to determine the extent of the contamination and to monitor its movement.

The selected drilling sites were characterized by surface deposits of cobbles and other dredge tailings overlying unconsolidated sand and gravel formations. Drilling depths would range from 300 to 700 feet. All drilling sites were restricted to existing State of California property, normally located within freeway right-of-ways.

A summary of the evaluation of the drilling rig selection is illustrated in Tables 3 and 4. The work was successfully completed using a combination casing hammer, air and mud rotary drilling program.

Case 2-San Joaquin County

A large agricultural chemical manufacturer was required by the Environmental Protection Agency and the State of California to implement a program of investigation to determine if the source of groundwater contamination found in the area was attributable to its plant operations. The contaminants consisted of both inorganic and organic chemicals including pesticides.

A program of exploratory drilling was commenced to define lithology, obtain soil and water samples from the borehole and measure certain conservative quality parameters in each aquifer sample as drilling continued. The initial attempt to obtain the above samples employed the use of a hollow stem auger rig and a peristaltic pumping system. Drilling depths through uniform sand and clay formations were anticipated to be approximately 200 feet. Extreme difficulty was experienced in hole construction and sampling. As a result, the drilling program was evaluated using the method described above; the results are illustrated in Table 4. The drilling method was subsequently changed to meet the desired objectives and the work was successfully completed using a dual-tube drilling rig for soil sample collection and fluid sampling of the aquifer. Subsequent construction of monitoring well clusters (three or four individual wells per site), after construction and abandonment of all the exploratory holes, was successfully accomplished using direct mud rotary drilling.

Monitoring Equipment

Much has been authored recently on the subject of extracting samples of water from monitoring wells. The amount of fluid that must be removed from a well casing to truly represent the water contained in the aquifer is still the subject of continued technical research. Those who have spent a number of years in the industry involved in pumping wells have experienced that a minimum of several casing volumes of fluid must be removed from a well to assure that the water being obtained represents the water in storage in the aquifer. The volumes to be removed from the casing should be increased both as the age of the well increases and the period of time between sampling increases.

To satisfy these concerns, two methods of providing pumping equipment for monitoring wells were adopted on specific projects in California on behalf of the Water Quality Control Board, the agency assigned the responsibility of protecting the quality of water in the state.

One method involved the permanent mounting of small submersible pumps in a series of wells requiring monitoring. The submersible wiring was brought to the surface and terminated in a weatherproof junction box. The motor controller containing the relays and capacitor for the submersible pump was mounted on a portable switchboard which was moved from well to well with a portable generator. The system is designed to receive a teflon bailer to extract an aquifer sample following well purging by the submersible pump. The bailer is lowered into the submersible pump discharge piping to increase the reliability of the sample.

The use of a permanent pump in a well that will be sampled frequently, allows the investigator the opportunity to collect samples and to define aquifer characteristics through well testing. Water level measurements for testing or for monitoring can be obtained using permanently installed pneumatic transducers which are capable of providing instantaneous readout or continuous recording of water levels.

The second method of well purging required the development of a self-contained portable pump unit.

Case 1
Table 3
Drilling Method Rating System

	Objectives	Cable Tool	Direct Mud Rotary	Reverse	Dual Tube-Air Rotary	Top Casing Drive Air/Mud	Air Rotary	Hollow Stem
1	Identification of lithology A. consolidated formations B. unconsolidated formations	3	4	L.	3	4	2	3
2.	Sampling of aquifer fluid A. non-volatile B. volatile				NOT REQ	UIRED		
3.	Rate of penetration A. consolidated formations hard soft B. unconsolidated formations							
4.	max size > 20mm max size < 20mm Ability to perform geophysical logging A. consolidated formations	1	2	2	1	3	1	0
5.	 B. unconsolidated formations Ability to complete borehole into monitoring well during construction A. consolidated formations B. unconsolidated formations 	0	5	3	0 NOT REQ	5 UIRED	0	0
6.	Ability to complete borehole into well following time lapse for log review A. consolidated formations B. unconsolidated formations	3	5	1	0	5	1	0
7.	Ability to obtain cores of sidewall samples				NOT REQ	UIRED		
8.	Ability to contain formation fluid and drill cuttings				NOT REQ	UIRED		
9	 Special site conditions A. lost circulation B. high formation pressure (exceeding surface elevation) C. flammable or explosive materials D. toxic materials E. other site-specific problems 				NON	ΡE		
_	Totals:	0	16	7	0	17	0	0

Method Chosen: tophead drive, casing hammer with machined air circulation

The system consists of a submersible pump, hose reel, power winch, pneumatic transducer for water-level measurements, flowmeter and generator, all mounted on a portable trailer. Two men can install the submersible pump to a depth of 200 feet in approximately 15 to 20 minutes. The well can then be pumped until the desired volume is extracted from the well. Samples of the pumped fluid can be taken directly from the pumping unit or, if desired, the sample can be obtained by the use of a bailer. The portable equipment is also designed to conduct pumped well tests by providing measurements of the pumping rate, static and pumping water levels and total water pumped during the pumped period.

Case 2 Table 4 Drilling Method Rating System

	Objectives	Cable Tool	Direct Mud Rotary	Reverse Rotary	Dual Tube-Air Rotary	Top Casing Drive Air/Mud	Air Rotary	Hollow Stem Auger
1.	Identification of lithology A. consolidated formations B. unconsolidated formations	4	3	3	5	3	2	5
2.	Sampling of aquifer fluid A. non-volatile B. volatile	5	1	0	5	3	ł	2
3.	Rate of penetration A. consolidated formations hard soft B. unconsolidated formations max size > 20mm max size < 20mm	1	3	3	2	3	0	0
4.	Ability to perform geophysical logging A. consolidated formations B. unconsolidated formations				NOT REQ	UIRED		
5. -	Ability to complete borehole into monitoring well during construction A. consolidated formations B. unconsolidated formations				NOT REQ	UIRED		
6.	Ability to complete borehole into well following time lapse for log review A. consolidated formations B. unconsolidated formations				NOT REQ	UIRED		
7	. Ability to obtain cores or sidewall samples				NOT REQ	UIRED		
8	. Ability to contain formation fluid and drill cuttings	3	3	0	5	2	0	3
9	 Special site conditions A. lost circulation B. high formation pressure (exceeding surface elevation) C. flammable or explosive materials D. toxic materials E. other size specific problems 	3	5	3	1	4	1	1
	TOTALS	16	15	0	18	15	0	0

Biography of Presenting Author

Eugene E Luhdortt Jr. is a partner in Luhdorff and Scalmanini Consulting Engineers of Woodland, California, an organization specializing in ground-water hydrology, development and management. A registered agricultural engineer in California, Luhdorff has more than 26 years of experience in the ground-water industry as a water well contractor and consultant. Luhdorff has authored several papers on water well construction practices and has lectured frequently in the University of California Extension system. He is a past president of the Associated Drilling Contractors of California, the California Irrigation Institute and the Ground Water Institute. Additionally, he served as a director in the National Water Well Association.

SMALL- VS. LARGE-DIAMETER MONITORING WELLS

Well diameter is one of the most important aspects of monitoring system design.

by Marjory B. Rinaldo-Lee

Designing an effective groundwater monitoring program and using proper monitoring well design is a matter of concern for both regulatory agencies and private industry. Although many factors must be considered when designing a groundwater monitoring program, such as location of monitoring points and the type of monitoring installation, well diameter is one of the important parts of the monitoring installation design.

In this article. small-diameter wells are considered 2-inch diameter or smaller. Two-inch diameter was chosen as the upper limit for smalldiameter wells for several reasons. First, the drilling methods used to install 2-inch or smaller wells are often different from those used to install wells with a larger diameter. Second. until quite recently submersible pumps were only available for 3-inch or larger diameter wells.

The factors which influence choice of well diameter for a monitoring program fall into two groups: economic and technical. Although technical and economic factors will be discussed separately, they should be considered concurrently when designing a monitoring program. Technical factors can influence the cost of a program and conversely economic factors can influence the extent of the technical program.

Technical Factors

In designing any ground-water monitoring program, the first issue to be addressed is the purpose of the program. The designer must ascertain what questions are to be answered by the investigation. The three main purposes for groundwater monitoring are baseline data accumulation. ground-water resource evaluation and groundwater contamination studies. The approach used for each of these types of studies is quite different.

Baseline data studies are usually initiated to provide data on longterm trends or general hydrogeologic conditions in an area. For some baseline data investigations, long-term water-level fluctuations are of interest. If the monitoring points are at remote locations, or continuous water-level readings are needed. automatic recorders may be desired. Since large-diameter wells can more easily accommodate floats for automatic recorders they would be preferred for this type of investigation. However, if the goal of the study is to define hydrogeologic conditions over a broad area where many well points are needed, small-diameter wells may be preferred due to their comparative ease of installation and lower cost. Thus, depending on the specific needs of the investigation. either small- or large-diameter wells may be preferred for a baseline study.

A ground-water resource investigation is quite different from a baseline data study. These investigations are usually initiated in response to a demand for a source of water supply. A ground-water resource investigation could be initiated because water is needed for drinking water, industrial processes. agricultural activity or some other use. Alternatively, a resource investigation could also be initiated to determine how to dewater an area for some activity requiring a lowered water table. such as construction or mining. A pump test is often needed for determining both the amount of water available for use, or the amount of water which must be withdrawn. A largediameter well may be needed to accommodate a submersible pump with a large enough capacity to allow a pump test to be conducted. However, small-diameter wells are adequate for observation wells to allow monitoring of drawdown and evaluation of pump tests. Thus, both large- and small-diameter wells are commonly used in ground-water resource investigations.

Monitoring requirements for ground-water contamination studies are quite different from those for the preceding studies. Often many wells are needed in various geologic formations to determine the extent of past contamination or the potential for contaminant migration from a proposed site. For ground-water contamination studies, small-diameter wells are often preferred because they are less expensive and more sampling points can be installed for a fixed amcunt of available funds. Another reason for the use of small-diameter wells in contamination studies is the comparative ease of sampling from such wells.

Wells are normally purged before sampling in contamination studies to remove stagnant water from the borehole and to ensure that the water sample is representative of formation water. The volume of water which must be removed from a small-diameter well is much less than that from a large-diameter well because the volume increases with the square of the well radius As shown in Figure 1, there are 0.16 gallons/ft of water in a 2-inch diameter well and 1.47 gallons/ft of water in a 6-inch diameter well. Because purging a well requires removing from three to 40 volumes of water from the well casing, considerably more water must be removed from a 6 meh diameter well than from a 2 inch diameter well. To purge 10 volumes of water from a well containing 40 feet of water in the casing, 16 gallons of water must be removed from a 2 inch diameter well, as opposed to 147 gallons of water from a 6-inch diameter well.

Another sampling consideration is obtaining a sufficient quantity of water from a well for analysis. Smalldiameter wells have a much smaller volume of water per foot of length (Figure 1). However, for many sampling situations, one gallon of water is sufficient for a large number of analyses. Table 1 demonstrates that a 6 13-foot column of water in a 2inch diameter well produces one gallon of sample, while a 0.68-foot column of water produces a gallon of sample in a 6-inch well.

A third factor which favors smalldiameter wells for contaminant sampling is the time of recovery. Because the time of recovery is directly proportional to the well volume, the time for recovery also increases with the square of the well diameter. For a given hydraulic conductivity. it takes less time for a small-diameter well to recover when a slug of water is removed than for a large-diameter well. Figure 2 illustrates the time of recovery for various diameter wells assuming a given hydraulic conductivity, screen length and instantaneous lowering of the water surface in the well. Assuming a hydraulic conductivity of 0.028 ft/day (1 x 10^{-5} cm/sec), screen length of 10 feet and an instantaneous lowering of the water table by 6 feet. It would take 11-1/2 minutes for a 2-inch diameter well to recover 5 feet. Twentythree and a half minutes would be required for the same recovery in a 3-inch diameter well and 42 minutes for the same recovery in a 4-inch diameter well. These recovery times are important in contaminant sampling because unlike ground-water resource investigations, the formation being investigated for a contamination study may be fairly impermeable. If a large-diameter well is purged before sampling in a finegrained soil. it may take many hours to recover, while a small-diameter well will recover more quickly.

Hydrogeologic conditions also influence the choice of well diameter. Hydrogeologic conditions can generally be divided into two categories: aquifer characteristics and the ground-water regime. Aquifer characteristics include the formation



Table 1 Comparison of Length of Well Casing Containing One Gallon of Water with Well Diameter

Well Diameter (inches)	2	3	4	5	6
Length of well casing needed to obtain					
1 gallon water (feet)	6.13	2.72	1.53	0.98	0.68

parameters which influence ground-water movement, such as hydraulic conductivity. Factors included under ground-water regime include depth to the potentiometric surface, the nature of the aquifer (whether confined or unconfined) and the number of aquifers being investigated. All of these factors influence the choice of well diameter.

If the formation of interest has a low hydraulic conductivity, smalldiameter wells are preferred for monitoring Not only do smalldiameter wells recover more quickly for water sampling, they stabilize more quickly after initial installation. In a clay formation with a low hydraulic conductivity $(3 \times 10^{-4}-3 \times 10^{-5} \text{ ft/day})$, it could take months for a 4-inch diameter well to stabilize.

Depth to the water table from the ground surface was once a limiting factor in using small-diameter wells. Bailers were the only means for withdrawing water from wells where the potentiometric surface was below the suction limit (about 25 feet) However, with the advent of a variety of small-diameter submersible pumps which fit inside 2-inch diameter wells and various air lift and positive displacement pumps for 2-inch diameter or 1-inch diameter wells, it is not necessary to use a

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Figure 2	Time required for	well recovery when	slug of water removed
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bailer to remove water from smalldiameter wells.

Depth to the potentiometric surface may be a limiting factor in the use of small-diameter wells where the water-table surface is very deep (i.e. several hundred feet). In the western U.S., where aquifers may be hundreds or thousands of feet deep. a small-diameter well may not be desirable due to difficulties in well construction procedures and the increased probability of well casing failure at depth. Although sampling devices have been developed for very deep wells, it can still be difficult to sample deep small-diameter wells. Larger diameter wells may be preferred in this situation.

Another geologic consideration is the number of aquifers or levels within a single aquifer being investigated by the monitoring program. If multilevel sampling points are needed to monitor various aquifers, or various levels within one aquifer, small-diameter wells are generally preferred due to their low cost and ease of installation.

Economic Factors

Along with technical factors, economic factors have a significant influence on the choice of well diameter. Funds for a ground-water investigation are generally limited and it is always desirable to obtain the most information for the least cost. The economic factors which influence the cost of installing monitoring wells include drilling cost, materials cost and labor cost.

Drilling costs depend on the method of well installation and the drilling contractor. One of the methods often used to install monitoring wells in unconsolidated deposits is the hollow-stem auger. Hollow-stem augers are used because soil samples can be taken during drilling and the monitoring well can be installed inside the hollow stem without collapse of the borehole. However, a normal hollow-stem auger has an inside diameter of only 2-1/4 to 3-3/4 inches so it cannot be used effectively to install a well with a diameter of more than 2 inches. A larger hollow-stem auger with a 6-inch inside diameter can be used to install up to 4-inch diameter wells: but the cost of drilling using the larger hollow-stem augers is greater. The cost of drilling and obtaining soil samples is about \$8/ft using a small-diameter hollow-stem auger compared to \$17.50/ft for the large hollow-stem auger (Table 2). Generally, a water well contractor is more cost-effective to use for drilling a 4inch or larger diameter well than a geotechnical-soil contractor. Since most water well contractors are not

equipped for soil sampling, if soil sampling were required to define subsurface conditions, it might require hiring both types of contractors.

Drilling costs for a geotechnicalsoils contractor to install wells in rock are generally higher than for drilling through unconsolidated deposits. The differential between drilling in rock and drilling in unconsolidated deposits is much greater if rock samples are required. Coring to obtain rock samples adds significantly to the cost of drilling. Rock coring by a geotechnical contractor is about \$26/ft for a hole large enough for a 2-inch diameter well and \$35/ft for a hole large enough for a 4-inch diameter well. Generally, a water well contractor is more cost-effective to use for installing large-diameter wells in rock formations. However, water well contractors are usually not equipped for rock coring. If this is deemed necessary to the investigation program, two contractors may be required to install monitoring wells in rock formations

Labor and material costs are also factors affecting choice of well diameter. Well installation, well development and well purging are all labor costs associated with a monitoring program Small-diameter wells are generally easier to install and therefore take less time. They also take less time to develop and purge since a smaller volume of water must be removed. Thus, labor costs are lower for small-diameter wells. Material costs are also lower for small-diameter wells (Table 2). The cost per foot of well casing and screen increases with well diameter for both PVC and stainless steel. the most common types of casing/ screen used in monitoring wells.

When drilling costs, labor costs and material costs are all taken into consideration. the total cost to install the same type of well. using different diameter well casings, can be compared (Table 3). If a 50-foot PVC well is installed with a 10-foot PVC well screen, the total installation cost in unconsolidated materials. including conventional standard split spoon sampling at intervals of 5 feet, would be \$1,200, or about S24/ft. The cost to install a comparable 4-inch diameter in the same unconsolidated material with standard sampling would be about \$2,500 or about \$50/ft, or more than twice the cost for the 2-inch well. The cost for installing a 2-inch diameter well after coring through rock would be about \$2,600 or \$52/ft. The increase

in cost of installing a well as the diameter of the well is increased will influence the design of the monitoring program.

Summary

Both technical and economic factors influence monitoring well design. Depending on the purpose of the monitoring program, the hydrogeologic conditions and the economic constraints, both smalland large-diameter wells have advantages (Table 4). The advantages of small-diameter wells are: 1) they stabilize quickly in low permeability formations: 2) they require removing only a small amount of water to purge them prior to sampling: 3) they develop more quickly: 4) they are generally more easily installed: and 5) the materials, labor and drilling costs are lower than for large-diameter wells.

There are certain monitoring situations which may require largediameter wells. Pumping tests for ground-water resource evaluation may require large-diameter wells for the pumping well. Ground-water investigations in very deep aquifers may also require large-diameter wells. In addition. specialized monitoring needs such as automatic water-level recorders or evaluation of remedial measures for groundwater contamination studies may also necessitate the installation of large-diameter wells.

In conclusion, small-diameter monitoring wells are economically advantageous because they cost less to install and less to maintain for long-term sampling purposes. Moreover, they can be used in the majority of monitoring situations. However, large-diameter wells are still necessary for a pumping test and may also be needed in areas where the water table is very deep.

Biographical Sketch

Marjory Rinaldo-Lee received a B.A. in geology from Mount Holyoke college and an M.S. in geology and water resources management from the University of Wisconsin. She is currently a hydrogeologist with Empire Soils Investigations/Thomsen Associates in Groton, New York, where she is responsible for management of hydrogeologic projects ranging from ground-water resource development to site contamination investigations. Previously she worked as a hydro-

Table 2 Comparison of Approximate Cost for Drilling and Materials for Monitoring Wells

		١	Well Diamete	r
Ec	onomic Factors	2-Inch	3-Inch	4-Inch
Drilling	Rock Coring	\$26.00	\$26.00	\$35.00
Cost/Ft	Hollow Stem Auger	\$8.00	\$17.50	\$17.50
Materials	Stainless Steel	\$11.00	\$14.50	\$20.00
Cost/Ft	PVC	\$ 2.50	\$ 5.50	\$700

Table 3 Comparison of Cost to Install Monitoring Wells

Geologic Type of		Diameter of PVC Pipe			
Material	Drilling	2-Inch	3-Inch	4-Inch	
Rock	Rock Coring	\$2,600	\$3,800	\$4.300	
	Rock Drilling	\$1.300	\$2.400	\$2.60 0	
Uncon-					
solidated	Drilling & Sampling	\$1,200	\$2.200	S2.500	
Deposits	Drilling	\$1.050	\$2.100	\$2.300	

Well casing and screen are PVC

Table 4 Comparison of Advantages of Small- and Large-Diameter Wells

Advantages of large-diameter wells	Advantages of small-diameter wells		
• Accommodate large submersible pumps for pumping tests	• Stabilize more quickly in low permeability formations		
• Accommodate automatic water level recorders easily	• Lower labor costs due to easier installation, quicker development		
• Accommodate specialized monitoring equipment easily for very deep wells or other specialized monitoring requirements	and smaller volume of water removed during purging • Lower materials cost		
	Lower drilling costs		

geologist for Residuals Management Technology Inc. in Madison, Wisconsin, where she was involved with hydrogeologic investigations and feasibility studies for waste disposal sites.

AN EVALUATION OF NESTED MONITORING WELL SYSTEMS

Ву

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ABSTRACT

The need for monitoring ground-water quality has grown dramatically over the last decade. Concurrently, nested monitoring well systems have evolved which produce information that better defines existing problems. Nested monitoring systems help the ground-water hydrologist deal with complex geologies, flow patterns, ground-water geochemistries, and pollution sources or types.

The major types of monitoring systems include fully screened wells, single wells with multiple sampling points, piezometers and nested well systems. The disadvantages and advantages of each including costs, ease of installation, reliability, ease of sampling, volume of sample required, and aquifer characteristics determined from each system, are discussed.

Four examples of ground-water investigations involving nested monitoring well systems are described. Included are geologic cross-sections and water quality and water level data from each investigation. The conclusions (based on the four examples) are that nested monitoring well systems provide data unavailable from other systems, the cost of installing additional wells is small, and the principal cost increase over the initial estimate is for obtaining additional samples and associated analyses.

INTRODUCTION

As the need for monitoring ground-water quality has sharply increased over the last decade, many monitoring methods have been tried and modified, and various methods have been developed to monitor both complex geologies and contaminant conditions. The ground-water hydrologist usually designs a monitoring system which can be installed during a detailed subsurface investigation. While such systems, particularly those required by regulation, are usually sufficient to provide meaningful data, they are often abbreviated because of budget limitations. This paper evaluates nested or clustered monitoring well networks in terms of the additional benefits they provide and the additional costs involved. Four examples representing varying geologies and contamination problems have been chosen to show that nested wells do provide additional useful information.

TYPE OF MONITORING SYSTEMS

Several systems are currently available for detecting and monitoring ground-water pollution, and recent improvements in technology have resulted in large variations in design and operation. There are four basic types of monitoring systems as shown in figure 1: the fully screened well, the single well with multiple sampling points, the piezometer, and the nested monitoring well system.

Each of these systems has advantages and disadvantages, and no one system is any better than the rest for any given situation. Factors to be compared are costs, ease of installation, reliability, ease of sampling, volume of sample required, and the aquifer characateristics that can be determined using the system.

Fully Screened Well

The system most commonly used in unconsolidated or semiconsolidated aquifers is a monitoring well which is fully screened throughout an entire portion of an aquifer. The well acts as an observation well for water levels and provides ground-water samples. In some cases fully screened wells penetrate the entire aquifer and provide composite samples.

The installation of a fully screened well in a single interval or in the entire aquifer is relatively easy and straightforward, and almost any drilling method can be used. Installation cost is minimal, involving no unusual hardware: well screens, casing, sand backfill and a cement seal at the ground surface. Only a single sample per well must be analyzed. A well properly designed for the existing geology and protected against vandalism should suffice.

Samples from wells in only one portion of the aquifer give no idea of the vertical distribution of a contaminant throughout the aquifer, while those which do fully penetrate the aquifer provide a composite sample which

8.2.2

A-15



(not to scale)

FIGURE 1

MONITORING SYSTEMS

8.2.3

A-18-

gives no information on vertical distribution, and, in addition, dilutes the actual concentration of a contaminant. Submersible, suction or air-lift pumps and hand bailers can all be used to evacuate water from the well and then sample, depending upon the well diameter, depth to water, and analyses to be performed. The well also provides a water level and can be used to test in-situ permeability. Water levels from a series of wells covering a site will indicate the water table or potentiometric surface contours to provide the direction, and possibly, rate of flow. However, interpretation may not be accurate in complex geologies where the well has penetrated independent aquifers.

Single Well - Multiple Sample Points

Some wells are constructed so that only portions of the well are screened and each screened area can be isolated with inflatable packers. This monitoring well usually penetrates the entire aquifer, but allows sampling from several discrete horizons within the aquifer. A second type is a prefabricated multi-level sampling device, consisting of a pipe with spaced screen sampling ports, isolated by individual recovery tubes.

This type of well is as easily installed as a fully screened well. Installation of wells with spaced screen sampling ports takes somewhat longer since it is usually done in the field based on existing geologic characteristics. Almost any drilling method can be used, and the installation cost is minimal, perhaps slightly more than that of a fully screened well. However, there are additional costs for collection and analysis of additional samples. Although wells designed and properly installed for the existing geology should be reasonably reliable, those with ports may have problems if the individual sampling assemblies are not properly installed.

The multi-sample point well yields excellent information about the vertical distribution of water quality throughout the aquifer, including the existence and degree of any pollution stratification. However, wells with ports are usually restricted to shallow water table depths because the samples are taken using suction lift. In both types of multi-sampling point wells, certain types of sample analysis may be unreliable because the possible sampling techniques are limited. Thus the analyses to be done must be compatible with the sampling procedure. Sampling equipment may require some specialization, or be somewhat unique, requiring additional time and money for its development. However, sampling procedures generally are not difficult and the cost of sampling per sample is one of the lowest of the various sampling systems.

Submersible, suction, or air-lift pumps can be used to sample if they can be isolated from the other sampling levels, are acceptable for the type of analyses being done, and do not draw in water from the other sampling zones because of high pumping rates. Water levels can be measured in a multiple screened well and the in-situ permeability of the different intervals can be determined if other intervals can be isolated satisfactorily.

8.2.4

The port well provides water levels from the different intervals if readings can be made within the tube of each port; however, most wells are not large enough to accept measuring devices. The ports can also be used to test the in-situ permeability at each location, although in materials with low to moderate permeability the relatively small cross-sectional area of the port makes this difficult. A system of multiple-screened wells can show water table or potentiometric surface contours to indicate direction and possibly rate of flow.

Piezcmeters

A piezometer is a pressure-measuring device modified to collect water samples. There are too many variations of piezometers to review individually, but an example of a new design is the BarCad sampling system. Each instrument is a porous, hollow cylinder from which water is removed via a small-diameter riser tube within a larger gas drive tube. This type of monitoring system will sample a discrete zone within an aquifer or, if properly designed, collect soil moisture from the zone of aeration. Most often the piezometers are narrow enough to permit placing many within one boring to provide samples from many different horizons within the aquifer, thus making it a multiple-level sampling system.

The installation of a single piezometer is generally easy, but they are more difficult to install in groups, since great care must be taken not to break or disrupt the confining materials between the individual piezometers. Many drillers avoid installation of piezometers because it is difficult to do quickly and efficiently. Many drilling methods can be used, except those requiring a drilling fluid other than water to keep the borehole from collapsing. The cost of installing a series of piezometers is higher than that of either a fully screened well or a multiple sampling point well, because of the time consumed in placing each individual piezometer within the same borehole. Also, a series of piezometers has higher costs associated with additional collection and analyses for the additional samples. Piezometers have been in use for many years and have become relatively reliable.

Piezometers provide excellent information about the vertical distribution of water quality in different zones of the aquifer and help define the degree of pollution stratification. Sampling procedures for piezometers are somewhat limited, although recent advances in design allow them to be sampled for most types of analysis. A possible problem is the long time needed to sample some piezometers, particularly if an expanded analysis program requires a large volume of sample per piezometer. Some new piezometers are designed for higher yields in a shorter time, but this varies from manufacturer to manufacturer and according to the existing conditions of each case.

The two most frequently used sampling methods are suction pumping or some form of air-lift pumping, although the former is limited to shallow aquifers. Generally piezometers used for sampling do not allow water level measurements to be taken, a severe problem in that water levels cannot be used to develop water table contours and help define direction, and possibly the rate of flow. It may be possible to test the in-situ permeability depending on the construction of the piezometer; however, most are not designed to be used for permeability testing.

Nested Monitoring Well Systems

Nested monitoring well systems are a combination of single piezometers and fully screened wells. They consist of two or more wells adjacent to one another with the screens set at different levels within an aquifer. These wells are normally constructed so that the screened portion is relatively short and acts as a piezometer. Each well provides water samples from a different portion of the aquifer, similar to piezometers and multiple sample single wells.

Nested monitoring well systems are installed like fully screened wells except that two or more wells are installed at different zones or intervals within an aquifer(s) and adjacent to each other. A nested system can be installed with any drilling method. In some cases all wells are installed within one borehole, although this is somewhat time-consuming and the borehole must be large enough to handle all the well casings. In other cases the wells are installed in separate boreholes; the drilling of individual boreholes is even more time-consuming, but it ensures that there is no "leakage" between wells. As with the other multiple sampling point systems there is an additional cost for additional sample analysis.

Nested monitoring well systems provide excellent information about the vertical distribution of water quality in different intervals of the aquifer and help define to what degree, if any, there is pollution stratification. Sampling of nested well systems is not difficult and any technique can be used. Nested well systems provide more volume than other systems except fully screened wells. The wells may be sampled with suction, submersible, or air-lift pumps as well as hand-bailers.

In addition to sample collection, the nested well system provides water level data which can be used for water table or potentiometric surface contours. The water levels within a single nested system can show differences in head, indicating whether they are in recharge or discharge areas of the aquifer. The wells can also be used to test the in-situ permeability of the different intervals in which the wells are screened. A wide choice of material and well diameters can be utilized, and larger diameter wells can be converted, if necessary, to recovery wells. The nested monitoring well system is widely used for determining pollution stratification because of its easy installation.

EXAMPLE SITES

During the last several years Malcolm Pirnie, Inc. has been involved with many ground-water contamination investigations. Four of these investigations, all in the eastern United States (Massachusetts, Connecticut, New Jersey and the Virginia coastal plain) will be used here to illustrate nested monitoring well systems. The budgets for the projects were sufficient to include some nested wells as part of each monitoring system.

Pirnie's standard operating procedure for monitoring systems is to install wells as part of a subsurface exploration program. After all available geologic and hydrologic data have been reviewed for a site, a detailed subsurface exploration program is developed to provide as much site-specific geologic and hydrologic data as possible. This is ususally done by selecting equally spaced boring locations, although modifications are sometimes made for complex geologic or hydrologic conditions. Continuous sampling in most or all of the borings, which usually penetrate to bedrock, provides good information about the unconsolidated soils. Most borings to bedrock are also cored for at least 10 feet to make certain they have not encountered a boulder and to confirm the bedrock lithology and hydrologic properties. Monitoring wells are installed close to the bottom of these borings, and usually constructed to act as a piezometer well. The piezometer wells are usually constructed of either 2-inch or 4-inch PVC with threaded flush joints. The screens are either 5 or 10 feet long and machine slotted to either 0.010-inch or 0.020-inch slots. A medium sized, well rounded, quartz sand is used as backfill around the well screen and up to 2 feet above the top of the screen. A one-foot thick layer of bentonite pellets is placed over the sand as a part of an impermeable seal. The remainder of the annulus is tremied with a cement-bentonite grout up to the ground surface to complete the impermeable seal. Once a deep piezometer well is installed, the boring rig moves two or three feet away and, without sampling, augers a second hole to a desired depth in which a second piezometer well is installed. The cost for a second shallow piezometer well placed in a non-sampled boring is very small compared to the rest of the exploration program.

The four examples selected for review are in shallow aquifer systems: the three in the northern east coast have shallow glacial soils overlying less permeable bedrock, and the Virginia example has shallow permeable soils overlying impermeable soils. In all four cases the nested wells included in the monitoring systems consist of only two wells each. The approximate additional cost to the exploration/monitoring well installation program ranged between 10 and 15 percent, although additional costs were incurred for collecting and analyzing extra samples.

Site One

Site one, an industrial establishment in Connecticut, is small and has only three monitoring locations, one of which has two nested wells. The study area lies in a bowl-shaped basin formed by bedrock ridges occasionally

A~20

broken with gaps, but the immediate site area has very little or no topographic relief. The bedrock in the site area is a slightly fractured and relatively impermeable gneiss. The glacial soils consist of about 15 feet of silt overlying the bedrock and about 55 feet of fine sand overlying the silt. A few feet of silt overlie the fine sand. Figure 2 shows a general geologic cross-section of the area. Ground-water samples were analyzed for some organics, many of the heavy metals, selected inorganics and nutrients. The chloride values from two sampling periods are shown in figure 2`as are the recorded water level elevations.

The difference in water levels between the two wells indicates a downward hydraulic component in the ground-water flow regime, i.e., the site is in an area of recharge to the ground-water system. The chloride values indicate that the well nest is within a plume and that the plume is more concentrated towards the top of the saturated zone. The lower chloride values in the deep well are much higher than an expected background value and verifies the downward hydraulic component indicated by the water levels.

The water levels in the three shallow wells show very little gradient. Without a nested well system it would be difficult to determine whether the site is an area of recharge, and thus has potential to contaminate the ground waters, or in an area of discharge, minimizing the impact of the local ground-water system. The lower chloride values in the deep well show that the plume leaving the site is not just in the upper portion of the ground-water system as might be expected based solely on water levels in the three shallow wells alone. It also appears that the plume is deepening as indicated by the smaller difference in chloride values measured during the second analysis.

Site Two

The second site, an industrial building in New Jersey, lies on a gentle slope where some portions have been graded flat or to short steep slopes. At the base of the slope, several hundred feet away, is an abandoned sand and gravel pit which has been graded flat. The bedrock underlying the site, a well fractured sandstone interbedded with shale, is a relatively good aquifer which supplies water for local domestic wells and to the local public water supply wells. Ground water in the bedrock comes from the secondary porosity within the aquifer. The glacial soils overlying the bedrock consist of 20 to 40 feet of varying amounts of silt, sand and gravel and between 5 and 10 feet of dense glacial till. Figure 3 shows a generalized geologic cross-section of the area. The nested well system at site 2 was installed to show the difference between the two aquifers. The shallow well, B-6S, is in the glacial soils and the deep well, B-6D, is in the bedrock. Analyses of ground-water samples included organics, heavy metals, selected inorganics and nutrients. Measured values for chloride, fluoride, sodium and water level elevations for two sampling dates (June 1981 and July 1981) are presented in Table 1.

8.2.8





SITE TWO GEOLOGIC CROSS-SECTION

	June	1981	July	1981
	B-65	B-6D	B-65	B-6D
Water level	333.9	330.8	333.6	330.3
Chloride (mg/l)	36	10	101	37
Sodium (mg/l)	21	11	32	8
Fluoride (mg/l)	0.04	0.24	0.10	0.16

The difference in water level elevations between the two wells clearly indicates a much lower head value in the bedrock aquifer. This shows that the site is an area of recharge to the bedrock aquifer and therefore that any contaminant in the upper glacial soils is likely to flow down into the bedrock. The water quality data show a measureable difference between the two aquifers: chloride and sodium values in the glacial soils are approximately three times those in the bedrock, whereas the fluoride value in the bedrock is two to six times the value in the glacial soil. The threefold change in choride values between the sampling dates in both aquifers suggests that a "slug" of contaminants was passing by the wells during the second sampling date. It is interesting to note that the chloride values from both the shallow and deep wells increased threefold, indicating that the plume extends down into the bedrock aquifer and that the ground-water velocities are nearly equal.

Site Three

Site three, located within a half mile of the Atlantic Ocean on the coastal plain of Virginia, is a sludge application field with very little topographic relief. There are seven monitoring sites, six of which are nested with two wells each. The soils underlying the site are Quaternary in age and deposited in an environment where the sea level rose and fell in response to glacial melting and reforming. The result is a deposit of alternating layers of fine and coarse sediments. Figure 4 shows two geologic cross-sections from the site area.

It had been agreed upon by the government agencies involved to monitor the first two water-bearing zones which are the primary zones used for drinking water. The site is adjacent to a large construction area with an extensive dewatering operation by means of deep wells. Ground- water samples were collected prior to any sludge applications and analyzed for certain heavy metals, selected inorganics, and nutrients. Table 2 presents chloride concentrations and specific conductance values, and water level elevations.

TABLE	1

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Well No.	Chloride (mg/l)	Specific Conductance	Elevations (ft Above or Below Mean Sea Level)
1S	37	285	1.0
1D	88	695	1.1
25	26	215	1.7
2D	18	190	1.1
35	15	200	0.2
3D	22	250	-0.3
45	31	415	-4.0
4D	45	710	-0.8
55	28	520	-0.6
5D	23	570	-0.4
65	322	1.900	1 2
55 6D	770	3,300	1 2
Ua	112	3,200	1.2

The differences between water levels in the shallow and deep wells are small, indicating a very slight downward movement of the ground water. The lower levels in wells 1S, 4S, and 5S are apparently the result of the dewatering at the adjacent construction site, and water levels in those nested well systems should return to normal once dewatering has stopped. The water quality data generally show a higher concentration of chloride and a higher specific conductance value in the deeper ground-water; this is probably due to a combination of precipitation diluting the upper groundwater system and salt water intrusion caused by the adjacent dewatering system.

Site Four

Site four, an industrial plant in Massachusetts, is located on a small topographically high area surrounded by low areas with poor drainage. The glacial soils underlying the site consist of 5 to 10 feet of outwash materials, mostly sands, overlying 5 to 25 feet of dense glacial till. The bedrock underlying the site is a relatively impermeable gneiss with many quartz-infilled fractures. There are over twenty monitoring stations in the area, but only three are nested systems of two wells each. Figures 5 and 6 show generalized geologic cross-sections in the area of three nested systems. Analyses of the ground-water samples are very complete and included priority pollutants, numerous other organic chemicals, heavy metals, selected inorganics, and nutrients. The values from some of the analyses are presented in Table 3.

TABLE 2

Water Level

8.2.13


SITE FOUR GEOLOGIC CROSS-SECTION

8.2.14

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8.2.15

A+28

	Date (1981)								
Well Number	April	May	June	August					
ph									
GW-175	6.4	6.1	6.6	5.6					
GW-17D	6.0	5.6	5.8	5.9					
GW-195	9.5	5.7	5.9	6.4					
G W-19D	5.8	6.5	5.5	6.8					
GW-22S	7.6	8.2	2.9	7.6					
GW-22D	3.0	5.4	4.3	3.8					
Chloride (mg/l)									
GW-175	235	204	225	210					
GW-17D	375	766	510	949					
GW-195	64	72	102	40					
G W-19D	1,046	536	1,633	1,999					
G W-225	480	378	434	730					
GW-22D	7,200	5,360	7,450	7,990					
Sulfate (mg/l)									
GW-175	930	863	1,500	875					
GW-17D	3,045	2,624	6,520	3,500					
GW-195	1,675	1,774	2,530	1,350					
G W-19D	1,839	1,265	6,080	3,400					
G W-225	2,620	1,880	4,330	4,050					
GW-22D	27,500	33,846	59,000	26,500					
Ammonia (mg/l)									
GW-175	46	48	45	56					
G W-17D	315	336	358	325					
GW-195	114	126	130	108					
G W-19D	609	353	974	1,204					
G W-225	675	427	490	1,081					
GW-22D	4,102	2,757	2,340	2,545					

TABLE	3
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8.2.16

		Date	Date (1981)		
Well Number	April	Мау	June	August	
Water Level Elevati	ons				
GW-175	78.6	78.7	78.9	77.4	
GW-17D	78.0	78.4	78,6	77.2	
G W-19S	81.0	81.1	81.3	80.5	
°G W-19 D	81.7	82.4	81.2	80.7	
GW-225	81.5	82.0	82.1	81.4	
GW-22D	80,6	80.4	81.1	80.8.	

TABLE 3 (continued)

Site four has an abundance of data which provide differences in water quality and hyrologic properties with depth and with time. The water quality data from the deep wells generally show much higher concentrations, even an order of magnitude larger. In the nested well system numbered CW-17, where there is a one-foot overlap between the top of the deep well and bottom of the shallow well, the differences in water quality are significant, although not always of equal proportion over time. This indicates that the glaical till, which the deep wells monitor, has a different permeability than the overlying soils. Thus as "waves" of contamination travel through the system, they pass much more slowly through the glacial till. Conversely, the soils overlying the till, with higher permeabilities, are flushed more quickly and are somewhat diluted by precipitation. The differences in water level elevations between the deep and shallow wells are significant. The nested well systems numbered GW-17 and GW-22 are areas of recharge to the ground-water system, a condition that did not vary during the study. Nested well system GW-19, located near a stream which crosses the site, is in an area of discharge from the ground-water system. This is expected since most streams receive a portion of their water from ground-water discharge and implies that some of the contaminated water is discharged into the stream. The water levels in the GW-19 nested system also show that during periods of low rainfall, such as the summer, the amount of discharge is very small.

CONCLUSIONS

- There are several different types of monitoring systems available to the ground-water hydrologist such as fully screened wells, single wells with multiple sampling points, piezometers, and nested well systems.
- Each type of system has its advantages and disadvantages which include costs, reliability, volume of sample required, ease of sampling, ease of installation, and aquifer characteristics that can be determined with each system.

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A-30

- Nested monitoring well systems are being used more frequently, expecially to deal with complex geologies, ground-water geochemistries, flow pattersn, and pollution sources or types.
- The four examples presented here of ground-water investigations involving nested monitoring well systems in shallow aquifer situations show that differences in water quality exist between the individual wells of each nested system. The differences are useful in defining the existance and locations of contaminant plumes and the variation of the plumes within different zones of the aquifer or within different aquifers.
- The nested wells also provided water levels which indicate whether the plumes are in areas of recharge to, or discharge from, the ground-water system. This is essential for defining the expected path of the plume if it reaches beyond the monitoring well network.
- The cost of the additional wells was approximately 10 to 15 percent more than a system of fully screened wells. The major additional cost to the entire investigation involves obtaining the additional samples from the extra wells, analyzing the additional samples, and reviewing the data provided by the additional wells.
- o In all four cases, only some of the monitoring points in the monitoring network have nested well systems. A few nested wells in key areas can help define an extensive monitoring program with little additional cost to the overall program. It is possible that continued monitoring of some wells could be discontinued based on data provided solely form the nested well systems.
- Nested well systems aid ground-water contamination investigations significantly without substantial increases to the overall project costs.

SELECTED REFERENCES

Nielsen, D., 1980, The importance of ground water monitoring: Water Well Journal, V. 34, No. 11, P. 38-39.

Pickens, J.F., Cherry J.A., Coupland, R.M., Crisak, G.E., Merrit, W.F. and Risto, B.A., 1981, A multilevel device for ground-water sampling: Ground Water Monitoring Review, V. 1, No. 1, P. 48-51.

Procedures Manual for Ground Water Monitoring at Solid Waste Disposal Facilities, EPA/530/SW-611, August 1977.

Water Well Journal, 1980, Monitoring device simplifies sample collection: Water Well Journal, V. 34, No. 11, P. 48-50.

8.2.18

A-31

Custom Designing of Monitoring Wells for Specific Pollutants and Hydrogeologic Conditions

by Richard W. Lewis, Engineering Enterprises Inc.

It is essential that every ground-water monitoring system be custom-designed to meet the local hydrogeologic conditions. Without site-specific data to design a well, the data collected in the future from that well may be false or misleading. In recent years, the scientific community has made government and the public aware of the devastating ground-water pollution brought on by man's activities. This awareness and the need for more water has precipitated a major interest in ground water.

This interest was compounded by the promulgation of first, the Safe Drinking Water Act, and later, the Resource Conservation and Recovery Act (RCRA). RCRA in particular has initiated the largest countrywide program of research on aquifers in history.

These ground-water research programs have created a demand for experienced professionals to design and conduct investigations regarding chemicals that five years ago could not be identified. To compound the problems even further, little or no information was available regarding chemical properties, mode of transport or attenuation and level of toxicity of the pollutants. When information did become available it generally was generated through laboratory experiments, where aquifer conditions were generally idealized. This is all very understandable, but quite often monitoring plans and well designs had to be made based on limited information concerning the properties of the potential pollutants and under geologic settings far from uniform.

It is not difficult to understand why monitoring systems have in many situations been found to be poorly designed for their particular function. Quite often the monitoring well (or, more correctly, the well designated as a monitoring well) was:

Designed to serve a totally different purpose

Designed by someone unsure of its purpose

• Designed by someone unfamiliar with aquifer mechanics

• Installed without proper knowledge of the geologic framework or

• Designed without adequate knowledge of the pollutants to be monitored and their mode of migration once they enter the aquifer.

Prior to installing or designing a well to monitor ground water, the purpose of the well should be evaluated. Typically, the purpose of the well will be one or a combination of the following:

• To determine aquifer properties, both geologic and hydraulic

• To determine the potentiometric surface of a particular aquifer

• To allow access for the collection of water-quality samples for detection of pollutants

• To monitor the migration of a plume of pollution.

Generally, the first three objectives are achieved during the process of establishing an adequate monitoring program. Examples of some of the tools available and considerations to be taken into account to properly design an aquifer water-quality monitoring program are presented in the following case histories. These particular examples do not imply that all the steps are required in every situation or that other techniques and methods are not as appropriate. The drilling techniques and materials used and discussed are widely available and were appropriate for these instances, but may not be if a more exotic monitoring program is required.

Example 1

This first monitoring program was conducted for an industry that used land application for disposal/treatment of biologically degradable wastes.

The initial step was a literature search for information concerning the geologic and hydrologic properties of the local aquifers. From this it was determined that the prominent local aquifer was a Quaternary unconfined alluvial aquifer roughly 40 feet in total depth. The aquifer contained wells that produced 50 to 300 gpm and had good to poor water quality depending on the effects of local oil-field activities.

The second step involved testing of the wastes being disposed at the site to evaluate the potential pollutants within the waste. To accomplish this task, composite samples of the waste streams were obtained along with estimates of waste application rates. These analyses revealed that 10 to 15 percent of the wastes were composed of long-chain petroleum residues. Several heavy metal ions were present in the waste stream in significant concentrations.

The third step of the monitoring program was the on-site field investigation. Since the monitoring program was required to meet the objectives set forth under RCRA, a minimum of four monitoring wells needed to be located. Three of these wells were to be downgradient from the site and one upgradient. It was also requested that the local hydrologic properties be determined so that the rate of migration within the aquifer of any given pollutant might be determined. Existing wells were identified near the study area, but none could be accessed to determine pumping or static water levels. Therefore, test holes were drilled to serve two purposes:

1. To obtain a detailed geologic profile and collect formation samples from which monitoring wells could be designed.

2. To determine the static ground-water elevation and the direction of local ground-water flow.

Our test-well drilling revealed that this alluvial aquifer was heterogeneous, having a number of interbedded sand, silt and clay layers. None of the clay layers appeared to be continuous since they were encountered at varying depths and thicknesses from well to well. However, to better determine exact elevations and thicknesses of the various layers a downhole natural gamma-ray geophysical log was run on each well. These logs were then compared to the geologist's notes which were collected while observing the well cuttings from either a hollow stem auger or water rotary drilling rig. The geophysical log revealed inaccuracies in the depths that particular layers were thought to have been encountered during drilling. Figure 1 depicts a typical gammaray log with lithologic interpretation. A surface resistivity survey was considered to further delineate the lateral extent of the various layers. However, underground and above ground piping made this impossible. Split spoon samples of the saturated zone were collected for grain size analysis and well design. At each of the test hole sites, 2-inch PVC slotted screens and casing were installed. Each well was developed using a surge block and air lift pumping equipment. The well logs indicated that clay layers, though possibly not continuous, existed between 11 and 18 feet. Based on the well logs and split spoon samples, two large-diameter (5-inch) wells were designed and constructed for evaluation of hydrologic properties (Figure 2). These wells were drilled using a straight rotary rig, gravel-packed and developed by surging, jetting and air lifting. One well was completed at



Figure 1. Typical profile of study area, example 1



Figure 2. Typical design of a five-inch diameter well

35 feet in the basal aguifer sands and the other at 14 feet in the uppermost sand layers. This allowed for the evaluation of aquifer hydraulics from pump tests in both sand zones. Test wells constructed previously were then used as observation wells during the pump testing of the aquifer. The importance of conducting pumping tests in both the upper and lower sands was twofold. First, one of the major potential pollutants at this site was a petroleum-base material which is immiscible with water. Therefore, if this pollutant reached the ground water it would flow on top of the water, but move no faster than the hydraulic conditions of that zone. Aguifer testing of the lower sands, where the coarsest materials existed, provided information enabling calculation of the travel time for the other pollutants that are soluble. These tests also enabled us to determine if the sand layers were hydraulically connected. Results of these tests showed that the sand layers in the vicinity of the disposal area were hydraulically connected. However, the clay layers appeared to be acting as an aquitard. This was confirmed when some preliminary ground-water quality measurements were made (Table 1). Samples obtained from the shallow portions of the aquifer were very different in chemical nature from the lower aquifer samples.

Table 1	
Water Quality of Aquifer	
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	As reported in literature	Analysis of shallow sands	Analysis of deeper sands		
Chloride mg/l	200	15	2 99		
Sulfate mg/l	120	19	93		
Iron mg/l	<1	28	< 1		

The water quality of the lower zones is similar to water quality of this aquifer as reported in the literature (high chloride and sulfate concentration). In contrast the shallow water appears to be influenced by local recharge and the local industrial facilities (high iron and low chloride and sulfate concentrations).

Once this preliminary investigation was completed and reviewed, decisions regarding the monitoring program were made. The first consideration was the selection of the monitoring well sites. The existing wells were reviewed as to which were located and constructed such that representative aquifer samples could be collected to detect the first sign of pollution from the disposal facility. Several operational considerations were reviewed, including what chemical parameters were to be determined, what method of sampling could be used to avoid contamination or bias and what volume of water would have to be removed to obtain a representative sample.

Typically it is recommended that five to 10 well-bore volumes be removed prior to sampling when feasible. Therefore it benefits the sampling program if this volume can be removed as quickly as possible. Smalldiameter wells (2-inch) are often the best since the well-bore volume is small. However, if there is a significant saturated thickness or if the well is deeper than 30 feet, pumping methods become limited and slow. Bailing the well when there is a large saturated interval requires a great deal of time and effort to remove the necessary well volumes. If the water level is below 30 feet, vacuum or peristaltic pumps become unusable due to suction lift limits. The use of recently developed small-diameter submersible pumps is a good alternative. but these pumps yield a very low flow rate (generally less than 1 gpm), hence removal of large quantities can be quite time consuming. The advantages of bailers, peristaltic pumps or small-diameter submersibles are: they are easy to handle; they are rather easy to clean between wells; they can be constructed of materials that will not contaminate the sample; and they generally cause minimal chemical changes through oxygenation.

Larger diameter wells (4-inch and larger) are generally most appropriate when well depths are great, there is a significantly large saturated thickness and formation transmissivities are high. Under these circumstances a pump capable of removing large volumes of water rapidly is required. Typically, large-capacity pumps cannot be installed in wells smaller than 4 inches in diameter; 5- to 6-inch wells are used most because of their greater versatility.

For the purposes of monitoring the disposal site in this instance, the primary monitoring zone was the shallow freshwater sand. Three of the 2-inch test wells were appropriately located during the exploratory drilling so that only one additional well had to be installed. These wells were rather shallow (less than 15 feet) and contained only 5 feet of saturated material (Figure 3). Therefore, either bailing or peristaltic pumps could be used for sample collection with ease and little expense.

Additional monitoring was necessary within the deeper aquifer because the greatest ground-water flow across the site occurs in this zone. Therefore, the monitoring program was expanded to include one upgradient and one downgradient well in this aquifer. These wells were completed below 30 feet with screens and gravel pack designed from earlier sampling and testing data. Large-diameter (5-inch) wells were deemed most appropriate for these deep wells since a large volume of water would have to be removed prior to each sampling. These wells then could accommodate submersible pumps for easier sampling.

Several specific modifications were made during this monitoring system design specifically related to the anticipated pollutants and the local aquifer characteristics. First, as shown in Figure 3, the shallow 2-inchdiameter wells were screened so that open screen existed above and below the water table. This was to allow for petroleum pollutants to enter the well if any seeped down to the water table. This design also was to allow for fluctuation in water levels due to natura seasonal effects. Secondly, the materials used in welconstruction and sampling equipment were evaluated to avoid sample contamination. Care to avoid use of PVC glue and metal parts in anything that contacted the samples was necessary to avoid biasing the laboratory determinations.

An additional item of concern during well design was the drilling fluid used. Air-rotary techniques could not be used since the formation would not remain open for well construction. Therefore, a hollow stem auger was used for construction of the 2-inch wells. For the larger wells, water rotary was attempted, but proved unsuccessful. Thus, an organic mud (Revert^{**}) was used. This choice was made since heavy metal concentrations were to be monitored and use of inorganic bentonitebase muds could bias the laboratory determinations by adsorption or absorption of the heavy metal ions. Thorough development of every well was also done to ensure efficient well performance and removal of all materials introduced during drilling.

Example 2

The second monitoring program again centered around RCRA monitoring requirements. However, this program was for a hazardous waste storage lagoon.

The initial hydrogeologic literature survey indicated that the site was situated on Permian age shale. The shallowest significant ground-water aquifer lay beneath the shale and was composed of interbedded sandstone and shale layers. The static water level in this aquifer was determined from wells within a mile of the site to be at least 200 feet below land surface. However, the sandstone/shale aquifer outcrops less than a mile to the east and recharge from precipitation was well documented.

The waste materials in the lagoon contained both organic compounds related to the manufacture of plastics and several heavy metal ions.

An initial site evaluation was made to determine in more detail the local hydrogeologic conditions. To accomplish this, an air rotary rig was used to drill six test holes from 20 to 100 feet in depth. By using air rotary in this instance, we are able to readily determine waterbearing zones if encountered. It was apparent from the well cuttings that state Geological Survey maps were in error. The locally predominant Permian shale layers shown on the maps had been eroded away at this site, thereby exposing the lower Permian sandstone/shale aquifer. Figure 4 is a typical profile and log of the materials encountered. The report detailing the depth to ground water was also in error. Water-bearing sandstone layers were encountered at 20 feet, 35 feet and 40 feet below ground level. Since the sandstone layers were very fine grained (effective grain size .15mm) and rather thin, downhole natural gamma-ray geophysical logs were taken.

Once the test holes were drilled and logged, the holes were left open and the water levels allowed to come to equilibrium. Water level elevations were then determined. Based on this data, the direction of groundwater flow appeared to be to the northwest. Review of the drilling and gamma-ray logs raised some concern as to which sandstone layer or layers should be monitored. The degree to which these sandstone layers were hydraulically connected was also unknown. Therefore, Test Hole #3 was completed with two piezometers. The



Figure 3. Typical design of a two-inch diameter well



Figure 4. Typical profile of study area, example 2

shallow screen was set from 18 to 23 feet and the second from 35 to 40 feet. The interval between the well screens was sealed with bentonite pellets. Once installed, both piezometers were developed by bailing. Water-level measurements made on the following day showed that these two sandstone layers were not hydraulically connected since a head differential of 4 feet existed between them.

This new data raised several questions:

1. What was the real direction of ground-water flow in both zones?

2. What was the lateral extent of these water-bearing zones?

3. What was the anticipated rate of transport of any pollutant once it reached either zone?

To determine the position of the potentiometric surface and the lateral extent of each sandstone layer, a second set of wells was drilled. In each new well two piezometers were installed. By extending the area of drilling it was determined that the ground water encountered at 20 feet was not areally extensive. The ground water in this zone was probably due to local recharge creating a perched water zone. The lower aquifer was apparently continuous and the direction of groundwater flow in it was from the southwest to the northeast.

Development of these wells indicated that both aquifers were low yielding. Therefore, rather than pumping the wells to determine aquifer properties, slug tests were performed. These tests yielded an average horizontal aquifer permeability of 5 feet/day (33.2 gpd/ft²).

Once these factors had been established, the final monitoring system could be determined. Special considerations in this site evaluation were:

• Should the perched zone or just the lower aquifer be monitored or both?

• What materials could be used for the well construction without sample contamination?

• What would be the means of sampling the aquifer?

A review of the RCRA requirements revealed that the monitoring network should evaluate the uppermost ground-water aquifer. However, in this instance monitoring the perched zone could provide an early warning of pollutant seepage, although the perched zone is not as significant as the lower aquifer. Therefore wells were constructed to monitor both zones. The wells penetrating the lower water-bearing zone were designated as the site's primary monitoring system. These wells were monitored for all required water-quality parameters. The shallow wells were treated as a secondary system and monitored for only the pollution indicator parameters.

To avoid introducing any drilling fluid contaminants, wells were constructed using an air rotary drilling rig. Because plastics and their derivatives and additives were potential pollutants, stainless steel screens and casing were selected. Figure 5 shows a typical example of the four monitoring installations with both gravel pack and bentonite seals. After construction each well was then thoroughly developed by bailing and air lift pumping techniques.

A small-diameter (1-3/4-inch) bladder pump was selected for sample collection. The pump was driven by compressed air which never came in contact with the sample. The internal pump components that did contact the sample were constructed from viton or teflon which are relatively inert. In this way sampling was done easily without contaminating or significantly affecting the chemical stability of the sample.



Figure 5. Detail of two well installation

Conclusions

These examples were selected to emphasize the importance of thoroughly understanding the details of the hydrogeological environment and the chemical parameters anticipated in designing and constructing a monitoring system. It is essential that final design and construction techniques be made in the field as the local hydrogeologic conditions become clear. Designing monitoring wells in the office based only on published literature seldom will accomplish the desired results. Some may feel that the examples described are overly elaborate and extensive. However, experience has shown us at many hazardous waste facilities the terrible consequences of pollution that have occurred when undetected by a poorly designed monitoring program. For this reason, proper design of a monitoring system cannot be overemphasized.

Biography of Presenting Author

Richard W. Lewis is currently a senior hydrogeologist for Engineering Enterprises Inc., Norman, Oklahoma,

where he is in charge of aquifer evaluations, RCRA monitoring programs and aquifer restoration from petroleum spills and other oilfield-related activities. He received his B.S. in both geology and biology from the State University of New York at Brockport, New York, in 1975. and his M.S. in geology from the State University of New York at Fredonia. New York, in 1977. Lewis attended post graduate courses in hazardous waste management and toxicology at Oklahoma University. In 1978 and part of 1979 he served as staff geologist for the Industrial Waste Division of Oklahoma's State Department of Health, where he was in charge of hazardous waste site permit reviews and pollution investigations.

Questions and Answers

Q. How do you complete a well with a screen extending above and below the water table? What method of development is used? Do you develop until you get a clean clear flow or do you anticipate field-filtering all samples you collect?

A. To complete a well with screen above and below the static water level, one must have information on the depth to ground water and the degree of seasonal water level changes. Once you know these two factors, you should choose screens of adequate length to accommodate seasonal level changes. Once the well has been constructed, it is very beneficial to develop-out any fine grained material in the screened zone. A developed well is a much more efficient water-producing well and samples gathered are less turbid. There are a number of development methods available that work very well. A few of the most common are: bailing, jetting or surging with a surge block followed by air lift pumping or just air lift pumping by itself. The length of time to complete development will often vary greatly from well to well. This is primarily controlled by the screen slot size and grain size distribution of the formation. Generally, development is considered complete when the discharge water clears. However, when dealing with 2-inch wells in a very fine grained aguifer, development may only reduce turbidity, not eliminate it. When the water is turbid, filtering the samples is beneficial. Of course, all samples that require acid treatment for preservation should be filtered regardless of the visual clarity of the sample.

Q. What length of time was there between air rotary drilling and sampling of ground water from the completed wells? What effect have you observed or would you expect on volatile organic contaminants in ground water from aeration during air rotary drilling? What precautions do you observe to minimize such effects?

A. The length of time between drilling each of the wells and sampling was at least two days. To minimize the effects of contaminants introduced during well construction, a considerable amount of water was withdrawn from each well during development. An additional five to 10 well bore volumes of water were also removed from each well prior to sample collection. This was done to ensure that samples representative of

the formation fluids were obtained. Through this process, we hoped to remove any ground water that had been altered by the well construction.

Q. 1) In your decision, to use an organic drilling mud for wells intended to monitor concentrations of trace metals, did you consider the possibility of complexation of the metals by the organic compounds in the mud, or is this not considered to be a problem? 2) Is stainless steel casing considered acceptable for wells intended for monitoring trace metal concentrations?

A. In monitoring well construction, one is often faced with compromises. Project budgets, drilling equipment availability and formation characteristics all place their own restraints on the way in which the well can be completed and what materials are used. In this particular instance, the local formations were not competent enough to keep the hole open during well construction without use of drilling muds. Organic muds were selected since they would biodegrade if they were not removed during well development. These muds were, therefore, thought to be less likely to bias heavy metal determinations than inorganic, bentonite clay base muds.

Stainless steel screen and casing were used for two reasons. First, a number of the parameters to be monitored were constituents in plastics such as PVC. Secondly, stainless steel is relatively inert, compared to other well construction materials. Therefore, stainless steel was selected since it would bias the water quality analyses less than other readily available well construction materials.

Q. The wells described in both your examples did not comply with RCRA requirements, i.e. screen 10 ft. into first aquifer. Did you negotiate with EPA for deviation from requirements?

A. To my knowledge, there is no requirement in the United States Environmental Protection Agency's Resource Conservation and Recovery Act regulations requiring monitoring wells to be screened 10 feet into the first aquifer.

Q. Could you please describe equipment and techniques employed in developing 2-inch wells? How was sand or silt drawn into the wells by development removed?

A. Methods of well development are described in the first answer and are discussed further by Herman Bouwer, 1978, in Groundwater Hydrology and in Ground Water and Wells, which is published by Johnson Division, Universal Oil Products Co. (1974).

Q. During installation of multiple screen wells in your second site example, how did you ensure that your drilling did not allow contamination access to either aquifer?

A. Contamination of the hydraulically isolated aquifers, in this instance, was felt to be minimal since the rotary drilling through clay layers between the aquifers tended to create a mud cake along the upper aquifer. This mud cake formed a partial seal for that aquifer. However, this was not what we depended upon for elimination of any cross contamination. Once the wells

were constructed and the bentonite seals were in place, each well was developed and considerable quantities of water were removed. In this way, if any communication between the aquifers had occurred, these fluids would have been removed. However, if these aquifers were very permeable and the water quality was significantly different between them, then more extensive steps would have been taken to avoid communication.

Q. In your first example, what levels of metallic ions did you encounter in the refinery waste? What are the chances of saturating the vadose zone with heavy metals?

A. The waste analysis of the materials being applied at the land treatment facility is as follows:

Arsenic	.005 mg/l
Barium	.07 mg/l
Cadmium	0.1 mg/l
Chromium	1.2 mg/l
Lead	1.6 mg/l
Mercury	.0022 mg/l
Selenium	.08 mg/l
Silver	.04 mg/1

In this instance, at the anticipated loading rates and the local soil cation exchange capacity, the expected time required to saturate just the first foot of the vadose zone with heavy metal ions is more than 60 years.



The authors describe a new cost-effective approach utilizing temporarily placed casing.

by Patrick W. Burklund and Ellen Raber

Introduction

Many hazardous waste landfill sites are underlain by multiple aquifers isolated from one another by layers of fairly impermeable bedrock (possible confining beds). In cases where aquifer contamination is believed to have occurred. It is important to know the actual distribution of contamination in both a vertical and lateral sense. To do this, one must be able to effectively isolate and sample the ground water from within the individual aquifers. This involves avoiding any mixing between the suspected contaminated aquifer and other. It is hoped. uncontaminated aquifer(s) during drilling and well completion procedures. This is important for two main reasons: (1) to avoid creating a pathway for the spread of contaminants, and (2) to be able to determine whether contamination has actually spread to deeper aquifers. Also, it is very time consuming, costly and sometimes impossible to remove all contamination incurred as a result of temporary aquifer interconnection.

An alternative procedure which could be employed to avoid ground-water mixing involves the use of a multi-cased well designed to seal off the upper contaminated zone before deeper drilling is performed (Edwards et al. 1983). This is achieved by drilling a relatively large-diameter borehole, inserting a permanent steel casing sealed at the bottom with grout, and then drilling through the grout to the lower level. This type of approach, although effective, requires an individual monitoring well for each specific zone to be sampled. Additionally, costs are increased due to the expense of the permanent steel casing required for each well.

Another approach would be to drill a larger diameter borehole for packer emplacements to isolate the individual aquifers. Problems associated with this method are packer blowouts and formation water leakage past the packer bladders. Expense may be prohibitive due to the costs of packers and associated equipment for installation. Where the water table is relatively deep, the most cost-effective approach to ground-water monitoring is to install multi-level sampling wells. This article reports a method that has been developed which avoids mixing of ground water between two different aquifers (watertable and underlying confined) within a single borehole during the entire drilling and well completion operation. This eliminates problems associated with potential cross-contamination of ground water between aquifers, and allows valid multi-level ground-water sampling. The method assumes that some knowledge of the local hydrogeologic conditions already exists. However, it does allow for the identification of previously undetected perched aquifer conditions.

The basic approach utilizes a combination of airrotary and continuous wire-line core drilling, although other drilling methods may be employed. Both aquifers are isolated by the use of temporarily placed casing while instrumentation is installed. Water sampling devices and pressure transducers are then permanently emplaced at the appropriate depths; first in the lower aquifer and then in the upper aquifer. Each set of instrumentation is isolated from the other using a combination of bentonite seals and cement grout. If desired, a standpipe piezometer may be placed in the uppermost aquifer. Although not discussed here, more than two aquifers could be isolated by this method This would involve several temporarily placed casings (one Inside the other) which would be installed in the same manner and removed sequentially (from the bottom up). However, this would require drilling a much larger diameter initial borehole.

An illustrated step-by-step explanation of this approach is presented. Additionally, a cost comparison is made between this approach and the alternative twoborehole method. The total depth of boreholes drilled ranged from 200 to 400 feet. This method of completion was used in three boreholes and was successful in two. It has proven effective and relatively simple except for some problems encountered due to very unstable borehole conditions in a lower aquifer.

Description of the Method

Drilling Procedure

Boreholes were drilled using an Ingersoll-Rand TH-60 Cvclone Drill, although other drilling equipment should be just as effective. This is a very versatile piece of equipment that permits drilling with high pressure air (750 CFM at 250 psi) as well as with water and/or mud and is capable of both rotary drilling and continuous coring. Prior to any drilling activities, the drill rig and all drilling equipment were thoroughly cleaned by steam cleaning and washing. The equipment included hollowstem augers, drill steel, casing, core rods, core barrels, tri-cone drill bits and any other associated equipment that would go downhole. This cleaning process was repeated after each borehole was drilled and before moving to the next location. Although time consuming. this effort was necessary to minimize the potential for introducing contamination into the subsurface. Additionally. special precautions were employed to minimize the use of drilling lubricants. since these are sometimes used in large quantities and they may contain many of the priority pollutants to be monitored.

Depending on the chemical constituents to be monitored, an assessment regarding the best drilling approach should be made. Additives or proprietary drilling muds and/or foams have been found to cause contamination problems in previous investigations as they remain in the borehole despite vigorous attempts to flush the well clean (Absalon and Starr 1980). Therefore, for our studies, the methods employed were augering, rotary and wire-line core drilling using air or water only. There are, however, some problems which may be encountered when drilling with high-pressure air. First, the possibility of entrained oil and/or lubricant from the drill rig air compressor exists, so this must be monitored. The equipment used in this investigation was relatively new and we did not experience any such problems. Second, one must expect that substantial aeration will occur downhole, especially in the uppermost water-bearing formation. Depending on the yield of the aquifer, it may take several months for certain parameters to reach steady-state equilibrium values. This will also be true when drilling with water if injection is into a more reducing environment. However, the amount of area affected by water-injection will usually be less than with air injection.

For this investigation, boreholes were started in unconsolidated material by using an 8.0-inch continuous flight, hollow-stem auger to advance holes and obtain soil samples. Once augering through the unconsolidated materials was completed, drilling was continued by using a combination of air rotary drilling and HQ wire-line core drilling. Rotary drilling with air and coring using air was successfully accomplished to depths of between 60 and 100 feet below ground surface in both unconsolidated and indurated materials. In this manner, the borehole was advanced down through the first aquifer into the confining bed.

After the top of the confining bed beneath the watertable aquifer was reached and identified, the wire-line core tools were removed and the borehole was then reamed to a 6.75-inch diameter down to the confining bed using a standard tri-cone roller bit (Figure 1). Geophysical logs were run in the borehole at this time. In our investigations, these included natural gamma, gamma-gamma density, self-potential, resistivity and



Figure 1 Borehole drilled to contining bed

Figure 2. Right-hand/left-hand square thread casing

caliper logs. Temporary casing was then set to within 6 inches of the bottom of the borehole in the manner described below.

The lowermost casing section consisted of flushjoint stainless steel with a left-hand, square thread. It was connected to a right-hand square thread, flushjoint carbon steel casing by a stainless steel coupling threaded right-hand at the upper end and left-hand at the lower end. An illustration of this casing design is shown in Figure 2. The stainless steel casing section is the same inside and outside diameter as the carbon steel casing and 8 feet in length including the righthand thread to left-hand thread coupling. Thin wall casing was selected in order to maximize working room inside the casing and to minimize borehole diameter. Flush joint casing was used to facilitate casing removal from the borehole. It is possible that casing couplings could cause problems during casing removal. if borehole swelling or borehole collapse occurred during the drilling or completion of the lower aquifer. Steel casing is recommended for this method rather than PVC since PVC casing could be broken by the drill rods while drilling inside of it (i.e., by rod whip or chatter).

The lower stainless steel casing section (threaded left-hand) was hand-tightened to the left-hand threaded end of the coupling. The coupling and stainless steel casing section were then attached to the carbon steel casing and the coupling was wrench-tightened to the temporary steel casing. All of the remaining casing sections were then wrench-tightened as the casing was lowered down the borehole (Figure 3). After the casing was in place, a quick-setting expansive grout plug (Calseal, a trademark of Halliburton Corp.) was poured via a tremie pipe into the borehole and allowed to circulate



both inside and outside the stainless steel casing section. The amount of grout was calculated to encase only 6 feet of the 8-foot casing section (Figure 4). The grout was allowed to set two to four hours.

Before drilling was resumed, all standing water in the casing was removed. The well was then allowed to stand for at least one hour to determine whether there were any leaks in the casing or the grout seal through which formation water could enter the borehole. Once it was determined that there were no leaks in either the casing or the grout seal, drilling resumed. Wire-line core drilling was resumed by drilling through the grout plug and out the bottom of the casing through the confining layer into the lower aquifer to total depth (Figure 5). When total depth was reached, drilling tools were removed from the borehole and geophysical logs were run in the bottom section of the hole. By using the stratigraphic information obtained from the geophysical logs and geological cores, instrument locations were determined.

Well Completion Procedure

Most available instruments may be used in conjunction with this method, including bundle-type piezometers and various multi-level sampling devices. Borehole sizes may vary depending on the instrument selected. The ground-water sampling devices used in this investigation, which was primarily concerned with toxic inorganic constituents, were gas-drive type (Barcad, a trademark of Barcad Systems Inc.) samplers. In addition, vibrating-wire type strain gauge transducers were placed at each sampling point to determine piezometric pressure. Each transducer was attached to the tubing just above the sampler. The entire assembly



Confined aquifer (sandstone)

Figure 3. Temporary casing set in open borehole drilled to confining layer

Confined aquifer

(sandstone)

was then placed in a polypropylene filter "sock" and backfilled with No. 3 sand (Figure 6). All instrumentation was tested on the surface for proper operation before being installed in the borehole.

Well completion of the lower confined aquifer was now ready to begin. A No. 3 sand footing was placed on the bottom of the borehole through the tremie pipe. The first sampler-transducer assembly was then lowered down the borehole and landed on the sand footing. Once the sampler-transducer assembly was in place, No. 3 sand was placed in the borehole through the tremie pipe to completely cover the unit. It should be noted that all instrument and backfill material locations were measured with a weighted tag line and that all stemming materials were placed with the use of tremie pipe. The sand quantities varied based on the vertical length of the borehole to be sampled. After the sampler-transducer assembly was completely covered with the No. 3 sand, a fine sand "cap" was placed on top of the No. 3 sand. No. 0 sand was used in this case; 2 feet was found to be sufficient. The purpose of the fine sand is to prevent bentonite and grout intrusion into the No. 3 sandpack. With the No. 0 fine sand "cap" in place, the area above the sampler was then sealed with a 5-foot bentonite plug. This was accomplished by washing ³/₈-inch diameter bentonite pellets down the tremie pipe. The borehole was then grouted to 2 feet below the next sampler-transducer location and the above procedure was repeated.

After the appropriate number of sampler-transducer units were installed, the borehole was grouted back into the stainless steel casing section, sealing off the underlying aquifer(s) (Figure 7). After the grout had cured, any standing water in the casing was removed and the borehole was monitored for at least one hour to determine if there was any leakage into the temporary casing from the lower formation. When it had been determined that there were no leaks, the temporary casing was removed from the borehole. Removing the casing was accomplished by turning the entire casing string to the right (clockwise) and unscrewing from the left-hand threaded, stainless steel casing joint. The carbon steel casing sections were then removed from the borehole (Figure 8).

The upper part of the borehole was then open to the formation and could be instrumented. The well completion in the upper aquifer was similar to the lower aquifer except that a standpipe piezometer was installed as the uppermost (water-table) aquifer sampling point. The standpipe piezometer was constructed of 3 1/2-inch diameter PVC with square threads and flush joints. No glues or solvents were used during piezometer assembly to avoid problems associated with degradation and leaching of contaminants from organic coupling cements (Baker 1980). The slotted sections of casing were typically 5-foot lengths with 0.020 slot width: 15 feet of slotted section was commonly used. The slotted section was packed with the No. 3 sand over its entire length. A 2-foot No. 0 sand "cap" was placed on top of the No. 3 sand to prevent bentonite or grout intrusion into the No. 3 sand pack. The borehole was then grouted to the surface. The subsurface portion of the monitoring well was now complete (Figure 9).





Figure 5 Borehole drilled to underlying confined aquifer

Figure 6. Instrumentation package

wells consisted of labeled. weather-tight enclosures mounted on steel support legs. The support legs were anchored into the ground with concrete a few feet from the well-head. The sampler tubes and pressure transducer cables were passed through a flexible conduit which serves as protection. The conduit is grouted to the top of the well and attached to the enclosure with weather-proof seals. The sampler tubes are plumbed to a prefabricated manifold mounted in the enclosure. These tubes are labeled with aluminum tags and kept inside the enclosure until used, protecting them from weather and vandalism. The surface completion is illustrated in Figures 10 and 11.

Field Problems Encountered

The procedure to isolate ground-water flow between two aquifers was relatively trouble free. However, there were a few problems encountered. As previously stated, this procedure was used in three boreholes with two successful completions.

Rotary drilling with air and coring using air was usually successfully accomplished. However, once the water table was encountered, wash boring was usually necessary to prevent mud collar buildup on the drill rods. This was due to the high clay content of the formations encountered at the project site. The main problem was associated with unstable borehole conditions below the temporary casing. Once the borehole was drilled to total depth and the wire-line core rods were removed to install instrumentation, the uncased lower portion of the borehole would often collapse.











Figure 9. Completed monitoring well

When collapse occurred, the borehole was re-entered with the wire-line core drilling rods (no core bit) by using water injection (low flow rate) to "wash" the rods down to the bottom of the borehole. After reaching total depth with the wire-line drill rods, the transducersampler unit and sandpack were emplaced through the drill rods. The rods were then carefully pulled back. using a light water injection to avoid binding. By completing the borehole in this manner. using a tag line to measure borehole depth, the bottom part of the borehole was instrumented and stemming materials emplaced. Tag-line measurements are imperative to verify satisfactory placement of backfill materials and to detect collapse following wire-line rod withdrawal. If it is suspected that unstable borehole conditions exist, it may be desirable to initially plan to complete through the rods. Wire-line coring in unconsolidated materials is an effective way to advance an unstable borehole. Although core recovery was minimal at times, the borehole is protected from collapse while drilling, since the rods always remain in the hole.

A more critical problem arises when the borehole collapses just below the confining layer, shortly after the grout has been poured. This displaces the grout plug up into the temporary carbon steel casing. This was the case with the one unsuccessful completion. After the grout had cured (two to four hours) and the temporary casing was removed, the sampler-transducer tubes, which were grouted into the temporary casing were pulled apart. Therefore, there was no way to salvage the lower instrumented portion of the borehole.



Figure 10. Typical wellhead completion



Figure 11. Closeup of wellhead enclosure

Improvements

It is suggested that the stainless steel casing section be longer in well completions of this type. Based upon this study, we recommend that it be at least 12 feet in length so that a good seal is ensured and grout quantities do not have to be as precise. With a 12-foot casing section and a 6- to 8-foot grout stage, this would allow more room in the stainless steel casing for the grout. This is important in the event that the bottom portion of the borehole collapses and grout is displaced upwards or grout quantities are slightly miscalculated.

Cost Companison

A comparison was made between this method and an alternative approach to isolate two separate aquifers. This comparison is based on a 400-foot deep borehole. To accomplish the same sampling strategy discussed in this article, without the use of the retrievable casing method, two individual boreholes would need to be drilled. One well would be similar to the multi-cased well design described by Edwards et al. (1983). Figure 12 illustrates the two-borehole approach which can be compared directly to the single-borehole method illustrated in Figure 9. The two boreholes necessary would be as follows: One borehole is drilled to 180 feet total depth to sample the water-table aquifer. The second borehole is then drilled to 400 feet total depth to sample the confined aquifer only, isolating it from the watertable aquifer. This is accomplished by drilling through the water-table aquifer into the confining bed above the confined agulfer. A permanent casing must then be set into the confining bed at the base of the water-table aquifer and grouted in place. Then drilling would



Figure 12. Two borehole completion method

The dollar values in Table 1 are based on the actual costs of materials and services, except where otherwise stated. The labor charges are estimated at \$35. per person per hour and may need to be adjusted depending on actual labor costs. As Table 1 illustrates, the single borehole method is definitely more cost-effective, representing a savings of approximately 30 percent.

	Single borehole method*	Two borehole method**
Total drilling cost (\$27.60/foot includes drillers labor)	11,040	16,560
Samplar/transducar	3.662	3,662
Completion materials	2,401	4,134
Surface completion	581	1,163
Labor costs (\$35.00 per person per hour)	5,250	7,875
Total cost	\$22,935	\$33,394

* Based on 400 ft deep borehole

** Based on one borehole at 180 ft and the second borehole at 400 ft

Table 1. Cost Comparisons

Conclusions

This borehole drilling and completion method has proven to be very useful in instrumenting relatively deep water-table aquifers with underlying confined aquifers. The method avoids mixing of ground water between two different aquifers within a single borehole, eliminating potential cross-contamination of aquifers and biasing of sampling points. It is a cost-effective approach which does not require the drilling and completing of two separate monitoring wells. Also, since this method can be accomplished in a relatively small borehole, overall drilling costs are minimized. With good field planning, this can be an extremely useful monitoring well completion method for hazardous waste landfill investigations.

Acknowledgment

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References

- Absalon, J.R. and R.S. Starr. 1980. Practical aspects of ground-water monitoring at existing disposal sites.
 U.S. EPA Conference on Management of Uncontrolled Hazardous Waste Sites. October 15-17.
 Washington, D.C.
- Baker, J. 1980. Field methods in contaminant hydrogeology. University of Waterloo, Canada. Short course notes.
- Edwards, R.E., N.A. Speed and D.E. Verwoert. February 21, 1983. Cleanup of chemically contaminated sites. Chemical Engineering, pp. 73-81.

Biographical Sketches

Patrick W. Burklund joined the Lawrence Livermore National Laboratory in 1977 and is a senior technologist assigned to the Nuclear Test Engineering Division. As lead technician for many geotech-

Will My Monitoring Wells Survive Down There?: Design and Installation Techniques for Hazardous Waste Studies

by Henry R. Richter and Michael G. Collentine

Introduction

Field experiences at hazardous waste management facilities, hydrocarbon spills and sanitary landfills have shown the necessity for on-site flexibility in the design and installation of successful monitoring wells. It is the authors' opinion that although the initial design criteria for a monitoring well network are typically reviewed "in-office," the final design criteria must be confirmed on the basis of site-specific field observations.

It is the objective of this paper to describe various design and installation methods used by the authors to complete monitoring wells and to critically evaluate those methods based on site-specific applications. Monitoring well sites presented herein include a diversity of geographic settings in Wyoming. Hydrogeologic settings include unconfined and semi-confined ground-water conditions in 1) Quaternary alluvial terraces, alluvium, aeolian sand and scoria and 2) Cretaceous shale, claystone and sandstone.

This paper describes the following:

- Design of monitoring wells
 - -Drilling methods
 - -Completion and development practices
- Decontamination
- Field examples.

Principal Factors Controlling Monitoring Well Design

Principal factors controlling monitoring well design include:

- Drilling methods
 - --Geologic applicability—the types of geologic materials to be drilled and sampled will influence the selection of well casing and the size of the well screen

- Borehole diameter—the borehole should be of sufficient diameter to allow the emplacement of a gravel or sand pack and necessary formation sealing materials such as bentonite or cement
- -Site accessibility-may limit type of drilling equipment
- -Availability of equipment
- -Budget
- Completion and development practices
 - -Chemical constituents—the types of chemical constituents to be monitored will strongly influence the decision to use galvanized steel, PVC or yelomine (fiberglass) casing. Obviously, the asing material must not deteriorate or contribute chemical constituents by deterioration to the sampled formation water
 - --Well diameter---the well diameter should be adequate for well development, water sampling and pump testing
 - Contaminant cleanup—the well should be of adequate design for use as an active contaminant cleanup well
 - -Hydrogeologic environment—under confined conditions, the confining layers must be sealed off from the contaminated aquifer or aquifers. Multiple completion wells may be required where several minor aquifers exist
 - -Availability of equipment
- -Budget.

Drilling Methods

Drilling methods used by the authors at monitoring well project sites include 1) hollow stem auger, 2) air rotary, 3) mud (or foam) rotary, 4) casing hammer and air rotary, 5) drive point and 6) backhoe. Other drilling methods commonly used include cable tool and solid stem auger. A comparative summary of drilling methods is listed in Table 1.

Comparative Summary of Commonly Used Drilling Methods

Comparative criteria	Hollow stem auger	Air rotary	Mud rotary and/or foam	Casing hammer and air rotary
Geologic applicability (drillable formations)	Unconsolidated materials and soft bedrock Poor in saturated "flowing" mater- ials. Poor below water table Best application to soils.	No restrictions	No restrictions	Unconsolidated materials and soft bedrock. Generally not good where boulders are present. Not good for hard rock.
Depth restrictions	± 100	None	None	Type of geologic material and pull capacity of rig
Diameter of hole	9 to 12 inches	None	None	Limited by hammer, gener- ally less than 12 inches
Rig mobility	Excellent; truck, skid and tractor mount.	Good to poor, difficulty increases with size of rig.	Good to poor, difficulty increases with size of rig.	Good to poor, difficulty increases with size of rig
Quality of formation sampl es	Excellent undisturbed sam- ples when accompanied with split spoon above water table Poor sampling below water table.	Poor, nearly impossible to obtain undisturbed sam- ples. Difficult to identify intervals of less than 6 inches. Easy to miss minor contaminated zones.	Poor at best Not recom- mended for sampling.	Good to fair Can obtain some moderately disturbed samples. Better control than conventional rotary. Can determine minor contami- nated lenses. Good sam- pling below water table
Cross-contamination potential	Low, causes little formation damage and generally does not promote circulating fluids. Potential increases if cotter-pins on auger flights are not cleaned. Augers are easy to clean Few parts contact formation material.	Large, may cause air injec- tion, circulation of fluids. Difficult to thoroughly decontaminate bit.	Large, induces circulation of fluids.	Low, limited chance for cross-contamination Seals off contaminated intervals
Drilling rate	Slow	Fast; variable	Fast; variable	Slow
Rig availability	Poor	Excellent	Excellent	Poor, usually must special order hammer, drive casing and drive shoe.
Cost	\$8 to 18/ft.	\$6 to 24/ft.	\$10 to 32/ft	\$15 to 35/ft.
Comments	When accompanied with split spoon sampler, this is the best method for precise sampling. Limited by drill- ing depth, geologic mate- rials and availability. Poor method where large cob- bles and boulders are pres- ent. Limited by inside diameter of hollow stem. Poor method if samples below water table are required. Drilling problems below water table are required. Drilling problems below water table. Difficult to place gravel pack around well casing due to restricted annulus. Can determine saturated zones quickly. Can determine minor con- taminated laminae easily in samples Can run packer tests easily. Can sample fluids within hollow stem. Preferred method of authors at most locations. Poor availability of rigs with larger than 4-inch hollow stems in Rocky Mountain area. Many rigs are under- powered and have limited drilling denths	Good when just making hole. Poor when formation sampling is critical Increas- es potential for cross-con- tamination Increases per- sonnel exposure to con- taminants by blowing out samples and fluids. Diffi- cult to quickly identify saturated zones Rigs are generally larger than neces- sary for shallow monitor- ing wells. Costs are gener- ally higher.	Not recommended unless making hole is only objec- tive Mudseals offlow perm- eability zones. Easy to miss contaminated lenses. May seal off water-bearing zones. Promotes cross-con- tamination by inducing fluid circulation. Time con- suming when decontami- nating. Logistical problems when drilling in sub-zero weather. Frequent fluid freezing problems Good method if formationsslough and/or swell.	Good method in soft sloughing materials Can obtain good samples Limited by driving hammer capac- ity. Can cause problems when pulling casing; casing may get stuck May dam- age production casing when pulling surface casing. Good method when precisescreen- ing placement of produc- tion casing is required Easy to complete wells inside sur- face casing. Very slow drill- ing. Most rigs are not set up to run casing hammer Expensive

Iable 1 Comparative Summary of Commonly Used Drilling Methods (continued)

Comparative criteria	Drive point	Backhoe	Cable tool	Solid stem auger
Geologic applicability (drillable formations)	Unconsolidated material	Unconsolidated material	Most materials, best in rubble and boulder debris.	Unconsolidated materials and soft bedrock.
Depth restrictions	Type of geologic material. Generally less than 50 ft.	Length of arm, generally less than 14 ft.	Up to 400 ft.	± 200 ft.
Diameter of hole	Less than B inches	Unlimited	Unlimited	18 to 20 inches
Rig mobility None. Generally driven by hand hammer or trailer- mount hammer.		Good	Good to poor	Excellent truck, skid and tractor mount.
Quality of formation samples	No samples of formation are obtained.	Good	Good. Undisturbed samples can be readily obtained Limited recommendation when samples are critical	Moderately disturbed sam- ples above water table. Poor to inaccurate sampling below water table
Cross-contamination potential	None	Extreme	Low	Low
Drilling rate	Limited by speed of hammer.	Fast	Moderate	Slow
Rig availability	Good	Good	Poor to Good	Poor
Cost	\$10 to 20/ft.	\$25 to 50/hr.	\$8 to 14/ft.	\$5 to 10/ft
Comments	Quick, inexpensive way to install water-level and chemical quality monitoring points. Good where depth to water is shallow.	Not recommended for sampling. Easy way to exca- vate shallow pits and to install very large-diameter casing.	Easy and accurate sampling. Easy to determine saturated zones. Can test saturated zones. Easy completion when surface casing is in- stalled. Excellent where boulders cause drilling problems. Can damage pro- duction casing when pulling surface casing. Only major disadvantages are drilling times in consolidated rock and rig availability in the Bocky. Mountain area	Good for making hole. Poor if materials slough. Larger- diameter holes are possible with solid stem than hollow stem.

Completion and Development Practices

Monitoring well completion and development practices are frequently determined more by the prejudices of the individual in charge of the monitoring program than by the objectives of the monitoring program. Careful decisions should be made concerning the diameter of the monitoring well, casing material and type of well development technique. It is the authors' opinion that flexibility in completion and development practices must be maintained, with the controlling factor being the objective of the monitoring well.

One of the first considerations in monitoring well design is casing diameter. The focus of current discussions seems to be: which is best 2-, 4-, or 6-inch diameter casing? Each size casing has distinct advantages; however, the principal issue is which one will best satisfy the monitoring objective.

When determining casing diameter, the following factors should be considered:

• Cost—unit costs for 4- and 6-inch casing can be two to 10 times the unit cost for 2-inch casing

• Well development—large-diameter wells can be developed faster; however, costs of development equipment and rig time are generally greater. Large-diameter

wells produce water with less silt, thus reducing filtration time during sampling. Larger sediment storage capacity is also available in large-diameter wells

• Aquifer testing—2-inch diameter wells are generally not suitable for pump testing

• Sampling—although new sampling devices are being manufactured for 2-inch wells, it is generally agreed that larger-diameter wells are easier to sample and there is a greater number of sampling devices suitable for large wells. Large volumes of water must be evacuated from large-diameter wells prior to sampling

• Contaminant cleanup—2-inch wells are generally not useful for activities other than sampling and monitoring water levels, whereas larger-diameter wells can be used for the above-mentioned activities, as well as active contaminant cleanup

• Hydrogeologic environment—multiple completion wells are generally more suitable to 2-inch diameter casing because of cost.

Another factor in completion design is casing material. Frequently used materials include galvanized steel, PVC and yelomine (fiberglass). Although casing costs vary greatly depending on the type of material, the principal consideration should be to utilize material that will not react with the chemical constituents to be monitored. Other considerations include well depth, well use duration, strength and material availability.

Decontamination

Decontamination of drilling and sampling equipment consists of physically removing contaminants and/or altering the contaminant chemical characteristics to innocuous substances. The extent of decontamination depends on a number of factors, of which the most critical factor is the type of contaminants involved.

There is no method to immediately determine the effectiveness of field decontamination of drilling equipment. Discoloration, corrosion and materials adhering to equipment may indicate contaminants have not been removed; however, observable effects identify surface contamination and not permeation. Also, many contaminants are not easily observed while field cleaning equipment.

At best, field personnel must rely on their own best judgment while cleaning. Care and attention to detail must be exercised during the decontamination process and, realistically, one can only hope that the cleaning was complete.

The authors' experience with decontamination of field and drilling equipment in remote parts of Wyoming has been frustrating. Subzero temperatures of -40 F have at times rendered conventional decontamination (with soap and water) impossible. Similarly, these temperatures have rendered steam cleaning impossible because intake lines from the water trucks freeze before the water can be heated.

A principal controlling factor in decontamination has been local climatic conditions. Experience in decontamination of field and drilling equipment at remote project sites under extreme temperature conditions requires drillers to have "extra" supplies on-site so that pre-cleaned equipment is used at each new hole. When supplies are exhausted, the equipment is loaded and transported to a constructed wash pad so that cleaning solutions and wash water can be recycled or collected for later disposal. Steam cleaning or highpressure spraying utilizing water with a general purpose low-sudsing soap and detergent is recommended. Physical scrubbing by disposable or easily decontaminated brushes may be necessary to loosen packed-on materials. Hot water is more effective than cold water. and flushing or rinsing should be done under high pressure to assure to removal of all soap. A thorough inspection of equipment, supplemented by a swipe test, is recommended and should be the controlling factor for length and method of decontamination. It is essential that all parts of the drilling equipment including drill pipe, collars, kelly derrick, under carriage, chassis and cab, be thoroughly cleaned.

A brief summary of decontamination solutions frequently used and various remarks are listed in Table 2.

Upon completion of decontamination, the decontamination process employed and the results of the visual inspection and swipe tests should be **documented** in an appropriate log book. As a rule, drillers initial the log book, indicating that all equipment was cleaned and inspected.

Table 2Decontamination Solutions

Name of solution	Remarks
Sodium bicarbonate	Effective for acids and bases. amphoteric, 5-15 percent aqueous solution
Sodium carbonate	Effective for inorganic acids, good water softener, 10-20 percent aqueous solution
Trisodium phosphate	Good rinsing solution or detergent, 10 percent aqueous solution.
Calcium hypochlorite	Excellent disinfectant, bleaching and oxidizing agent. 10 percent aqueous solution.

Field Examples

Monitoring well projects supervised by the authors include the following:

• An industrial facility utilizing land farm, landfill, high strength, waste water evaporation pond and excess service water containment facilities

• A petroleum pipeline spill onto agricultural land

• An industrial facility assessing the potential for a spilled hydrocarbon recovery program

• A municipal landfill containing unrecorded quantities of hazardous, toxic and sanitary substances.

The purpose of this section is to briefly present selected project examples where monitoring well design was significantly changed from initial design based on key field observations and water-quality analyses.

Example 1

Example 1 involves an industrial facility utilizing a landfill, a chemical evaporation pond and excess service water containment facilities. A ground-water monitoring network was designed to comply with regulations specified under the Resource Conservation and Recovery Act (RCRA). The project site was located in Wyoming, and hydrogeologic environments included recent aeolian sand, quaternary alluvium and alluvial terrace deposits, and cretaceous shale and sandstone deposits. Ground-water conditions were unconfined to semi-confined and static water levels ranged from a few feet to about 25 feet below the ground surface.

Initially, monitoring wells were drilled using air, mud or foam rotary techniques. Wells were constructed with nominal 4-inch schedule 40 galvanized steel pipe, joined by threaded, galvanized steel collars. Well screens were 3 feet in length and constructed of galvanized steel. All wells were backfilled with washed silica fracsand and drill cuttings. Galvanized steel pipe was believed necessary because of possible contact with organic solvents and corrosive water.

Logistical problems were encountered almost im-

mediately with the rotary drilling. Hole collapse and collection of poorly correlated samples were the principal obstacles. Hole collapse was remedied by use of heavy weight mud; however, the mud masked drill cuttings, thus making observations of contaminated cuttings nearly impossible. The heavy mud also plugged off low-permeability sand lenses that had a high contamination potential.

To correct the hole collapse and sampling problems, a casing hammer and air rotary drilling program was initiated. This method proved to be satisfactory for well installation: however, drilling and completion time was nearly tripled. The increased time significantly elevated costs and a halt to drilling was called so that other drilling techniques could be evaluated.

During the drilling shutdown, water-quality samples were collected and analyzed. It was found that although previously reported, there were no organic solvents or corrosive water encountered in the sampled aquifer. This allowed us to eliminate the use of galvanized steel casing. Also during this time, one of only two hollow stem auger operators in the state was contacted.

It was then decided that as long as galvanized steel casing was not required, PVC casing and screens would be used. It was also agreed that the hollow stem auger would be used: however, the diameter of the hollow stem was only 3 inches and so all wells were reduced to 2-inch diameter.

The result of these final design changes allowed more monitoring wells to be installed in less time and at a lesser cost than had originally been estimated. The increased number of monitoring wells facilitated a better delineation of the contamination plume and ultimately expedited abatement procedures.

Example 2

Example 2 involves a petroleum pipeline spill onto agricultural lands. The spill occurred several years prior to the site investigation. The authors were contacted and requested to conduct a three-hour reconnaissance survey of the potentially contaminated area. The authors were informed that a drilling rig was available for use.

The hydrogeologic setting included a scoria aquifer overlain by clay. Depths to water ranged from 6 to 10 feet. The objective of the reconnaissance survey was to visually determine if hydrocarbons were present in the aquifer. Water-quality sampling was not an objective.

Because of the limited time allowed for the survey, the authors tried to determine the quickest way to penetrate the clay and reach the water table and also cover the greatest possible area. A steel tape and an Oil Recovery Systems Inc. ProbeTH were available for hydrocarbon detection.

The authors believed that a rotary drilling rig would be too slow. Because the water table was relatively shallow in the area, it was decided that a backhoe could be effectively used for excavation of test pits. The backhoe proved to be adequate and six test pits were excavated and tested. Four of the six test pits contained variable quantities of hydrocarbon product.

Although the areal extent of the hydrocarbon plume could not be delineated during the three-hour

survey, sufficient evidence was obtained to document the need for further studies. Although the authors conot recommend this practice for investigating hydrocarbon spills, nonetheless, it accomplished the objective.

Example 3

The final example involves an industrial facility experiencing possible contamination of an alluvial aquifer by a leaking chemical evaporation pond. The owners of the facility requested that monitoring wells be drilled at appropriate locations so that any contamination from the pond could be detected. The facility owners were interested only in obtaining waterquality analyses.

The alluvial aquifer was 8 to 10 feet thick. Depth to water ranged from 3 to 5 feet. The lithologic character of the alluvial deposits was well-known to the authors because the authors had installed numerous monitoring wells in the alluvium adjacent to this particular site.

Although the facility owners had requested that a drilling program be initiated, it was thought that drilling numerous shallow monitoring wells would be unjustifiably expensive and time consuming. It was the authors opinion that hand-driving sand-point or drive-point wells would accomplish the monitoring objectives and do so at the lowest possible cost. For example, by cost comparison, the drive-point wells could be installed at a cost ranging between \$25 and \$45 per hour, whereas drilling costs for rotary and hollow-stem auger rigs were \$150 and \$105 per hour respectively.

Summary

Numerous design criteria must be considered when drilling and completing monitoring wells at hazardous waste management facilities. It has been the intent of this paper to present what the authors believe are the principal controlling factors. However, the ultimate criterion in monitoring well design is making sure that the well(s) meet the objectives of the monitoring project.

The authors have found that designing monitoring wells in the office based only on published data does not always meet the objective of the monitoring program. Although the authors believe that in-office design is necessary and a good place to start, it is, however, critical that on-site flexibility in design be employed. As field information becomes available, it is not uncommon to make changes in drilling methods, casing, completion and development. Often these changes decrease costs and improve the efficiency of the well.

References

- Minning, R.C. 1982. Monitoring well design and installation. Proceedings of the Second National Symposium on Aquifer Restoration and Ground Water Monitoring. National Water Well Association, Worthington, Ohio, pp. 194-197.
- Schalla, R. and P.L. Oberlander. 1983. Variation in the diameter of monitoring wells. Water Well Journal, v. 37, no. 5, pp. 56-57.
- Schmidt, K.D. 1982. The case for large-diameter mon-

itoring wells. Water Well Journal, v. 36, no. 12, pp. 28-29.

Biographical Sketches

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Michael G. Collentine is currently a hydrogeologist with Western Water Consultants Inc., a Wyomingbased water resources consulting firm. He received his B.S. degree in geology and his M.S. degree in water resources management, both from the University of Wisconsin—Madison. His experience includes groundwater resource exploration and evaluation, design and installation of ground-water monitoring systems, analysis of ground-water/hydrocarbon interaction and geologic field mapping. He is a member of the National Water Well Association, the Wyoming Water Well Association and the Colorado Ground Water Association.

Questions and Answers

Q. What decontamination procedures would you recommend when drilling and sampling at sites contaminated with PCB?

Kim Kesler A. According to a representative at the General Electric Oil Testing Lab in Denver, Colorado, there are several solvents available that can be used to decontaminate PCB contaminated metal or glass drilling and sampling equipment. The solvents include acetone, hexane, trichlorobenzene, trichloroethane and a host of other "electrical grade solvents." All clothes, rags, rubber compounds or plastics used and/or possibly contaminated with PCB during drilling, sampling or cleaning, should be burned in an EPA-approved incinerator or disposed of at an approved disposal site. Such materials absorb PCB and cannot be decontaminated.

Special care should be taken during cleaning to avoid personal contact with contaminated rinse water, solvents or cleaning materials and to ensure that PCB contaminated water, solvents or cleaning materials do not come in contact with soils in the cleaning area. A self-contained pad should be required where PCB contaminated equipment is cleaned.

Q. How significant is adsorption of organics from incompletely developed 2-inch monitoring wells; and don't you run the risk of obtaining non-representative samples by filtering the water sampled from a poorly developed well?

A. In most cases, the concentration of organics in the sampled water after filtration in the field or lab is equal to the concentration in water from an adequately developed well, assuming that the silts and clays that remain in the formation have adsorbed as much of the organics as they are capable of. The analytical results will still be representative of the sampled water, and the filtered sediments will be representative of the extent of adsorption of organics that has taken place on the clays and silts in the formation.

Q. When working at hazardous waste sites, have you used acetone and hexane to clean your drilling tools and sampling equipment?

Bill Clarke

A. We have used acetone to clean tools and equipment. Our usual practice is to completely submerge the tool or sampler in acetone and then rinse it with hot water under pressure. This has proven to be a satisfactory method for decontaminating materials made of metal and glass.

Q. Do you use rubber seals between sections of hollow stem augers? If not, how do you avoid inflow at joints and subsequent cross-contamination?

Rich Anderson

A. Yes, we use rubber seals called 'O-rings' between the auger sections.

Q. In redeveloping silted-in wells, it is impractical to use air to accomplish the process in all cases (i.e. clays from voids, caves, etc.). What is your view toward utilizing water to blow out accumulated sediments? C.F. Bieze

A. When dealing with clays packed into the bottom of a well, it is our opinion that jetting with either air or water is equally effective, since air jetting essentially moves water into the sediments at a high velocity Experience has shown that the packed clays can only be removed by physical means such as brushing or reaming to loosen the sediments, followed by either air or water jetting.

Other methods, such as the addition of dispersing agents which react with clay and silt particles by placing a small, but similar electrical charge on each particle causing the particles to repel one another, are available. Again, methods which disperse the sediments should be followed by jetting.

Q. In utilizing the rotary air technique, problems with "jamming" (i.e. friction) often hinder drilling. What is your view on utilizing a common dishwashing fluid to facilitate lubrication? This assumes such fluid is analyzed for possible cross-contamination.

C. F. Bieze

A. I can't see any reason why common dishwashing fluid would present any problems. The drilling fluid must be of sufficient viscosity to carry drill cuttings out of the borehole. I would suggest clearing any such fluid with your driller before assuming that the fluid will provide both lubrication for the drill bit and sufficient viscosity to move cuttings away from the bit. Drilling foam is a soaplike substance commonly used to provide lubrication and cutting removal.

Q. What is your opinion of installing small-diameter wells in bedrock in borings drilled with double tube diamond coring equipment?

B. Camlin

A. The coring method is best utilized in areas where the monitoring system objective is to install shallow wells in bedrock units which crop out at the surface. Samples obtained from the borehole may be accurately correlated to depth and/or tested for vertical permeability. This method may be extremely slow where the well depth requires repeated withdrawal of the core barrel.

Q. Shouldn't well screen design take into account potential for direct ground-water flow measurement? For instance, maximizing directional accuracy and lowering resistance to flow?

William B. Kerfoot

A. As stated in our paper, the most important consideration in the well design should be the objective of the monitoring system. The primary reason to design the well screen as described in the question is to accommodate measurements with a ground-water flowmeter.

Where this instrument will be utilized, wells should certainly be designed to give the least distortion possible to the flow of ground water.

It is our opinion, however, that the present state of the art of ground-water flowmeters does not warrant their use as a reliable tool to estimate ground-water flow direction. It has been our experience in the field that currently available flowmeters give misleading results. When it comes to estimating the flow direction of hazardous wastes in ground water, we have found that the potentiometric surface determined from water levels in properly installed monitoring wells is the most reliable method.

A Technique for Renovating Clogged Monitor Wells

by William H. McTigue and Robert G. Kunzel

This paper describes a technique for renovating 2inch PVC monitor wells that have been clogged by intrusion of silt from the surrounding soil and that have, in this case, been cross-contaminated by bailer sampling.

For about two years, a series of 2-inch diameter PVC monitor wells had been sampled by using the same bailer. As a result, there was extensive cross-contamination, especially by volatile organic compounds. Furthermore, the large slot size of the well screen and the uniform gradation of the surrounding pea gravel "filter pack" had allowed silt to be drawn into the well, completely filling the well screen in some cases.

The wells were cleaned by simple jetting with clean water to remove the silt and the contaminated water. Then, a 1-1/2-inch diameter gas-displacement sampling device was lowered into the screen section and surrounded by a suitably graded filter sand. Samples taken from the gas-displacement samplers over more than a year have shown no cross-contamination and no turbidity or intrusion of silt.

Turbid ground-water samples and clogged monitor wells are becoming common experience. Most frequently, these situations occur where monitor wells are installed in low-yield saturated materials, such as silt, clay or glacial till. Our experience indicates that this often is a result of inappropriate design of either the well screen, the filter pack material, or both.

Design of monitor wells has naturally evolved from water well design. These design concepts have necessarily been extended from application to saturated media of high permeability to those of very low permeability. However, it is not uncommon in finegrained materials (silt, very fine sand, till), that monitor wells that have been designed and installed by professionals will produce turbid samples and the wells themselves become clogged with intruded silt and clay particles.

A fundamental criterion of well design is to allow pore water to flow through the surrounding porous media and into the well screen, while fine particles in the media are excluded. In a more productive $(k=10^{-2})$ cm/sec) water-bearing medium, such as might provide a yield of 50 gallons per minute to a 2-inch gravel pack well, sizing of the well screen slot and gravel pack are matters of general experience. However, in fine-grained materials, say k=10⁻⁵ cm/sec, the yield of the same 2-inch well would be reduced to about 0.07 gpm. Not surprisingly, wells are seldom installed in such low-yield material, except for construction dewatering and ground-water monitoring applications. Hence, when the demand for monitor wells to obtain ground water from such fine-grained materials expanded dramatically, the frequent results were customary "gravel pack" wells of smaller diameter, which failed to exclude fine soil particles when water was extracted from the well. In fact, little attention is given to this aspect of design in reference and practice manuals, e.g., EPA 1980 and EPA 1982.

An example of this type of monitor well failure occurred at a hazardous waste disposal site in Illinois, where 35 monitor wells were designed and carefully installed to monitor ground water in loess and glacial till deposits. Following two years of sampling with a bailer. most of these wells had substantial amounts of silt intruded into the well, in many cases completely filling the screened section. Ground-water samples were turbid and, because a single bailer was used in sampling all the wells, considerable cross-contamination had occurred.

The design of the monitor wells is shown schematically in Figure 1. A 2-inch plastic well casing and screen was surrounded by a gravel pack described as "pea



Figure 1 Typical monitor well installation



Figure 2. Partical size distribution relationships

gravel." Figure 2 shows particle size distribution curves for the natural formation materials, characterized by the right-hand curve; and the gravel pack material, characterized by the left-hand curve. Considering only these two materials, it is readily evident that fine particles from the formation would easily move through the very coarse, uniformly graded gravel pack.

The shaded areas of Figure 2 depict two criteria commonly used for designing filter materials to exclude fine formation particles from a pumping well. The John-

son criteria (Johnson Div., UOP 1975) are recommended for water-supply well design, with the assumption that the well will be aggressively developed, i.e., as much as 30 to 50 percent of the formation fines will be drawn into the well during the development operation. This criterion also assumes significant gradation of the particle sizes in the natural media; it will be less effective in uniform-grained media, such as pure silt. The trapezoidal shaded area represents criteria employed in construction dewatering well design (Powers 1981); the particle size distribution curve of an acceptable filter must pass through the shaded area, in the manner of the line shown.

The two shaded areas of Figure 2 have been fixed by applying these criteria to the natural formation curve shown on the right. It is evident that the dewatering design criteria produce filter materials of finer average particle size and somewhat wider allowable gradation. As a result, these criteria have been found to produce good filtering effectiveness, allowing very slight movement of fine particles, even in uniform fine sands and silts.

As a general approach to the design of filter packs for monitor wells, an appropriate filter material might be specified to lie within the boundaries defined by the two criteria shown in Figure 2. Additionally, the finer boundary might be preferred in the case of uniform, very fine-grained natural formations.

In this case, it was evident that the gravel pack was allowing intrusion of large amounts of the natural finegrained materials each time the well was bailed. The objective of the renovation program was to clean out the monitor wells and to reconstruct them in such a way as to produce clear ground-water samples and permit accurate measurement of the piezometric surface. This was to be done, if possible, without redrilling and complete reconstruction of the monitor wells.

The technique selected consisted of the installation of a properly filtered gas-displacement sampler inside the 2-inch PVC casing and screen of the existing monitor wells. The first step in the procedure was thorough cleaning of each monitor well. This was accomplished by a water jetting system, using clean water from the municipal water system, which was not recirculated after being introduced into the well. A truck-mounted tank, small centrifugal pump and simple piping were used in a manual jetting procedure. Progress of the manual procedure was rapid, even at the maximum well depth of 40 feet. Jetting tools were cleaned after each well was jetted.

After the intruded silt had been washed out of the casing and screen of each well, and after the jetting water returned consistently clear, the jetting tools were withdrawn from the well casing, making sure that the water level in the casing was not allowed to drop during the withdrawal. This procedure maintained a positive head inside the well and prevented the tendency for intrusion of fine materials from the silt-clogged filter pack during the withdrawal of jetting tools.

A gas-displacement sampler with a porous polyethylene tip section and rigid PVC riser pipe was inserted into the clean monitor well and screen. The outside diameters of sampler and riser pipe were 1-1/2 and 1 inch, respectively. The sampler unit itself was approximately 16 inches in length. All piping connections were threaded and no solvents or glue were used. The general arrangement is diagrammed in Figure 3.

After the sampler unit was carefully centered in the well, filter sand was poured slowly into the well casing. This filter sand filled the space between the sampler and the well screen so as to produce a new, properly graded filter throughout the full length of the monitor well screen section. The purpose of this filter sand was to allow the movement of ground water into the monitor well and into the gas drive sampler while excluding the fine particles now lodged in the original gravel pack. Selection of the filter sand was based on the application of dewatering criteria which, conveniently, were satisfied by a locally available, sterilized "play sand" that was readily available at local hardware stores. Uniformity of the sand grain size distribution was particularly important, so that the sand would not segregate while being poured into the water-filled well.

The filter sand was placed in the monitor well until its measured depth indicated that the screen section had been completely filled. The filter sand was tamped frequently with a tamping rod to eliminate voids and to measure the amount of sand in place. A seal of bentonite pellets was placed in the well casing at the top of the filter sand column. The remainder of the well casing was then filled with readily available material to complete the inst. llation as shown in Figure 3.

After installation, the gas-displacement sampler was operated as a pump to extract residual wash water in the filter sand and to ensure that the entire system was purged and refilled with natural ground water. Because of the low permeability of the surrounding formation, comparatively long times were required for the sampling device to refill after purging. In the shallower wells, periods of four to eight hours were required to accumulate one liter of sample. Clear ground-water samples were obtained from all renovated monitor wells and evidence of cross-contamination had disappeared by the end of the second sampling and testing cycle.

The device installed in the well was a dual-function sampler/piezometer. The fluid level in the 3/4-inch riser pipe (Figure 3) moves freely in response to changes in water pressure in the media surrounding the porous tip. Therefore, water levels can be measured at any time, using an ordinary electric well probe inside the 3/4-inch riser pipe.

The renovated monitor well installation, in addition to achieving the initial objectives of clear samples, no risk of cross-contamination, and maintenance-free operation, has several further advantages, resulting from the gas-displacement sampling technique. Because the sampler device and the 3/4-inch riser pipe involve the storage of smaller sampler volumes, the time required to recharge the sampler after purging is much less than that required for the predecessor monitor well casing. Because the ground-water sample is displaced by gas under pressure, the pressure in the sample fluid is



Figure 3. Renovated monitoring well showing gasdisplacement sampler

not reduced during sampling, which tends to prevent the vaporization of volatile constituents of the sample. Smaller volumes of purged water are involved, which simplifies procedures if this water must be separately managed, and the sampling becomes a one-man, rather than two-man, operation. Finally, the sampling procedure is simple and easily controlled, particularly in winter or other adverse weather conditions or when contact with sampled fluid is to be avoided.

Renovation of these 35 monitor wells, which averaged 25 to 30 feet in depth, was accomplished during adverse weather and site conditions in March 1982 at an average cost of \$350 per well. Recent experience with similar renovation projects indicates that this is a relatively high unit cost.

References

- Johnson Division, UOP Inc. 1975. Ground water and wells.
- Powers. J.P. 1981. Construction dewatering: a guide to theory and practice. John Wiley and Sons. New York.

vation of water and wastewater. EPA-600/4-82-029. EPA. 1980. Procedures manual for ground-water monitoring at solid waste disposal facilities. SW-611.

Biographical Sketches

William H. McTigue is president of GeoEngineering Inc. He has more than 25 years experience in heavy construction, geotechnical engineering, water resource development, ground-water control systems, business administration and management. McTigue received his B.S. from Massachusetts Institute of Technology and his M.S. from New Jersey Institute of Technology. He is also a past president of the Association of Soil and Foundation Engineers and of the Consulting Engineers Council of New England. McTigue is a licensed professional engineer in the states of New York and New Jersey.

Robert G. Kunzel is an associate and currently the senior technician of GeoEngineering Inc. Kunzel has nearly six years experience in a broad range of field activities, including geotechnical drilling, sampling and instrument installation, geophysical surveys, topographic and location surveys and aquifer pumping tests. He is responsible for the production, marketing and installation of the GeomonTM Ground-Water Sampler/ Piezometer System. During this time he has been involved in design, installation and operation of groundwater monitoring systems throughout the United States and in Europe. APPENDIX B

AN EXAMPLE PRESCRIPTIVE GROUNDWATER SAMPLING PROTOCOL (NO IMMISCIBLES)

 $(A \in \mathcal{A})$

WDR223/009/1

SAMPLING PROCEDURES

Groundwater sample collection procedures are discussed in several steps:

- o Measurement of static water level
- o Purging
- o Measurement of field parameters
- o Sample withdrawal
- o Decontamination

Measurement of Static Water Elevation

Measurements of static water elevations are used to determine groundwater hydraulic gradients, which in turn are used to predict groundwater flow directions and velocities. Steps in the measurement process are described below. Figure A.1 is a diagram showing typical well construction and specific well measurement points.

- All sampling team members wear new and clean disposable gloves or thoroughly decontaminated rubber gloves to protect team members from exposure to potentially contaminated groundwater, and to minimize the potential for contaminating the sample (sampling team members are a potential source of contamination).
- o Remove the lock from the locking cap covering the well. The measurement reference point should be marked on the top of the protector casing below the locking cap. The elevation of that reference point should be established in relation to mean sea level within an accuracy of ±0.01 foot.
- DO NOT remove the bailer from the well prior to measuring the static water elevation.
- Place a clean, flat object across the top of the protector casing, centered on the measurement reference point.
- o Lower a thoroughly decontaminated measurement instrument to the water surface. A narrow steel tape or an electric probe may be used. If a tape is used, the bottom few feet of the tape are chalked and lowered into the well to the anticipated water depth so that the chalked portion of the tape is in the water. Subtract the measurement from the wetted portion of the chalk from the tape reading at the flat object which is



Height of Water Column (ft) = (A to C) – (A to B) Well Volume (gal) = Height of Water Column (ft) X Inside Area of Well (ft²) X 7.48 gallons/ft³

Figure A.1 Diagram for Static Water Elevation Measurements at the measurement reference point to determine the distance to the water surface. Align an even foot mark on the tape with the measurement reference point to simplify calculations. Lower the tape continuously to that even foot mark. If the tape is lowered below the foot mark an erroneous reading will result. If an electric probe is used, it should give an audible or visual signal (a light or a milliammeter) upon contact with the water surface.

- Record the distance from the reference point to the water surface to the nearest 0.01 foot.
 Table A.1 provides conversions from inches to decimals of a foot.
- o If the well has a dedicated bailer, remove the dedicated bailer and place the rope and bailer on a clean surface ("Dedicated" meaning that the bailer is used for one well only, and is removed only to collect samples.) If the bailer gets soiled or otherwise contaminated, it should be cleaned before it is placed back in the well. If the rope gets dirty or contaminated, it should be replaced with new rope constructed of inert material (e.g., polypropylene).
- Lower the measurement probe to the bottom of the well. Record the depth to the bottom of the well to the nearest 0.01 foot.
- Remove the measurement probe, decontaminating the probe as it is brought to the surface. The decontamination procedure is as follows:
 - Saturate clean paper towel with 20 percent methanol solution. All decontamination solution solvents should be reagent quality or higher. Water used to make up the solution should be from a clean, potable supply.
 - Wipe along the length of the probe, discarding and replacing the towel as it becomes soiled.
 - Rinse the rewound spool of the probe with clean water, using a hand sprayer (household plant spray bottles work well).
 - Place the measurement probe in a clean container. The probe is ready for use at the next well.

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0	Foot	0839	1667	9500	9339	4187	*000	6933	6687	75.00	6933	0167	
1-92	0028	0859	1601	2526	9:150	4193	5026	5850	6607	25.00	8450	0104	
1-16	0052	ONKS	1210	2552	3345	4219	5052	5NH5	6710	7559	1005	0.010	1 -34
8-32	.0078	0911	1745	2578	3411	4215	5078	5911	6745	7578	8411	4245	8 30
1-8	.0104	.0938	1771	2604	31.0	4271	5104	59:48	6771	7604	HA:H	0.71	1_8
5-32	.0130	0964	1797	2630	3464	4297	5130	5964	6797	7630	8464	9297	5.9
8-16	.0156	.0990	1823	.2600	.3490	4323	.5156	5990	6623	7656	8490	9323	8_16
7-32	.0182	.1016	.1849	.2682	.3516	.4349	.5182	.6016	.6849	.7682	.8516	.9349	7-3
1-4	.0208	.1042	1875	2708	3542	4375	5208	6042	5875	7708	8542	0375	1.4
9.32	.0234	1068	1901	2734	3568	4401	5234	6064	6901	77.4	H56H	0401	0.9
5-16	0260	1091	19.7	2760	3594	4427	5260	6094	8927		8594	0427	5.16
11-32	.0286	1120	1953	2786	3620	.4453	5286	6120	6953	7786	8620	9453	11_3
8-8	.0313	.1146	.1979	.2813	3646	.4479	.5313	6146	6979	2813	8646	+179	3.6
13-32	.0339	.1172	.2005	.2839	.3672	.4505	.5339	.6172	7005	7839	8672	9505	13-32
7-16	.0365	.1198	.2031	.2865	.8698	.4531	.5365	.6198	.7031	7865	6698	.9531	7-10
15-32	.0391	.1224	.2057	.2891	.8724	.4557	. 5391	.62:4	.7057	.7891	.8724	.9557	15-3
1-2	.0417	.1250	.2083	.2917	.8750	.4583	.5417	.6250	.7083	.7917	.8750	. 9583	1-2
17-82	.0443	.1276	.2109	.2543	.8776	.4609	.5443	. 6276	.7109	.7943	.8776	.9609	17-39
9-16	.0469	.1302	.2135	.2969	.3802	.4635	.5469	.6302	.7135	.7969	.8802	.9635	9-16
19-32	.0495	.1328	.2161	.2995	. 3828	.4601	. 5495	.63:28	.7161	.7995	. 68.28	.9661	19-3:
5-8	.0521	.1354	.2168	. 3021	.88.4	.4688	.5521	.6354	.7188	.8021	.8854	.9685	5-8
21-32	.0547	.1350	.2214	.3047	.3460	.4714	.5547	.63 80	.7214	.8047	.8880	.9714	21-3.
11-16	.0573	.1406	.240	. 3073	.3900	.4740	.5573	.6406	.7240	.8073	. 8906	9740	11-16
23-32	.0099	. 1432	2266	. 8093	.3003	.4760	. 5599	6432	. 7266	.8099	. 8932	.9766	23-3:
8-4	.0625	.1458	.2292	.3125	.3958	.4792	5625	.6458	.7292	.8125	. 8958	.9792	8-4
25-32	.0651	.14%4	.2318	.3151	.3984	4R18	5651	.6454	.7318	.8151	.8984	9818	3-3
13-16	.0077	. 1 510	.2344	.3177	.4010	.4844	. 5677	.6510	.7.144	8177	. 9010	.9844	13-16
27-32	0703	.1536	.2370	. 3:20:3	.4036	.4870	. 5703	.6546	7370	.8903	. 9036	. 9 870	27-32
7-8	.0729	.1563	2396	.3:5:59	.4063	.4896	.5729	.6563	.7396	.82.9	.9063	.9896	7-8
29-32	.0755	.1589	.24:22	.:255	4069	.49:22	.5755	.6589	1.74:22	.8255	. 9089	.9922	29-32
16-16	.0781	.1615	2448	.92HI	.4115	.4948	.5781	. 6 615	.7448	.8281	. 9115	.9948	15-16
8182	.0807	. 1641	. 2474	.3307	4141	.4974	5807	.6641	.7474	.8307	.9141	.9974	31-35
	0	1	2	8	4	5	6	7	8	9	10	11	

B-4

Table A-l

Purging

Standing water should be purged from the well, allowing formation water representative of in situ conditions to flow into the well for sampling. Purging procedures vary depending on the yield of the well. High yielding wells recharge rapidly enough to be purged continuously until they are sampled. Low yielding wells are purged intermittently prior to sampling.

Higher yielding wells may be purged either with a pump or a bailer. Separate purging procedures are described below:

Purging With a Pump

- Sampling team members wear either new and clean disposable gloves, or decontaminated rubber gloves.
- o Lower the thoroughly decontaminated pump down the well. For wells with a low volume of water in the well, it is recommended that the same pump be used for both purging and sampling. For large diameter (4-inch ID or greater) and/or deep wells, a separate, higher yield pump may benefit the monitoring program. If a second pump is used, it will also require decontamination between each use.
- Calculate the volume of water in the well, multiplying the height of the water column (depth of the well minus the depth to the water surface) by the inside area of the well. Figure A-1 demonstrates how to make this calculation. Table A.2 presents casing dimensions and volumes for various well pipe sizes.
- Collect discharge in a graduated container for volume measurements.
- o Measure the following field parameters after each well volume of purge water: pH, Eh, conductivity, and temperature. These parameters are physically or cheically unstable when groundwater is exposed to the atmosphere, and should be measured in an air-tight chamber connected to the discharge tubing. A diagram of this setup is shown in Figure A-2.
- o Record field measurements on a table. A suggested format is shown in Table A.3. Continue purging until the following stability criteria are met.
Table A-2

WELL CASING DIMENSIONS AND VOLUMES

ſ		8CH. 5			8CH. 40			SCH. 80	<u> </u>
Nominal Pipe Size, Inches	0.D. Inch	I.D. Inch	VOL. gal/ft	0.D. Inch	I.D. Inch	VOL. gal/ft	O.D. inch	I.D. Inch	Vol. gal/tt
	1.32	1.19	· 0.06	1.32	1.05	0.04	1.32	0.96	0.04
11/2	1.90	1.77	0.13	1.90	1.61	0.11	1.90	1.50	0.09
2	2.38	2.25	0.21	2.38	2.07	0.17	2.38	1.94	0.15
3	3.50	3.33	0.45	3.50	3 .07	0.38	3.50	2.90	0.34
4	4.50	4.33	0.77	4.50	4.03	0.66	4.50	3.83	0.60
5	5.56	5.35	1.17	5.56	5.05	1.04	5.56	4.41	0.79
6	6.63	6.41	1.67	6.63	6.07	1.50	6.63	5.76	1.35
8	8.63	8.41	2.88	8.63	7.98	2.60	8.63	7.63	2.37
Conversion Fo	rmulas								
3785 ml = 3	3.785 liter	s = 1 gallo	n	1 g	allon water	at 62 deg.	F = 8.34	pounds	
7.48 gallons = 1 cubic foot			1 p	si = 2.307	feet water	head = 2.	04 inches	of mercur	



Figure A.2 Diagram of Field Parameter Measurement Apparatus

 Table A.3

 FORMAT FOR DATA TABLE FOR RECORDING GROUNDWATER FIELD PARAMETERS

Pump	Pump*		Pumping					
Start	Stop		Time	Volume	рH	Eh	Conductivity	Temperature
(x)	(x)	Time	(minutes)	(gallons)	(units)	(mv)	(umhos/cm)	(°C)

Well	No.: _		Date:	<u> </u>		
Site	No.: _	·	Purge	Interval:	From	То
Pump	Depth:		Sampli	ng Team:		

*Rationale for stopping the pump before the purging process is completed should be explained on the data sheet.

- Conductivity, temperature, and pH values vary less than ±10 percent for three consecutive well volumes.
- Eh values vary less than 50 millivolts or ±10 percent for three consecutive well volumes, whichever is larger.
- Purged water should be disposed on the ground surface such that the water can infiltrate. Water should not be disposed into surface waters or the well.
- When stability criteria are met, the pump may be shut off temporarily in order to prepare for sample collection.

Purging with a Bailer

- Sampling team members wear either new and clean disposable gloves, or decontaminated rubber gloves.
- o If a dedicated bailer is already in the well, no bailer decontamination step is required.
- If a new bailer or portable bailer ("portable" 0 meaning that the bailer is used for more than one well) is used, the bailer must be decontaminated by rinsing with a steam cleaner and/or washing the bailer with three bailer volumes of trisodium phosphate (TSP) solution followed by three bailer volumes of a 20 percent methanol solution. The outside of the bailer and cord should be decontaminated by wiping with a clean paper towel saturated with a 20 percent methanol solution, then rinsed with clean water using a hand sprayer. For the purposes of this monitoring plan, "clean water" is defined as water transferred directly from a drinking water supply tap to a detergentwashed and tap-water rinsed container.
- o Lower the bailer into the well. The bailer should be lowered slowly to minimize splashing.
- Bring the bailer to the surface, emptying purge water into a graduated bucket to measure purge volumes. Prevent contact of the bailer and rope with the ground surface.
- When a well volume of water is purged, empty the bailer into a separate container and measure and record field parameters. These measurements may

be affected by exposure to the atmosphere, but still provide the best means of determining when representative formation water has reached the well. Use the stability criteria described previously (in "purging with a pump") for determining when the purging process is complete.

Purging Low Yield Wells

Low yield monitoring wells are defined for the purpose of this report as those that do not recharge rapidly enough to be purged continuously. For these wells, the purging process is as follows:

- Remove water from the well with a dedicated or a decontaminated portable bailer until all water in the well has been removed.
- o Empty purge water into a graduated container.
- o Measure and record field parameters.
- Allow the well to recharge, closing and locking the well cap if the sampling team moves to another location.
- o If feasible, purge a second well volume from the well, measuring and recording field parameters.
- Once the well has recharged (based on remeasurement of the water level), remove a sufficient volume to measure and record field parameters. The remaining volume will be withdrawn for samples.

Sample Withdrawal

Samples should be withdrawn either with a positive displacement bladder pump or with a bailer. All sampling and purging equipment should be decontaminated before they are lowered into a monitoring well.

Sampling With a Pump

After the purging process is complete pump the water sample directly into sample bottles bypassing the field parameter measurements chamber. Special procedures are required for volatile organic analysis samples and filtered samples, as described below.

Volatile Organic Analysis Samples. The pump discharge must be adjusted to achieve a flow rate low enough to fill a volatile organic analysis (VOA) vial or a total organic halide (TOX) bottle without aerating the sample. If the flow cannot be adequately controlled, VOA and TOX samples should be collected with a bailer, as described below. Invert filled VOA vials and TOX bottles and check for air bubbles. Discard the sample and refill if any air bubbles are present.

Filtering Samples. When sampling for dissolved metal constituents, samples should be filtered prior to preservation. To filter samples, attach the pump discharge tubing to the inlet side of a filtering apparatus. Discharge from the filter should flow directly into the appropriate sample container.

Sampling With a Bailer

- Lower the bailer slowly through the water column; avoid aeration or agitation.
- Withdraw the bailer slowly; keep the bailer rope clean.
- Pour the sample slowly into sample jars, filling to the proper volume. Check VOA vials for air bubbles and refill if any air bubbles are present.

Filtering Bailed Samples. When a bailer is used to collect a sample, pour the sample into a clean container and use a small pump to transfer the sample from the container through the filter and into the sample jar. A hand-powered or small electric pump is recommended. The transfer pump should be decontaminated between each use.

Decontamination

This discussion on decontamination applies to portable sampling equipment that is used at more than one well or sampling location. This equipment must be thoroughly cleaned prior to taking each sample to minimize the potential for the sampling equipment to be a source of contamination.

Decontamination requirements are reduced for dedicated or single-use disposable sampling equipment. Dedicated or disposable equipment should be handled in such a way that it does not come into contact with dirty and potentially contaminated surfaces (including the sampling team members' hands). If dedicated equipment does come into contact with potentially contaminated surfaces, it should be cleaned using the decontamination procedures outlined for portable equipment. If the dedicated apparatus is difficult to decontaminate (such as a bailer rope), it should be replaced.

- Sampling team members wear new and clean disposable gloves or decontaminated rubber gloves.
- o While withdrawing the tubing and pump from the well, decontaminate the exterior of tubing by spraying with a trisodium phosphate (TSP) solution and wiping with clean paper towel saturated with a 20 percent methanol solution. Once all of the tubing has been removed from the well, cleaned, and wound onto a spool, rinse the tubing with clean water from a sprayer.
- Decontaminate the exterior of the pump by spraying with the 20 percent methanol solution.
- Place the pump (with the exterior now cleaned) into a decontamination tube consisting of a section of PVC pipe with a water-tight cap on the bottom. The decontamination tube should be approximately 2 feet longer than the pump.
- Fill the decontamination tube with a TSP solution and turn on the pump. While pumping, add a total of 2 gallons of TSP solution followed by 2 gallons of methanol solution into the tube. Discharge water should be allowed to infiltrate into the soil away from the well. When the pump is no longer discharging any solution, turn the pump off. Store the pump in the decontamination tube until it is ready to be placed in the next well. The tube should be occasionally rinsed to keep it clean.

Note: Storing the pump in the decontamination tube for extended periods of time (e.g., between seasonal sampling events) may deteriorate the pump unless the tube is thoroughly dried.

Decontamination of Bailers

Dedicated bailers do not need to be decontaminated if sampling team members wear clean gloves and the equipment is only in contact with clean surfaces. New and clean plastic bags or plastic sheeting are suitable for placing dedicated sampling equipment in or on once that equipment has been removed from the well. This plastic should not be reused at another well unless it is decontaminated.

For portable bailers, the bailer should be filled and drained twice with TSP solution; then filled and drained twice with a 20 percent methanol solution. The exterior and

interior of the bailer should be cleaned with the methanol solution, wiped with a clean towel, then rinsed with clean water.

Decontamination of Filtration Apparatus

- Sampling team members wear new and clean disposable gloves or decontaminated rubber gloves.
- Disassemble filtration apparatus, discarding any disposable filters, prefilters, etc.
- Spray all interior surfaces of the filtration apparatus with a TSP solution followed by a methanol solution, placing all parts on a clean surface.
- Reassemble filtration apparatus with filters in place.
- Store the filtration apparatus in a clean container, ready for use at the next site.

Note: Single-use disposable filter apparatus with selfcontained filters are available through sampling equipment manufacturers. These are connected directly to the pump discharge tube and disposed after each sample.

SAMPLING EQUIPMENT

A combination of proper sampling procedures and sampling equipment is necessary to collect groundwater samples that are representative of actual conditions in the field. A positive-displacement bladder pump is recommended for collecting groundwater samples. Other groundwater sampling mechanisms have a greater potential for altering the in-situ chemistry of the groundwater. Positive-displacement bladder pumps typically pump at a rate between 0.25 and 1.5 gallons per minute (gpm). Table A.4 contains general recommendations for groundwater sampling mechanisms.

The pump, as well as other tools and instruments lowered into the well, should be constructed from inert materials which will minimize chemical alteration, microbial colonization, sorption effects, or leaching effects. Recommendations for rigid and flexible materials in sampling applications are provided in Tables A.5 and A.6 respectively.

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Table A.4 PERFORMANCE EVALUATION OF GROUNDWATER SAMPLING MECHANISMS

	Overall	
Mechanism Category	Performance Ranking	Remarks
Positive displacement (bladder)	Above average	Expected to provide both efficient well purging and representative samples over a range of conditions with minimal difficulty in field operations.
Grab samplers (conventional bailer) (dual-check valve bailer) (syringe pump)	Average Average Averagebelow average	Unsuitable for well purging; requires very careful operation and sample handling precautions under field conditions; field performance open to question.
Positive displacement (mechanical)	Averagebelow average	Suitable for well purging; sampling performance very dependent on specific design and operational details.
Gas displacement (gas drive; not gas lift)	Averagebelow average	May be suitable for well purging if used in conventional installations; malfunc- tions are difficult to assess or repair; significantly lower recoveries of purge- able organic compounds and gases may occur depending on field conditions and operator experience.
Suction (peristaltic)	Below average	Suitable for well purging at depths to approximately 20 feet; significantly lower recoveries of purgeable organic compounds and gases will result from sampling with this mechanism.

Reference: Practical Guide for Ground-Water Sampling, Illinois State Water Survey, ISWS Contract Report 374. 1985.

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Table A.5 RECOMMENDATIONS FOR RIGID MATERIALS IN SAMPLING APPLICATIONS (In decreasing order of preference)

Material	Recommendations
Teflon (flush threaded)	Recommended for most monitoring situations with detailed organic analytical needs, particularly for aggressive, organic leach- ate impacted hydrogeologic conditions. Virtually an ideal material for corrosive situations where inorganic contaminants are of interest.
Stainless Steel 316 (flush threaded)	Recommended for most monitoring situations with detailed organic analytical needs, particularly for aggressive, organic leachate impacted hydrogeologic conditions.
Stainless Steel 304 (flush threaded)	May be prone to slow pitting corrosion in contact with acidic high total dissolved solids aqueous solutions. Corrosion products limited mainly to Fe and possibly Cr and Ni.
PVC (flush threaded) other noncemented connections, only NSF* approved materials for well casing or potable water applications	Recommended for limited monitoring situa- tions where inorganic contaminants are of interest and it is known that aggressive organic leachate mixtures will not be contacted. Cemented installations have caused documented interferences. The potential for interaction and interfer- ences from PVC well casing in contact with aggressive aqueous organic mixtures is difficult to predict. PVC is not recommended for detailed organic analytical schemes.
	Recommended for monitoring inorganic contaminants in corrosive, acidic in- organic situations. May release Sn or Sb compounds from the original heat stabil- izers in the formulation after long exposures.
Low-Carbon Steel Galvanized Steel Carbon Steel	May be superior to PVC for exposures to aggressive aqueous organic mixtures. These materials must be very carefully cleaned to remove oily manufacturing residues. Corrosion is likely in high dissolved solids acidic environments, particularly when sulfides are present. Products of corrosion are mainly Fe and Mn, except for galvanized steel which may release Zn and Cd. Weathered steel surfaces present very active adsorption sites for trace organic and inorganic chemical species.

^{*}National Sanitation Foundation approved materials carry the NSF logo indicative of the product's certification based on meeting industry standards for performance and formulation purity.

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Reference: Practical Guide for Ground-Water Sampling. Illinois State Water Survey, ISWS Contract Report 374. 1985.

Table A.6 RECOMMENDATIONS FOR FLEXIBLE MATERIALS IN SAMPLING APPLICATIONS (In decreasing order of preference)

Material	Recommendations
Teflon	Recommended for most monitoring work, par- ticularly for detailed organic analytical schemes. The material least likely to introduce significant sampling bias or im- precision. The easiest material to clean in order to prevent cross-contamination.
Polypropylene Polyethylene (linear)	Strongly recommended for corrosive high dissolved solids solutions. Less likely to introduce significant bias into analytical results than polymer formulations (PVC) or other flexible materials with the exception of Teflon.
PVC (flexible)	Not recommended for detailed organic ana- lytical schemes. Plasticizers and stabil- izers make up a sizable percentage of the material by weight as long as it remains flexible. Documented interferences are likely with several priority pollutant classes.
Viton Silicone (medical grade only)	Flexible elastomeric materials for gaskets, O-rings, bladder and tubing applications. Performance expected to be a function of exposure type and the order of chemical resistance as shown. Recommended only when a more suitable material is not available for the specific use. Actual controlled expo- sure trials may be useful in assessing the potential for analytical bias.

Reference: Practical Guide for Ground-Water Sampling. Illinois State Water Survey, ISWS Contract Report 374. 1985.

Table A.7 PROCEDURE CHECKLIST FOR GROUNDWATER SAMPLING

Procedure

Pre-Sampling Preparations

- 1. Prepare sample bottles with proper preservatives and coordinate schedule with the laboratory.
- 2. Prepare Site Safety Plan.
- 3. Collect equipment needed for all tasks (see equipment checklist).

Sampling Procedures

- 4. Unlock well.
- 5. Perform air monitoring as required by Site Safety Plan.
- 6. Measure and record water level in well.
- 7. Measure and record depth of well.
- 8. Decontaminate water level measuring equipment.
- 9. Set up to purge well with either pump or bailer.
- 10. Purge well until parameters are stabilized.
- 11. Decontaminate purging equipment if necessary.
- 12. Set up to collect water samples including any blanks and duplicates.
- 13. Collect samples and filter if necessary.
- 14. Decontaminate water sampling equipment.
- 15. Close and lock well.
- 16. Move to next sampling location.
- 17. Prepare samples for shipping to laboratory at the end of the day.

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Table A.8

EQUIPMENT CHECKLIST FOR GROUNDWATER SAMPLING

Equipment

- 1. Key to well locks
- 2. Disposable or rubber gloves
- Health and safety equipment required by Site Safety Plan
- 4. Water level measurement device
- 5. Logbook and permanent marker
- 6. Tape measure or wooden rule
- 7. Hand sprayer with clean water
- 8. Hand sprayer with 20 percent methanol solution
- 9. Paper towels
- 10. Plastic garbage bags
- 11. Groundwater purge and sampling pump with tubing and power source
- 12. Graduated bucket
- 13. pH meter with probe and calibration buffer solutions
- 14. Eh meter with probe
- 15. Conductivity meter with probe
- 16. Thermometer
- 17. Air-tight chamber for field parameter measurement
- Sample jars (with preservatives already in them, as appropriate)
- 19. Filter apparatus
- 20. PVC decontamination tube for pump with stand
- 21. Bailer and rope
- 22. TSP
- 23. Twenty percent (20%) methanol solution
- 24. Chain-of-custody forms
- 25. Coolers with ice to store collected samples

APPENDIX C

EXCERPT OF THE RCRA GROUND-WATER MONITORING TECHNICAL ENFORCEMENT GUIDANCE DOCUMENT (1986)

(p.-17)

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SAMPLING AND ANALYSIS WORKSHEET

The following worksheets have been designed to assist the enforcement officer in evaluating the techniques an owner/operator uses to collect and analyze ground-water samples. This series of worksheets has been compiled based on the information provided in Chapter 4 of the TEGD.

I. Review of Sample Collection Procedures

A. Measurement of well depths elevation:

	1.	Are measurements of both depth to standing water and depth to the bottom of the well made?	(Y/N)
	2.	Are measurements taken to the nearest centimeter	(Y/N)
	3.	What device is used?	
	4.	Is there a reference point(s) established by a licensed surveyor?	(Y/N)
в.	Det	ection of immiscible layers:	
	1.	Are procedures used which will detect light phase immiscible layers?	(Y/N)
	2.	Are procedures used which will detect dense phase immiscible layers?	(Y/N)
c.	Sam	pling of immiscible layers:	
	1.	Are the immiscible layers sampled separately prior to well evacuation?	(Y/N)
	2.	Do the procedures used minimize mixing with water soluble phase?	(Y/N)
D.	Wel	l evacuation:	
	1.	Are low yielding wells evacuated to dryness?	(Y/N)
	2. 3	three casing volumes are removed? What device is used to evacuate the vells?	(Y/N)
	э.		
	4.	If any problems are encountered (e.g., equipment malfunction) are they noted in a field logbook?	(Y/N)
E.	San 1	ple withdrawal: For low-vielding wells, are first samples tested for	
	••	pH, temperature, and specific conductance after the	
		well recovers?	(Y/N)

2.	Are samples collected and containerized in order of the parameters volatilization sensitivity?	(Y/N)
3.	For higher-yielding wells, are samples retested for pH, temperature, and specific conductance to determine	· · · · · · · · · · · · · · · · · · ·
۵	purging efficiency? Are samples withdrawn with either fluorocarbon resins	(Y/N)
т. 5	or stainless steel (304, 316, 2205) sampling devices?	(Y/N)
5.	or positive gas displacement bladder pumps?	(Y/N)
6.	If bailers are used, is fluorocarbon resin-coated wire, single strand stainless steel wire, or monofilament	· ·
_	used to raise and lower the bailer?	(Y/N)
7.	If bladder pumps are used, are they operated in a	(V / N)
8.	If hailers are used, are they lowered slowly to	(1/M)
9.	prevent degassing of the water? If bailers are used, are the contents transferred	(Y/N)
	to the sample container in a way that will minimize	
	agitation and aeration?	(Y/N)
10.	Is care taken to avoid placing clean sampling equipment	
	on the ground or other contaminated surfaces prior to insertion into the well?	(Y/N)
.11.	If dedicated sampling equipment is not used, is	
	equipment disassembled and thoroughly cleaned between	
12	If samples are for inorganic analysis does the clean-	(1/N)
	ing procedure include the following sequential steps:	
	a. Nonphosphate detergent wash?	(Y/N)
	b. Dilute acid rinse (HNO3 or HCl)?	(Y/N)
	c. Tap water rinse?	(Y/N)
	d. Type II reagent grade water?	(Y/N)
13.	It samples are for organic analysis, does the cleaning	
	a Nonphosphate detergent wash?	(V/N)
	b. Tap water rinse?	(Y/N)
	c. Distilled/deionized water rinse?	(Y/N)
	d. Acetone rinse?	(Y/N)
	e. Pesticide-grade hexane rinse?	(Y/N)
14.	Is sampling equipment thoroughly dry before use?	(Y/N)
15.	Are equipment blanks taken to ensure that sample	
16	cross-contamination has not occurred?	(Y/N)
τά.	II VOIGLILE SAMPLES ARE LAKEN WITH A POSITIVE GAS	
	100 ml/min?	(Y/N)

In-	situ or field analyses:	
1.	Are the following labile (chemically unstable) parameters	
	determined in the field:	
	a. pH?	(Y/N)
	b. Temperature?	(Y/N)
	c. Specific conductivity?	(Y/N)
	d. Redox potential?	(Y/N)
	e. Chlorine?	(Y/N)
	f. Dissolved oxygen?	(Y/N)
	g. Turbidity?	(Y/N)
	h. Other (specify)	· · · · · · · · · · · · · · · · · · ·
2.	For in-situ determinations, are they made after well	
	evacuation and sample removal?	(Y/N)
3.	If sample is withdrawn from the well, is parameter	
•••	measured from a split portion?	(Y/N)
4	Te monitoring equipment calibrated according to	(
	manufacturers' specifications and consistent with	
		(Y/N)
5	Te the date procedure and maintenance for emigment	····/
٦.	as the date, procedure, and maintenance for equipment	(V/N)
	calibration documented in the field logbook:	

II. Review of Sample Preservation and Handling Procedures

F.

A.	Sam	ple containers:	
	1.	Are samples transferred from the sampling device	
		directly to their compatible containers?	(Y/N)
	2.	Are sample containers for metals (inorganics) analyses	
		polyethylene with polypropylene caps?	(Y/N)
	3.	Are sample containers for organics analysis glass	1
		bottles with fluorocarbon resin-lined caps?	(Y/N)
	4.	If glass bottles are used for metals samples are	
		the caps fluorocarbon resin-lined?	(Y/N)
	5.	Are the sample containers for metal analyses cleaned	
		using these sequential steps?	
		a. Nonphosphate detergent wash?	(Y/N)
		b. 1:1 nitric acid rinse?	(Y/N)
		c. Tap water rinse?	(Y/N)
		d. 1:1 hydrochloric acid rinse?	(Y/N)
		e. Tap water rinse?	(Y/N)
		f. Type II reagent grade water rinse?	(Y/N)
	6.	Are the sample containers for organic analyses cleaned	
		using these sequential steps?	
		a. Nonphosphate detergent/hot water wash?	(Y/N)
		b. Tap water rinse?	(Y/N)
		c. Distilled/deionized water rinse?	(Y/N)
		d. Acetone rinse?	(Y/N)
		e. Pesticide-grade hexane rinse?	(Y/N)

	7.	Are trip blanks used for each sample container type to verify cleanliness?	(Y/N)
Β.	Samı 1.	<pre>ple preservation procedures: Are samples for the following analyses cooled to 4°C: a. TOC? b. TOC? c. Chloride? d. Phenols? e. Sulfate? f. Nitrate? g. Pesticides/Herbicides? h. Coliform bacteria? i. Cyanide? j. Oil and grease?</pre>	(Y/N)
	2 [.] 3. 4.	 k. Volatile, semi-volatile, and nonvolatile organics? Are samples for the following analyses field acidified to pH <2 with HNO₃: a. Iron? b. Manganese? c. Sodium? d. Total metals? e. Dissolved metals? f. Radium? g. Gross alpha? h. Gross beta? Are samples for the following analyses field acidified to pH <2 with H₂SO₄: a. Phenols? b. Oil and grease? Is the sample for TOC analyses field acidified to pH <2 with H₂SO₄ or HC1? Is the sample for TOX analysis preserved with 	(Y/N) (Y/N)
	6.	<pre>1 ml of 1.1 M sodium sulfite? Is the sample for cyanide analysis preserved with NaOH to pH >12?</pre>	(Y/N) (Y/N)
	7.	Are pesticides pH adjusted to between 6 and 8 with NaOH or H_2SO_4 ?	(Y/N)
c.	Sp(1. 2.	ecial handling considerations: Are organic samples handled without filtering? Are samples for volatile organics transferred to	(Y/N)
	-	the appropriate vials to eliminate headspace over the sample?	(Y/N)
	3.	Are samples for metal analysis split into two portions?	(Y/N)
	4.	is the sample for dissolved metals filtered through a 0.45 micron filter?	(Y/N)

	5. 6.	ls the second portion not filtered and analyzed for total metals? Is one equipment blank prepared each day of ground-water sampling?	(Y/N) (Y/N)
111. <u>R</u>	evie	w of Analytical Procedures	
λ.	Lab	poratory analysis procedures:	
	1.	Are all samples analyzed using an EPA-approved method (SW-846)?	(Y/N)
	2.	Are appropriate QA/QC measures used in laboratory	
		analysis (e.g., blanks, spikes, standards)?	(Y/N)
	3.	Are detection limits and percent recovery (if	
		applicable) provided for each parameter?	(Y/N)
	42.	are split samples run for comparison purposes?	(V/N)
	5.	Are samples analyzed within specified holding	(1/11/
	-	times?	(Y/N)
	Tab	varatory larbook.	· · · · · · · · · · · · · · · · · · ·
Б.	1.	Is a laboratory logbook maintained?	(Y/N)
	2.	Are experimental conditions (e.g., temperature,	(1/11/
		humidity, etc.) noted?	(Y/N)
	3.	If a sample for volatile analysis is received	• • •
		with headspace, is this noted?	(Y/N)
	4.	Are the results for all QC samples identified?	(Y/N)
	5.	Is the time, date, and name of person noted	
		for each processing step?	(Y/N)
IV. <u>Re</u>	<u>vie</u> v San	of Chain-of-Custody Procedures	
А.	ാദന 1	y te rancia: Die rancia:	(V/N)
	2.	Do they provide the following information:	(1/N/
		a. Sample identification number?	(Y/N)
		b. Name of collector?	(Y/N)
		c. Date and time of collection?	(Y/N)
		d. Place of collection?	(Y/N)
	-	e. Parameter(s) requested:	(Y/N)
	3.	Do they remain legible even if wet?	(Y/N)

в.	Samj	ple seals:	
	1.	Are sample seals placed on those containers to	
		ensure the samples are not altered?	(Y/N)

APPENDIX D

EXCERPT OF THE RCRA GROUND-WATER MONITORING COMPLIANCE ORDER GUIDANCE (1985)



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Examples of Basic Elements Required by Performance Standards	Examples of Technical Inadequacies that may Constitute Violations	Regulatory Citations
7. Samples from background and down- gradient wells must be properly collected and analyzed	 failure to evacuate stagnant water from the well before sampling 	§265.90(a) §265.92(a) §265.93(d)(4) §270.14(c)(4)
	 failure to sample wells within a reasonable amount of time after well evacuation 	§265.90(a) §265.92(a) §265.93(d)(4) §270.14(c)(4)
	 improper decisions regarding filtering or non-filtering of samples prior to analysis (e.g., use of filtra- tion on samples to be analyzed for volatile organics) 	§265.90(a) §265.92(a) §265.93(d)(4) §270.14(c)(4)
	 use of an inappropriate sampling device 	§265.90(a) §265.92(a) §265.93(d)(4) §270.14(c)(4)
	 use of improper sample preserva- tion techniques 	§265.90(a) §265.92(a) §265.93(d)(4) §270.14(c)(4)
	 samples collected with a device that is constructed of materials that interfere with sample integrity 	§265.90(a) §265.92(a) §265.93(d)(4) §270.14(c)(4)
	 samples collected with a non- dedicated sampling device that is not cleaned between sampling events 	§265.90(a) §265.92(a) §265.93(d)(4) §270.14(c)(4)
	 improper use of a sampling device such that sample quality is affected (e.g., degassing of sam- ple caused by agitation of bailer) 	§265.90(a) §265.92(a) §265.93(d)(4) §270.14(c)(4)

Examples of Basic Elements Required by Performance Standards	Examples of Technical Inadequacies that may Constitute Violations	Regulatory Citations
Samples from background and downgradient wells must be properly collected and analyzed (continued)	 improper handling of samples (e.g., failure to eliminate headspace from containers of samples to be analyzed for volatiles) 	§265.90(a) §265.92(a) §265.93(d)(4) §270.14(c)(4)
	 failure of the sampling plan to establish procedures for sampling immiscibles (i.e., "floaters" and "sinkers") 	§265.90(a) §265.92(a) §265.93(d)(4) §270.14(c)(4)
	 failure to follow appropriate QA/QC procedures 	§265.90(a) §265.92(a) §265.93(d)(4) §270.14(c)(4)
	 failure to ensure sample integrity through the use of proper chain- of-custody procedures 	§265.90(a) §265.92(a) §265.93(d)(4) §270.14(c)(4)
	 failure to demonstrate suitability of methods used for sample analysis (other than those specified in SW-846) 	§265.90(a) §265.92(a) §265.93(d)(4) §270.14(c)(4)
	 failure to perform analysis in the field on unstable parameters or constituents (e.g., pH, Eh, specific conductance, alkalinity, dissolved oxygen) 	§265.90(a) §265.92(a) §265.93(d)(4) §270.14(c)(4)
	 use of sample containers that may interfere with sample quality (e.g., synthetic containers used with volatile samples) 	§265.90(a) §265.92(a) §265.93(d)(4) §270.14(c)(4)
	 failure to make proper use of sample blanks 	§265.90(a) §265.92(a) §265.93(d)(4) §270.14(c)(4)

	Examples of Basic Elements Required by Performance Standards		Examples of Technical Inadequacies that may Constitute Violations	Regulatory Citations
	8. In Part 265 assessment monitoring the O/O must sample for the correct substances		failure of the O/O's list of sam- pling parameters to include cer- tain wastes that are listed in §261.24 or §261.33, unless ade- quate justification is provided	§265.93(d)(4)
		•	failure of the O/O's list of sam- pling parameters to include Appendix VII constituents of all wastes listed under §§261.31 and 261.32, unless adequate justifica- tion is provided	§265.93(d)(4)
	 In defining the Appendix VIII makeup of a plume the O/O must sample for the correct substances 	•	failure of the O/O's list of sam- pling parameters to include all Appendix VIII constituents, unless adequate justification is provided	§270.14(c)(4)
	10. In Part 265 assessment monitoring and in defining		failure of sampling effort to iden- tify areas outside the plume	§265.93(d)(4) §270.14(c)(4)
	a plume the O/O must use appropriate sampling methodologies	•	number of wells was insufficient to determine vertical and horizon- tal gradients in contaminant concentrations	§265.93(d)(4) §270.14(c)(4)
			total reliance on indirect methods to characterize plume (e.g., elec- trical resistivity, borehole geophysics)	§265.93(d)(4) §270.14(c)(4)
	11. Part B applicants who have either detected con- tamination or failed to imple- ment an adequate part 265 GWM program must deter- mina with confidence		failure of O/O to implement a monitoring program that is capable of detecting the existence of any plume that might emanate from the facility	§270.14(c)(4)
	whether a plume exists and must characterize any plume	9	failure of O/O to sample both upgradient and downgradient wells for all Appendix VIII constituents	§270.14(c)(4)
			See also items #1, #2	