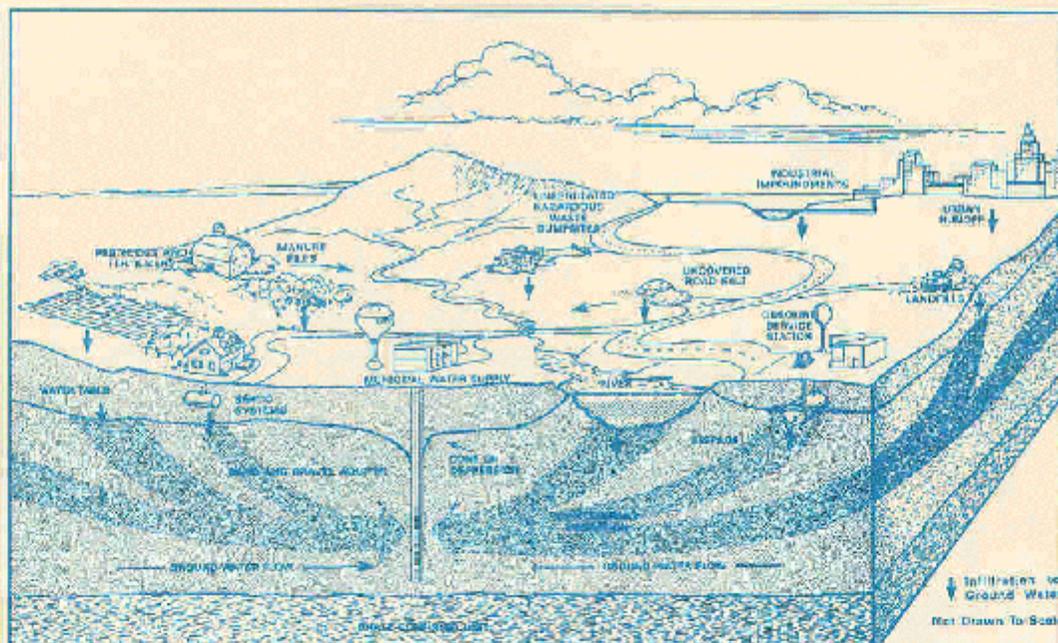


# Technical Guidance Manual for Hydrogeologic Investigations and Ground Water Monitoring

February 1995



Ohio Environmental Protection Agency  
Division of Drinking and Ground Waters  
1800 WaterMark Dr.  
Columbus, Ohio 43215-1099

**TECHNICAL GUIDANCE MANUAL FOR HYDROGEOLOGIC  
INVESTIGATIONS AND GROUND WATER MONITORING**

**Division of Drinking and Ground Waters  
Ohio Environmental Protection Agency  
122 South Front Street  
Columbus, Ohio 43126-1049**

**February 1995**

## NOTICE

A draft version of this document was issued for public comment on July 22, 1993. The comment period ended on December 10, 1993. Comments received were considered in the development of this final document.

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## PREFACE

Ohio EPA utilizes laws, rules and policy to exercise its authority to require ground water monitoring and/or hydrogeologic investigations. **Laws and rules** pertinent to ground water monitoring are embodied in the Ohio Revised Code (ORC) and the Ohio Administrative Code (OAC), respectively. Additionally, Ohio EPA may assist U.S. EPA in implementing some of the **regulations** contained in the Code of Federal Regulations (CFR). **Policy** statements are used to clarify regulatory requirements and establish consistency in the way programs are conducted.

Ohio EPA utilizes **guidance** to aid regulators and the regulated community in meeting laws, rules, regulations and policy. Guidance outlines recommended practices and explains their rationale. It is important to note that the term implies no enforcement authority. The Agency may not require an entity to follow methods recommended by this or any other guidance document. It may, however, require an entity to demonstrate that an alternate method produces data and information that meet the pertinent requirements. Ohio EPA recognizes that inflexibility in the language and/or interpretation of guidance can lead to the adoption of inappropriate measures, delay, and inefficiency. The procedures used to meet requirements usually should be tailored to the specific needs and circumstances of the individual site, project, and applicable regulatory program, and should not comprise a rigid step-by-step approach that is utilized in all situations.

This guidance manual was developed by the Agency's Division of Drinking and Ground Waters (DDAGW), Ground Water Program. The Ground Water Program is responsible for establishing a statewide comprehensive approach to ground water protection and management. As part of its duties, the Program provides technical support to the Divisions of Emergency and Remedial response (DERR), Hazardous Waste Management (DHW), Solid and Infectious Waste Management (DSIWM), Surface Water (DSW), and Environmental Financial Assistance (DEFA), as well as other state agencies, local officials, the regulated community and the general public.

This document is separate from the series of policy and guidance that the Ground Water Program has issued beginning in 1989. This series, which is organized by number (PP-, later changed to DDAGW-prefix for policy and procedures; GD-prefix for guidance documents) generally clarifies or interprets the ground water-related regulatory requirements of other Ohio EPA Programs. The focus of this manual is not regulatory at all; rather, it is technical, and the document should be used in tandem with the PP-, DDAGW-, and GD-series documents to develop workplans and reports that meet requirements.

## ACKNOWLEDGMENTS

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**Jeff Patzke** served as editor and project coordinator.

**Lisa Koenig** had primary responsibility for writing Chapters 2 (Regulatory Overview), 3 (Characterization of Site Hydrogeology), 4 (Slug and Pumping Tests), 5 (Monitoring Well Placement), 8 (Monitoring Well Development), 9 (Monitoring Well and Borehole Abandonment), 11 (Soil Gas Analysis Section), and 12 (Ground Water Quality Data Organization and Interpretation). She made significant contributions to many of the other chapters as well.

**Dan Tjoelker** was a primary author for Chapters 6 (Drilling and Sub-Surface Sampling), 7 (Monitoring Well Design and Installation), 10 (Ground Water Sampling and Analysis), 11 (Geophysics and In-Situ Ground Water Sampler Sections), and 14 (Ground Water Modeling).

**Susan Snyder** had primary responsibility for writing the initial version of Chapter 13 (Statistics for Ground Water Quality Comparisons). The initial chapter was expanded upon by **Katie Crowell**.

Others who helped with the writing include **Barb Lubberger, Grover Thompson, Lindsay Taliaferro, III, and Scott Sutliff**. Thanks are also due to **Ginger Houk, Donna Roberts, Susie Noskowiak, Rhonda Cordial** and **John Antolino**, who provided word processing support, **Pattie McKean** (PIC), who prepared the cover, and **Ruth Ann Evans** and **Marilyn Brizz** (Library), who were instrumental in obtaining reference material.

The Ohio EPA would also like to thank the numerous people who provided input on the document during its developmental stages. The comments and recommendations of DDAGW-District Offices, other Ohio EPA Divisions, State and Federal Agencies, private consultants, and the regulated community were greatly appreciated.

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**TECHNICAL GUIDANCE MANUAL FOR HYDROGEOLOGIC  
INVESTIGATIONS AND GROUND WATER MONITORING**

**CHAPTER 1  
INTRODUCTION**

**February 1995**

# CHAPTER 1

## INTRODUCTION

This guidance manual identifies the technical considerations for performing hydrogeologic investigations and ground water monitoring at potential or known ground water pollution sources. Ground water pollution sources include, but are not limited to, hazardous waste facilities, solid waste landfills, wastewater facilities (including non-toxic flyash, bottom ash, foundry sand, and coal pile runoff collection facilities), underground injection wells, underground storage tanks, septic tanks, leaks and spills, mining activities, and application of fertilizers, pesticides and herbicides.

In Ohio, the authority over pollution sources is shared among various divisions of the Ohio EPA and other agencies as indicated in Table 1.1. In general, this document was designed for those sites/facilities that are under the jurisdiction of the Ohio EPA (with the exception of Class I injection wells<sup>1</sup>). However, the technical considerations for hydrogeologic investigations and ground water monitoring generally are applicable to most pollution source evaluations, regardless of the regulatory framework. A responsible party may be required to: 1) evaluate and monitor the impact of a known or potential pollution source to underlying ground water, 2) determine if site hydrogeology is favorable for location of a proposed waste disposal facility, or 3) remediate contaminated ground water.

It is hoped that this document will aid the regulated community in implementing technically sound investigations that meet Ohio EPA's requirements. However, the Agency expects those conducting investigations to be qualified ground water scientists. While the State of Ohio does not maintain a certification program, the Ohio EPA considers a person to be qualified if he/she has received a baccalaureate or post-graduate degree in the natural sciences or engineering and has at least five years relevant experience in ground water hydrology and related fields that enable that individual to make sound professional judgements regarding ground water monitoring, contaminant fate and transport, and corrective actions.

In general, the organization of this document reflects the conceptual order in which tasks are implemented. Regulatory requirements should be understood before any investigation is begun; consequently, Chapter 2 is an overview of the Agency's regulatory authority. An adequate characterization of underlying geologic materials and the movement of ground water within them is fundamental to successful ground water monitoring, siting determinations, and ground water remediation. As a result, the next two chapters, 3 and 4, address methods for investigating site hydrogeology. If ground water monitoring is an objective, wells need to be installed to provide samples from appropriate water-bearing zones. Chapters 5-9 cover procedures for placement, drilling, construction, development, and abandonment. Chapter 10 provides recommended methods for ground water sampling and analysis. Chapter 11 discusses supplemental methods that may be helpful for subsurface characterization or ground water quality determination. The final three chapters cover techniques that can be used after ground water samples have been collected and analyzed. Chapter 12 covers data organization and interpretation, Chapter 13 addresses statistical comparisons, and Chapter 14 handles modeling.

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<sup>1</sup>Class I wells are those wells used to inject hazardous or non-hazardous waste beneath the lowermost formation containing, within one-quarter mile of the well bore, an underground source of drinking water. Due to construction constraints and depth of monitoring at some Class I injection sites, techniques that are not discussed in this document may be necessary.

Ohio's ground water is a vital natural resource, and its importance must not be underestimated. Approximately 1300 of Ohio's communities derive at least a portion of their water supplies from ground water. Consequently, adequate monitoring and remediation of contaminated aquifers and protection of uncontaminated aquifers is essential. If the procedures used to carry out ground water monitoring and hydrogeologic investigations are inadequate, the data obtained may not be reliable and may lead to decisions that will be costly and harmful to human health and the environment. Therefore it is hoped that this document can assist responsible people in their efforts to protect Ohio's ground water resources.

**Table 1.1 Potential Pollution Sources and the State Agency With Regulatory Authority**

| <b>POTENTIAL POLLUTION SOURCE</b>  | <b>REGULATORY AGENCY</b>   |
|--|--|
| Regulated Hazardous Waste Facilities   | Ohio EPA<br>Division of Hazardous Waste Management<br>(614) 644-2917   |
| Regulated Solid Waste Sites  | Ohio EPA<br>Division of Solid and Infectious Waste Management<br>(614) 644-2621  |
| Unregulated Hazardous Waste Pollution Sources & Voluntary Action Properties  | Ohio EPA<br>Division of Emergency & Remedial Response<br>(614) 644-2924  |
| Underground Injection Wells<br><br><ul style="list-style-type: none"> <li>•Class I &amp; V</li> <li>•Class IV (Prohibited)</li> </ul><br><br><ul style="list-style-type: none"> <li>•Class II &amp; III</li> </ul> | Ohio EPA<br>Division of Drinking and Ground Waters<br>Underground Injection Control Unit<br>(614) 644-2752<br><br>Ohio Department of Natural Resources (ODNR)<br>Division of Mineral Resources<br>614-265-6633 |
| Wastewater Facilities  | Ohio EPA, Division of Surface Water<br>(614) 644-2001  |
| Petroleum Underground Storage Tanks  | Ohio Department of Commerce<br>Division of State Fire Marshal<br>Bureau of Underground Storage Tank Regulation<br>(BUSTR) (614) 752-7938   |
| Spill Response   | Ohio EPA<br>Division of Emergency & Remedial Response<br>Emergency Response Special Investigation Section<br>(614) 644-2083  |
| Oil and Gas  | Ohio Department of Natural Resource (ODNR)<br>Division of Mineral Resources<br>(614) 265-6633  |

**Table 1.1 Potential Pollution Sources and the State Agency With Regulatory Authority**

| <b>POTENTIAL POLLUTION SOURCE</b>                   | <b>REGULATORY AGENCY</b>   |
|---|--|
| Mining Operations                                   | Ohio Department of Natural Resources (ODNR)<br>Division of Mineral Resources<br>(614) 265-6633 |
| Sewage Disposal (Household)                         | Ohio Department of Health<br>(614) 644-8562  |
| Application of Pesticides, Herbicides & Fertilizers | Ohio Department of Agriculture<br>Ohio Residence: 1-800-282-1955<br>All other: 614-728-6200    |

**TECHNICAL GUIDANCE MANUAL FOR HYDROGEOLOGIC  
INVESTIGATIONS AND GROUND WATER MONITORING**

**CHAPTER 2  
REGULATORY OVERVIEW**

**February 1995**

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## **CHAPTER 2**

### **REGULATORY OVERVIEW**

Hydrogeologic investigations and ground water monitoring are mandated by state and federal laws, rules, and regulations. These requirements often govern the siting, operation, and closure of waste management facilities or the remediation of contaminated sites. The purpose of this chapter is to summarize Ohio EPA's authority to require ground water monitoring and/or hydrogeologic investigations at hazardous waste, solid waste, and wastewater facilities and unregulated sites requiring corrective actions.

#### **REGULATED HAZARDOUS WASTE FACILITIES**

The Ohio EPA's Division of Hazardous Waste Management (DHWM) has exclusive responsibility for the supervision, regulation, and enforcement of regulated hazardous waste facilities. Ohio's program is based on Subtitle C of the Resource and Conservation and Recovery Act (RCRA) of 1976 and is revised regularly to reflect changes in federal regulations. Ohio's rules, located in Chapters 3745-49 through 3745-69 of the Ohio Administrative Code (OAC), are substantially equivalent to the federal regulations located in 40 CFR 260 to 270. Chapter 3745-51 of the OAC identifies those wastes that are subject to the rules.

The DHWM shares responsibility for permitting with the Ohio Hazardous Waste Facility Board (HWFB). The HWFB has responsibility for acting on applications for new facilities and modifications of existing facilities, while the DHWM has responsibility for acting on applications for revisions of existing facilities and permit renewals.

Facilities in Ohio can be categorized as follows: 1) Part A-permitted facilities that received a Hazardous Waste Installation and Operation Permit from the HWFB (commonly known as interim status facilities; this includes facilities that were in operation prior to October 9, 1980 and have applied for a permit pursuant to OAC 3745-50), 2) facilities that have received a Part B permit from the HWFB or Ohio EPA (known as permitted facilities), 3) facilities that qualified for a permit by rule under provisions found in OAC 3745-50-40(C), 4) illegal or unpermitted facilities (treatment, storage or disposal of hazardous waste occurred after enactment of RCRA), and 5) facilities operating under an exemption that have yet to receive a final action on their permit application. The following discussion identifies the major types of facilities for which ground water monitoring and/or hydrogeologic investigations are required.

#### **PART A FACILITIES (INTERIM STATUS)**

Until final administrative disposition of their permit applications, owners/operators of interim status and illegal, unpermitted hazardous waste surface impoundments, landfills, and land treatment units are required to implement a ground water monitoring program capable of determining their facility's impact on the underlying uppermost aquifer (OAC 3745-65-90 through 94). If any interim status facility does not receive a permit, it must be closed in a manner that complies with the standards found in OAC 3745-66-10 through 20. Ground water monitoring may be required to document that

standards have been met. If a facility cannot be "clean-closed," then it will have to be closed as a landfill and the owner/operator must comply with monitoring regulations contained in OAC 3745-65-90 through 94 [OAC 3745-68-10 (B) (2)].

## **PART B FACILITIES (PERMITTED)**

Owners/operators of permitted hazardous waste surface impoundments, landfills, waste piles, and land treatment units must conduct a ground water monitoring program capable of determining the facility's impact on the underlying uppermost aquifer (OAC 3745-54-90 through 99). Closures of permitted facilities that are not classified as surface impoundments, landfills, waste piles, or land treatment units (such as treatment and storage facilities) must meet the standards of Chapter 3745-55-10 through 20. If a unit cannot be clean-closed, it must be closed as a landfill and compliance with post-closure ground water monitoring requirements [OAC 3745-57-10 (B) (3)] must be documented.

## **CORRECTIVE ACTIONS**

Ground water corrective action is mandated by OAC 3745-55-01, which addresses contamination that has migrated from a permitted hazardous waste surface impoundment, landfill, waste pile, or land treatment facility.

The Hazardous and Solid Waste Amendments (HSWA) to RCRA were enacted on November 8, 1984. These amendments provide authority for U.S. EPA to require clean-up of releases from solid waste management units (SWMUs)<sup>1</sup>. One of the major provisions of these amendments is Section 3004(u), which requires corrective action for releases of hazardous waste or hazardous waste constituents from SWMUs at permitted treatment, storage, or disposal facilities (TSDs). The objective is to evaluate the nature and extent of any release and the measure(s) appropriate to protect human health and the environment. Permits may contain schedules of compliance when corrective action cannot be completed prior to issuance. Section 3004(v) authorizes U.S. EPA to require corrective action beyond the facility boundary. Section 3008(h) provides U.S. EPA with authority for facilities that are operating or that had operated under interim status. As of this date, the State of Ohio is not authorized to implement the corrective action provisions of the RCRA as amended by the HSWA. Ohio EPA currently serves as an agent of the U.S. EPA through mutual agreement.

According to the U.S. EPA, facilities subject to the HSWA encompass every TSD facility that had "interim status" within the federal definition of the term. The categories include: 1) those facilities for which owner/operators submitted a Part A application to the U.S. EPA subsequent to the effective date of the RCRA regulations that required any owner/operator who treated, disposed, stored, or accepted hazardous waste prior to November 1980 and requested to continue these

---

<sup>1</sup>A SWMU is defined as "Any discernible unit at which solid or hazardous wastes have been placed at any time, irrespective of whether the unit was intended for management of solid or hazardous waste. Such units include any area at which hazardous waste or hazardous waste constituents have been routinely and systematically released." (U.S.EPA, 1989)

practices to submit the application; 2) those facilities for which owners/operators submitted a Part A permit application, in the category above, yet did not choose to submit a Part B application for a TSD, deciding instead to remain as a "generator" only, storing for less than ninety days; and 3) those facilities that held interim status and have since closed or ceased operation. These types, whether in operation or not, are subject to corrective action because they held federal interim status at some point. The U.S. EPA has stated (Federal Register, Vol. 53, No. 122, June 24, 1988, p. 23981) that it does not have authority to compel Subtitle C corrective action at facilities classified as protective filers. This type of facility includes generators, transporters or recyclers that have filed Part A permit applications for treatment or storage as a precautionary measure only.

Finally, facilities that have operated or are operating without interim status may be subject to corrective action requirements. These facilities will be determined on a case-by-case basis as they are discovered, and will most likely be addressed through an enforcement action under Section 3008(h). The basis for application of 3008(h) to facilities without interim status is discussed in a December 16, 1985 internal memo to Regional Administrators (U.S.EPA, 1985).

## **SOLID WASTE LANDFILLS**

The Ohio EPA's Division of Solid and Infectious Waste Management (DSIWM) has regulatory authority over solid waste landfills. Municipal landfills must meet Ohio's approved Subtitle D-based rules, as amended in June 1994 (OAC Chapter 3745-27). The rules require that new landfill capacity be designed to incorporate state-of-the-art technology. This means starting with a site that has geologic characteristics that impede or restrict the movement of contaminants. These characteristics are enhanced by required engineering features. The rules detail siting criteria, leachate collection systems, surface water management systems, a cap system, ground water monitoring/corrective action criteria, operational criteria, closure criteria, post-closure criteria, and financial assurance requirements for closure and post-closure activities.

In 1992, Ohio formally recognized that seven types of industrial wastes do not need to be regulated as stringently as municipal solid waste. New rules (OAC Chapter 3745-30) went into effect on January 13, 1992. The wastes are termed "residual wastes" in this Chapter. The rules provide for four classes of landfills based on characterization of the specific waste streams. Class I residual waste landfills must meet the criteria for municipal solid waste landfills. Requirements for siting, design, operations, closure, and post-closure at Class II and Class III landfills are not as stringent as the corresponding Class I requirements. Class IV residual waste landfills need to meet minimal siting criteria and their owners are not required to perform ground water monitoring.

On June 1, 1994, Ohio promulgated separate rules (OAC 3745-29) for landfill facilities exclusively disposing of industrial solid waste not covered under the residual rules. These rules are similar to OAC 3745-27. While all municipal landfills in operation as of March 1, 1990 are subject to the ground water monitoring requirements of OAC 3745-27-10 as of June 1, 1994, not all facilities are subject to all of the provisions in the residual and industrial rules as of the rules' effective date. New landfills and expansions of existing landfills are under all of the residual and industrial rules. Existing

facilities are not evaluated under the siting or ground water monitoring provisions until a decision on a mandated permit to upgrade to Ohio's approved rules is issued. Ground water monitoring provisions are also required of existing facilities in an approved closure plan. Table 2.1 summarizes the regulatory citations for residual waste landfill Classes I, II, and III; municipal solid waste landfills; and industrial solid waste landfills relating to ground water monitoring, siting, corrective actions and hydrogeologic investigations.

**Table 2.1. Regulations for ground water monitoring and hydrogeologic investigations at solid waste landfills.**

| <b>REQUIREMENT</b>                      | <b>MUNICIPAL</b>       | <b>INDUSTRIAL</b>    | <b>CLASS I, II and III<br/>RESIDUAL</b> |
|---|------------------------|----------------------|---|
| General ground water monitoring program | OAC 3745-27-10         | OAC 3745-29-10       | OAC 3745-30-08                          |
| Hydrogeologic investigation report      | OAC 3745-27-06 (C) (2) | OAC 3745-29-06(C)(2) | OAC 3745-30-05 (C) (3)                  |
| Siting criteria                         | OAC 3745-27-07 (B)     | OAC 3745-29-07(H)    | OAC 3745-30-06 (B)                      |
| Corrective actions                      | OAC 3745-27-10 (F)     | OAC 3745-27-10(F)    | OAC 3745-30-08 (F)                      |

### **WASTEWATER FACILITIES**

The Ohio EPA's Division of Surface Water (DSW) has regulatory authority over facilities subject to Ohio's Clean Water Act (ORC 6111), including industrial and municipal wastewater treatment, non-toxic flyash, bottom ash, foundry sand, and coal pile runoff collection facilities. The Agency's Division of Environmental Financial Assistance (DEFA) provides loans for construction of municipal wastewater treatment facilities. State water pollution control regulations do not specify requirements for ground water monitoring. However, monitoring requirements for wastewater facilities are determined on a site-by-site basis, taking into account the location, engineering, and type of waste to be treated.

### **UNREGULATED HAZARDOUS WASTE SITES**

The Ohio EPA's Division of Emergency and Remedial Response (DERR) has authority over remedial activities conducted at unregulated hazardous waste sites. "Unregulated" sites are those where the treatment, storage, or disposal of hazardous waste occurred prior to the enactment of RCRA. Pursuant to the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) of 1980, and as amended by the Superfund Amendments and Reauthorization Act

(SARA) of 1986, the U.S.EPA promulgated regulations that describe the technical requirements of remedial projects. These regulations are known commonly as the National Contingency Plan (NCP) 40 CFR Part 300 et seq. Under Ohio law (ORC Sections 3734 and 6111), responsible parties may be required to conduct hydrogeologic investigations and install and sample monitoring wells as part of a remedial project to define the presence or extent of contamination or to monitor the progress of a selected remedy.

The Ohio General Assembly recently passed legislation, Sub. S.B 221, which creates a program under ORC 3746 to allow people to voluntarily clean up contaminated (hazardous substances and petroleum) property and receive a "Covenant Not to Sue" for the State of Ohio. Covenants will provide volunteers and subsequent property owners with civil liability protection from having to perform additional cleanup work. All Covenants will be conditioned on cleanups meeting applicable standards and remedies operating properly. An interim program began on September 28, 1994 that allows some volunteers to receive covenants prior to the adoption of final rules by Ohio EPA. The Agency is required to have the rules in place by September 28, 1995.

## **REFERENCES**

U.S.EPA. 1985. Internal Memo (12/16/85) to Regional Administrators. OSWER Directive 9502.1985(09). Office of Solid Waste and Emergency Response. Washington, DC.

U.S.EPA. 1989. RCRA Facility Investigation Guidance, Interim Final. EPA/540-SW-89-031. Office of Solid Waste and Emergency Response. Washington, DC.

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**CHAPTER 3  
CHARACTERIZATION OF SITE HYDROGEOLOGY**

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## CHAPTER 3

### CHARACTERIZATION OF SITE HYDROGEOLOGY

Investigations of existing or potential ground water pollution sources must include an adequate characterization of site hydrogeology. Typically, an evaluation must include a three-dimensional assessment of the underlying geologic materials and the movement of ground water within the materials. This information is needed to enable proper decisions and ensure adequate monitoring well network design.

The scope of an investigation should be based on regulatory requirements, technical objectives, and site-specific conditions. The following approach should be used:

- **Define the requirements and technical objectives.** The requirements and objectives are dictated by the regulatory program.
- **Perform a preliminary evaluation.** A preliminary evaluation is a comprehensive review of existing information, including regional and site-specific hydrogeologic data. The evaluation should be utilized to develop a preliminary conceptual model.
- **Collect site-specific geologic and ground water data.** The results of the preliminary evaluation, along with project requirements and technical objectives, should be utilized to design the first phase of a site-specific investigation. Information gathered can be utilized to refine the conceptual model and assist in developing additional phases, if needed. In general, the characterization is considered complete when enough information has been collected to satisfy regulatory requirements and the potential pathways for contaminant migration have been defined and characterized. Prior to performing any field work, it is important that a site safety plan be developed in accordance with the Occupational Safety and Health Administration (OSHA) requirements of 29 CFR 1910.120.

#### REQUIREMENTS AND TECHNICAL OBJECTIVES

An important first step is to define the information required. An entity may be investigating an existing or potential pollution source to: 1) determine if the hydrogeologic characteristics of the site are compatible with its intended use; 2) ascertain the impact of a past, existing, or proposed activity on the ground water resources of the region; and/or 3) provide a basis for a site clean-up program. Chapter 2 summarizes types of sites and facilities that are regulated by the Ohio EPA. Project requirements and objectives should be discussed with the appropriate Agency representative prior to initiating studies.

#### PRELIMINARY EVALUATIONS

Characterization should begin with a review of available regional and site-specific hydrogeologic information. Wastes or constituents of concern should also be investigated if information is

available. This preliminary evaluation should serve as the basis for the conceptual model and field investigation. Information that may be gathered includes, but is not limited to, the following:

- Logs from private, public, industrial, agricultural, or existing monitoring wells.
- Logs from building or quarry activities.
- Records documenting local influences on ground water flow and use (e.g., on- or off-site production wells, irrigation or agricultural use, river stage variations, and land use patterns, etc.).
- Geologic and ground water data obtained from various reports for the area or region.
- Topographic, geologic, soil, hydrogeologic, and geochemical maps and aerial photographs.
- A chronological site history with a description of processes, wastes, and raw materials managed.
- The structural integrity of waste and/or raw material management units and physical controls on waste migration from the units.
- The chemical composition and character of waste and/or raw materials contained in waste management units throughout their history, and those wastes expected to be contained in the future.

Information may be obtained from the sources listed below.

***Division of Water, Ground Water Resources Section, Ohio Department of Natural Resources*** (Fountain Square, Columbus, Ohio 43224-1387. Phone: 614-265-6717). The Ohio Department of Natural Resources (ODNR), Division of Water, Ground Water Resources Section, is responsible for the quantitative evaluation of ground water resources. Specific functions include ground water mapping, administration of Ohio's ground water well log and drilling report law, and special assistance to municipalities, industries, and the general public regarding local geology, well drilling and development, and quantitative problem assessment. Ground water availability maps have been published for most counties (Figure 3.1). Maps for other counties are planned. The Division's file of logs include records for water supply and monitoring wells. Other available information includes ground water reports and bulletins. The Division is involved in drafting pollution potential maps, which are now available for several counties (Figure 3.2). These maps can be used for general planning purposes.

***Soil Conservation Service, Department of Agriculture*** (State Office Tower, 200 North High Street, Columbus, Ohio 43017. Phone: 614-644-6932). The Soil Conservation Service has produced detailed soil maps for virtually all counties in Ohio (Figure 3.3). These maps illustrate major soil types and their agricultural and engineering attributes. Maps also are available through the ODNR, Division of Soil and Water Conservation.

**Division of Soil and Water Conservation, ODNR** (Fountain Square, Columbus, Ohio 43224-1387. Phone: 614-265-6610). The Division of Soil and Water Conservation, ODNR, has a variety of responsibilities, including performing investigations to determine soil characteristics, inventorying critical natural resource areas, and administering the Ohio Capabilities Analysis Program, which provides mapping and analysis concerning geology and ground water availability. Aerial photographs can be obtained from this Division (614-265-6770).

**Division of the Geological Survey, ODNR** (Fountain Square, Columbus, Ohio 43224-1387. Phone: 614-265-6576). The Division of the Geological Survey, ODNR, is responsible for the collection and dissemination of information relating to bedrock and surficial geology. Through mapping, core drilling, and seismic interpretation, the Survey compiles maps and inventories of bedrock and surficial materials and offers advice concerning mining-related issues. Published reports regarding bedrock and glacial geology are available for many counties. Additional information on bedrock geology is available from files of logs produced for oil and gas exploration. The USGS 7½ minute topographic maps are available from the Survey. These maps can provide basic information on spatial location of buildings (e.g., homes, schools, factories, etc.), roads and streams, surface elevations and topography, and general land use. The Survey is currently in the process of assembling 1:24,000 scale maps that display bedrock geology, structure, and topography.

**United States Geological Survey (USGS), Department of Interior** (6480 Double Tree Avenue, 43229-1111). The mission of the U.S.G.S., Water Resources Division is to provide the hydrologic information and understanding needed for the optimum utilization and management of the Nation's water resources for the overall benefit of the United States. A summary of the Survey's program in Ohio can be found in Open-File Report 93-458 (U.S.G.S., 1993). Responsibilities include collection of the basic data needed for determination and evaluation of the quantity, quality, and use of Ohio's water resources, conductance of analytical and interpretive water-resources appraisals describing the occurrence, availability, physical, chemical, and biological characteristics of surface water and precipitation, and implementation of similar appraisals associated with ground water. The U.S.G.S. publishes an annual series of reports titled "*Water Resources Data-Ohio, Volume 1 and 2*" in which the hydrologic data collected during each water year are presented.

**Ohio EPA** (Lazarus Government Center, P.O. Box 1049, 122 S. Front Street, Columbus, Ohio 43216-1049). Geologic or hydrogeologic information for a geographic area of concern can be obtained from Ohio EPA files if names of specific facilities/sites are known. Information on waste and/or material management history also can be obtained. Requests to conduct file searches need to be in writing and include site name, regulatory division, county, city, and address. The request should be addressed to the District Public Information Specialist (Figure 3.4). Requests for review of Central Office files should be addressed to Central Office, Legal Section (phone: 614-644-2037).

### **Figure 3.1: Production Status of the Ground Water Resources Mapping Program of Ohio.**

Map not included on this version of the Technical Guidance Document in order to reduce the size of the document. Please see the most current map on the Ohio Department of Natural Resources Web Page

ODNR: <http://www.dnr.state.oh.us> Go to the Division of Water, Publications, Maps of the Division

Direct Link to Availability Map: [http://www.dnr.state.oh.us/water/pubs/fs\\_div/fst10map.htm](http://www.dnr.state.oh.us/water/pubs/fs_div/fst10map.htm)

### **Figure 3.2 Availability of Pollution Potential Maps.**

Map not included on this version of the Technical Guidance Document in order to reduce the size of the document. Please see the most current map on the Ohio Department of Natural Resources Web Page

ODNR: <http://www.dnr.state.oh.us> Go to the Division of Water, Publications, Maps of the Division

Direct Link to Availability Map: [http://www.dnr.state.oh.us/water/pubs/fs\\_div/fsht09map.htm](http://www.dnr.state.oh.us/water/pubs/fs_div/fsht09map.htm)

### **Figure 3.3: Availability of Ohio Soil Surveys.**

Availability map not included on this version of the Technical Guidance Document in order to reduce the size of the document. Please go to the National Soil Survey Center for the most current information on Soil Survey availability.

National Soil Survey Center: <http://www.statlab.iastate.edu/soils/nsdaf/>



Figure 3.4

### CENTRAL & DISTRICT OFFICES

|  |  |   |
|--|--|---|
| <p><b>CDO</b> Central District Office<br/>3232 Alum Creek Drive<br/>Columbus, Ohio 43207-3417<br/>(614) 728-3778<br/>(614) 728-0160 FAX<br/>1-800-686-2330</p> | <p><b>NWDO</b> Northwest District Office<br/>347 North Dunbridge Road<br/>Bowling Green, Ohio 43402<br/>(419) 352-8461<br/>(419) 352-8468 FAX<br/>1-800-686-6930</p> | <p><b>SWDO</b> Southwest District Office<br/>401 East Fifth Street<br/>Dayton, Ohio 45402-2911<br/>(937) 285-6357<br/>(937) 285-6249 FAX<br/>1-800-686-8930</p> |
| <p><b>NEDO</b> Northeast District Office<br/>2110 E. Aurora Road<br/>Twinsburg, Ohio 44087<br/>(330) 963-1200<br/>(330) 963-4760 FAX<br/>1-800-686-6330</p>    | <p><b>SEDO</b> Southeast District Office<br/>2195 Front Street<br/>Logan, Ohio 43138<br/>(740) 385-8501<br/>(740) 385-6490 FAX<br/>1-800-686-7330</p>                | <p><b>CO</b> Central Office<br/>Lazarus Government Center<br/>122 South Front Street<br/>Columbus, Ohio 43215<br/>(614) 644-2752<br/>(614) 644-2909 FAX</p>     |

## CHARACTERIZATION OF SITE GEOLOGY

A proper evaluation of site geology should include, but not be limited to, identification of the lateral and vertical extent of subsurface materials, the type of materials, and the geological influences that may control ground water flow (e.g., high permeability zones, fractures, fault zones, fracture traces, buried stream deposits etc.). **Direct information** must be collected through borings, test pits, and field and laboratory identification of subsurface materials. **Indirect information** (e.g., geophysical data) can be used to augment the direct methods or to guide their implementation, but should not be used as a substitute.

### DIRECT TECHNIQUES

#### Borings

Site characterization must include a boring<sup>1</sup> program. The objectives are to collect data that reflect site conditions and to begin to refine the conceptual model derived during the preliminary evaluation.

In general, most programs should include collection of subsurface material samples using a coring device, split spoon sampler, thin wall sampler, and/or a continuous sampler. Detailed information pertaining to drilling and sampling is covered in Chapter 6.

The location and spacing of borings necessary is dependent upon subsurface complexity. In general, the density should be greater when characterizing geology that is more complex. Table 3.1 lists factors that should be considered. If existing data do not define site stratigraphy, additional boreholes and ancillary investigative techniques should be implemented. The number and placement of additional borings should be based on the preliminary conceptual model, refined with data obtained from the completed borings and other investigatory techniques. The locations of individual borings should depend on site hydrogeology, geomorphic features, spatial location of waste (or suspected waste), and anthropogenic (human-made) impediments such as underground utility lines. Boreholes should not be installed through waste material; however, in some instances this is unavoidable. Authorization from Ohio EPA is required before drilling through waste (ORC 3734.02(H))<sup>2</sup>.

The proper sampling interval and depth also depend on subsurface complexity. At a minimum, initial borings should be sampled continuously. Once control has been established, the continuous approach may no longer be necessary. It should be noted that the proper interval may not be constant and may depend on the target zone(s) of interest.

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<sup>1</sup>Borings not to be converted into wells must be properly abandoned (See Chapter 9).

<sup>2</sup>The Ohio Revised Code (ORC) states that: No person shall engage in filling, grading, excavating, building, drilling or mining on land where a hazardous waste facility, or solid waste facility was operated without prior authorization from the Director.

**Table 3.1. Factors influencing the spacing of boreholes (Modified from U.S. EPA, 1986d)**

| <p style="text-align: center;"><b>FACTORS THAT MAY SUBSTANTIATE REDUCED DENSITY OF BOREHOLES</b></p>   | <p style="text-align: center;"><b>FACTORS THAT MAY SUBSTANTIATE INCREASED DENSITY OF BOREHOLES</b></p>   |
|--|--|
| <ul style="list-style-type: none"> <li>• Simple geology (e.g., horizontal, homogeneous geologic strata that are continuous across site and unfractured) substantiated by site-specific and regional information</li> <li>• Use of geophysical data to correlate boring data</li> </ul> | <ul style="list-style-type: none"> <li>• Fractured zones encountered during drilling</li> <li>• Suspected pinchout zones (i.e., discontinuous units across the site)</li> <li>• Formations that are non-uniform in thickness</li> <li>• Suspected zones of high permeability that would not be defined by drilling at large intervals</li> <li>• Laterally and/or vertically transitional geologic units with irregular permeability (e.g., sedimentary facies changes)</li> </ul> |

Special precautions should be taken when drilling through a possible confining layer to ensure that the borehole does not create a pathway for the migration of contaminants, particularly dense non-aqueous phase liquids (DNAPLs). To properly penetrate a confining layer, initial borings should be performed in uncontaminated areas to characterize the lower units. Then, telescoped casing can be used to prevent cross-contamination (see Chapter 6).

**Test Pits and Trenches**

Pits and trenches may be cost-effective in characterizing shallow, unconsolidated materials and determining depth to shallow bedrock or a shallow water table. Fifteen feet is considered to be the most economical vertical limit of excavation. However, greater depths have been reached when conditions justify the expense (U.S. EPA, 1987). Depth is limited to a few feet below the water table. A pumping system may be necessary to control water levels.

Test pit/trench locations should be accurately surveyed with the dimensions noted. Field logs should contain a sketch of pit conditions, approximate surface elevation, depth, method of sample acquisition, soil and rock description, ground water levels, and other pertinent information such as waste material encountered or organic gas or methane levels (if monitored). Any significant features should be photographed (scale should be indicated).

Backfilling should be completed in a manner that prevents the pit/trench from acting as a conduit. One method is to use a soil-bentonite mixture prepared in proportions that represent a permeability equal to or less than original conditions. The material should be placed in a manner that prevents bridging and subsequent subsidence. Since proper sealing is difficult, pits/trenches should be limited to the vicinity of a proposed waste disposal site (i.e., within the area to be excavated) or adjacent to suspected areas of contamination.

Disadvantages of test pits/trenches include potential handling/disposal of contaminated soils (see Chapter 6), disruption of business activities, and safety hazards. If entry into excavations is necessary, several Occupational Safety and Health Administration (OSHA) regulations must be followed. The reader should refer to 29 CFR 1926, 29 CFR 1910.120, and 29 CFR 1910.134. A detailed description of test pit/trench programs can be found in a A Compendium of Superfund Field Operations Methods: Volume 1 (U.S. EPA, 1987).

## **Description and Classification of Unconsolidated Materials**

Both laboratory and field testing are necessary for an accurate description of unconsolidated materials. Characteristics that are discussed in this section include particle size, moisture content, color, plasticity and consistency, and classification. A discussion on permeability/hydraulic conductivity and porosity can be found in the section of this chapter entitled "Characterization of Ground Water Occurrence." Effort must be made to ensure quality and consistency in field descriptions.

Other physical properties that may be useful include dry strength, dilatancy, toughness, and cementation. Criteria for describing these are given in ASTM 2488-90 (1992). If the goal of an investigation is to determine if material will attenuate contaminant migration, bulk density, cation exchange capacity, soil pH, and mineral content may need to be determined. Table 3.2 gives references and analytical methods for these parameters.

### ***Particle Size***

Sedimentary deposits are classified broadly into gravel, sand, silt, and clay. Particle size generally is determined in the field by visual observation and in the laboratory by sieve analysis (particles larger than 75 micrometers) or use of a hydrometer (particles less than 75 micrometers) (ASTM 422-63).

### ***Moisture Content***

Relative moisture content should be determined in the field, with the material classified as dry, moist, or wet. Table 3.3 recommends general criteria (ASTM D2488-90). The actual moisture content is the ratio of the weight of water to the total weight of solid particles. It is critical when determining the adequacy of a lining material or conducting vadose zone monitoring and, in some cases, when designing remedial methods.

Laboratory methods include thermo (ASTM D2216-90, D4959-89), gravimetric, chemical extraction, mechanical extraction (ASTM D1557-91), and immersion and penetration (ASTM 3017-88). Field methods include electromagnetic, electrothermal, and nuclear. Detailed procedures and discussions are available in the literature (Morrison, 1983). The procedures should be evaluated to determine which is most appropriate for any particular situation.

**Table 3.2 Additional physical properties used to characterize subsurface materials.**

| <b>PARAMETER/PROPERTY</b>   | <b>USED TO DETERMINE</b>  | <b>METHODOLOGY</b>                                    |
|---|---|---|
| Soil bulk density   | <ul style="list-style-type: none"> <li>• Estimate of porosity</li> <li>• Characteristics of contaminants</li> </ul>                 | ASTM D2167-84<br>ASTM D1556-90                        |
| Atterberg Limits  | <ul style="list-style-type: none"> <li>• Soil cohesiveness</li> <li>• Classification of soils</li> </ul>                            | ASTM D427-93<br>ASTM D4318-84<br>ASTM D4943-89        |
| Cation exchange capacity  | <ul style="list-style-type: none"> <li>• Attenuation properties of soils</li> </ul>   | SW846, Methods 9080 and 9081 (U.S. EPA, 1986a & b)    |
| Organic carbon content  | <ul style="list-style-type: none"> <li>• Attenuation properties, contaminant mobility, and time required for cleanup</li> </ul>     | SW846, Method 9060 (U.S. EPA, 1986g)                  |
| Soil pH   | <ul style="list-style-type: none"> <li>• pH effect on sorption capacity</li> <li>• Soil-waste compatibility</li> </ul>              | SW846, Method 9045 (U.S. EPA, 1986f)<br>ASTM D4972-89 |
| Mineral content   | <ul style="list-style-type: none"> <li>• Attenuation capacity and type of clays</li> <li>• Chemical compatibility</li> </ul>        | Petrographic analysis, X-ray diffraction              |
| Specific gravity and density  | <ul style="list-style-type: none"> <li>• Estimate of porosity</li> <li>• Phase relationship between air, water, and soil</li> </ul> | ASTM D2937-83<br>ASTM D854-91                         |
| Infiltration  | <ul style="list-style-type: none"> <li>• Evaluation of surface covers</li> <li>• Water mass balance</li> </ul>                      | ASTM D3385-88   |
| Evapotranspiration  | <ul style="list-style-type: none"> <li>• Infiltration rates</li> </ul>  | US EPA, 1992  |
| General References: Jury, W.A. (1986); Black, C.A. (1965 a & b); and Annual Book of ASTM Standards. |   |   |

**Table 3.3 Criteria for describing moisture content (ASTM D2488-90).**

| <b>DESCRIPTION</b> | <b>CRITERIA</b>   |
|--------------------|---|
| dry                | absence of moisture, dry to the touch                     |
| moist              | damp, no visible water                                    |
| wet                | visible free water, usually soil is below the water table |

## Color

Color can help identify materials of similar origin. Many minerals are light gray, but soils can often be red, yellow, brown, or black. Color changes can indicate contamination, although variations also can be caused by natural conditions such as changes in the amount of organic matter content. Mottling may indicate impeded drainage or a seasonal high water table. Brown colorization can indicate oxidizing conditions (above the water table), while gray can indicate a reducing environment (below the water table). The identification should be standardized by use of a color chart for two reasons: 1) a color often is described differently by different persons, and 2) a given color appears differently when seen next to other colors (e.g., gray can appear bluish when next to orange or brown earth colors) (Compton, 1985).

## Consistency and Plasticity

Consistency is the relative ease with which soil can be deformed. It can be determined by blow counts from split-spoon sampling<sup>3</sup> or with a pocket penetrometer. If a penetrometer is not available, consistency can be approximated according to Table 3.4.

**Table 3.4 Criteria for describing consistency (ASTM-2488-90).**

| DESCRIPTION | CRITERIA   |
|-------------|--|
| Very Soft   | Thumb will penetrate soil more than 1 in. (25 mm)              |
| Soft        | Thumb will penetrate soil about 1 in. (25 mm)                  |
| Firm        | Thumb will indent soil about 1/4 in. (6 mm)                    |
| Hard        | Thumb will not indent soil but readily indented with thumbnail |
| Very hard   | Thumbnail will not indent soil                                 |

Plasticity is the property of soil or rock that allows it to be deformed beyond the point of recovery without cracking or exhibiting appreciable change in volume. The relative plasticity can be estimated in the field by using Table 3.5.

Plasticity and consistency also can be described by Atterberg Limits. Atterberg Limits are defined as indices of workability or firmness of an artificial mixture of soil and water as affected by water content (Holtz and Kovacs, 1981). The indices include the liquid limit, plastic limit, and the plastic index. The liquid limit (upper plastic limit) is the point at which soil becomes semi-fluid. The plastic limit (or lower plastic limit) is the water content at which soil begins to crumble when rolled into a thread (i.e., lower limit to which it can be deformed without cracking). The plastic index is the difference between the liquid limit and the plastic limit and is an indication of plasticity. Atterberg

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<sup>3</sup>A standard split spoon sampler is driven by a 140 lb hammer falling 30 inches. The number of blows required to drive the sampler 6 inches is the standard penetration resistance or blow counts, N.

Limits are used widely in soil classification systems and for evaluation of clay liners. They can be determined by ASTM Methods D4318-84, D4943-89, and D427-83.

**Table 3.5 Criteria for describing plasticity (ASTM-2488-90).**

| DESCRIPTION | CRITERIA   |
|-------------|--|
| Nonplastic  | A 1/2-in. (13-mm) thread cannot be rolled at any water content.  |
| Low         | The thread can barely be rolled and the lump cannot be formed when drier than the plastic limit.   |
| Medium      | The thread is easy to roll and not much time is required to reach the plastic limit. The thread cannot be rerolled after reaching the plastic limit. The lump crumbles when drier than the plastic limit.                          |
| High        | It takes considerable time rolling and kneading to reach the plastic limit. The thread can be rerolled several times after reaching the plastic limit. The lump can be formed without crumbling when drier than the plastic limit. |

### ***Fracturing***

Fractures are breaks in geologic material due to structural stress. As they play an important role in the movement of water through subsurface materials, their existence needs to be determined. Fractures can be observed during the boring and soil sampling program. Angled borings may be helpful in locating vertical fractures.

It should be noted that fractures can be induced from drilling and coring. It is difficult to distinguish between natural and induced occurrences. Often, natural fractures show signs of oxidation or secondary mineral growth. However, the absence of those features does not necessarily imply inducement. Information concerning natural versus induced fractures in rock cores has been provided by Kulander et al. (1990).

### ***Classification***

Unconsolidated materials should be classified both by field and laboratory analysis. A sufficient number of samples from each stratigraphic zone should be analyzed in the laboratory as a check for proper field classification. It is recommended that ASTM Methods 2488-90 and 2487-90, which are based on the Unified Soil Classification System, be utilized in the field and laboratory, respectively. The system is widely used and enables the grouping or classification of soils with similar characteristics and properties. At a minimum, field classification should include:

- Particle size, including identification of the major and minor components using descriptive terms such as trace, little, some, and mostly (see Table 3.6).
- Color.

- Moisture content.
- Plasticity.
- Consistency.

Other methods can be used as long as the system is identified, described adequately, and used consistently. At a minimum, the method should account for all particle sizes encountered, color, relative moisture content, and consistency. If possible, the sedimentary environment should be identified. In general, unconsolidated sediments within Ohio can be described as glacial, lacustrine, fluvial, colluvial, residual, or eolian.

**Table 3.6. Relative percentage of particles by visual observation (ASTM D2488).**

| <b>PARTICLE AMOUNT</b> | <b>PERCENTAGE</b> |
|------------------------|-------------------|
| trace                  | less than 5 %     |
| few                    | 5 to 10 %         |
| little                 | 15-25%            |
| some                   | 30 to 45 %        |
| mostly                 | 50 to 100 %       |

### **Description and Classification of Consolidated Materials**

The uppermost consolidated units (bedrock) in Ohio are sedimentary and generally consist of carbonate rock, sandstone, shale or coal that ranges in age from Ordovician to Permian. Distinctive characteristics that are influential with respect to ground water movement include porosity, permeability, fracturing, and bedding. Porosity and hydraulic conductivity measurements are discussed later in this chapter. Fractures can be identified by a boring program and fracture trace analysis. Bedding plane spacing, strike, and dip should be indicated. Prominent bedding planes should be distinguished from banding due to color or textural variation. An attempt should be made to determine the formation name to assess regional characteristics.

The competence of the consolidated materials can be described by the Rock Quality Designation (RQD). The RQD is calculated by measuring the total length of all competent core pieces greater than four or more inches, dividing it by the length of the core run, and multiplying by 100. In general, the higher the RQD, the higher the integrity. Table 3.7 lists RQD and a description of rock quality (Davis et al., 1991).

**Table 3.7 RQD**

| <b>RQD</b> | <b>Description of Rock Quality</b> |
|------------|------------------------------------|
| 0-25       | Very Poor                          |
| 50         | Poor                               |
| 75         | Fair                               |
| 90         | Good                               |
| 100        | Excellent                          |

## **SUPPLEMENTAL TECHNIQUES**

Supplemental techniques such as geophysics, cone penetration tests, and aerial imagery can be used to help guide and implement a boring program and assist in defining site geology. Use of these techniques can be cost-effective, as they may reduce the number of borings necessary.

### **Geophysics**

Geophysics may be used either to augment direct field methods or to help guide their implementation. Surface geophysical techniques can provide information on depth to bedrock, types and thicknesses of geologic material, presence of fracture zones and solution channels, structural discontinuities, and depth to the water table. Borehole geophysical methods may indicate areas of high porosity and hydraulic conductivity, ground water flow rates and direction, subsurface stratigraphy, lithology of bedrock units, and chemical and physical characteristics of ground water (Repa and Kufs, 1985). Chapter 11 discusses techniques that may be useful.

### **Cone Penetration Tests**

Cone penetration testing (CPT) is applicable where formations are uncemented and unlithified; free from impenetrable obstructions such as rock ledges, hardpans, caliche layers, and boulders; and conducive to penetration with minimal stress to the testing equipment (Smolley and Kappmeyer, 1991). The technique consists of advancing a mechanical or electronic rod to determine the end-bearing and side friction components of resistance to penetration (ASTM D3441-86). These two parameters typically are different for coarse-grained and clayey soils, making the CPT a particularly useful tool for defining and correlating the occurrence of sands and gravels versus clays and silts (Smolley and Kappmeyer, 1991).

The use of cone and friction-cone penetrometers, both mechanical and electrical type, is addressed by ASTM Method D 3441-86 . The mechanical penetrometer operates incrementally using a telescoping tip, which results in no movement of the push rod. Design constraints for a mechanical penetrometer preclude a complete separation of the end-bearing and side components. Electric penetrometers advance continuously and permit separation. Differences in shape and method of

advancement between tips may result in significant differences in one or more resistance components.

At sites where the technique is applicable, CPT surveys can provide a continuous vertical profile of subsurface stratigraphy and indications of permeability. In all cases, the data must be compared with information from borings and geologic material sampling. Use and interpretation of penetrometer data was discussed by Robertson and Campanella (1986). The use of CPT is limited by the availability of equipment and contractors.

## **Aerial Imagery**

Aerial imagery can be used to help: 1) identify rock and surface soil types, geomorphological features, and the nature and extent of joint and fault patterns; 2) approximate stream flow, evapotranspiration, infiltration, and runoff values; and 3) map topographic features such as streams, seeps, and other surface waters not readily apparent from ground level (Repa and Kufs, 1985). Comparing old and new topographic maps and aerial photographs can help ascertain changes over time such as those caused by cut and fill activities, drainage alteration, and land use (Benson, 1991). Contaminant plumes may be located by vegetative stress. Aerial photographs may be obtained from the ODNR, Division of Soil and Water Conservation (614-265-6670) or from the U.S. Department of Agriculture, Agriculture Stabilization and Conservation Service (ASCS) offices in each county.

Fracture trace analysis can help locate fractures. Fracture traces are surface expressions of joint concentrations or faults. On aerial photos, natural linear features appear as tonal variation in soils, alignment of vegetative patterns, straight stream segments or valleys, alignment of surface depressions, gaps in ridges, or other features showing linear orientation (Fetter, 1994). Valley and stream segments tend to run along fractures and joints because these zones are more susceptible to erosion. Alignment of sinkholes or surface sags are typical surface expressions in areas of carbonate bedrock.

## **CHARACTERIZATION OF GROUND WATER OCCURRENCE**

Geologic findings should be augmented by ground water information to ascertain the nature of flow and occurrence at a site. Necessary determinations include zones that may restrict or enhance ground water movement, including depth, thickness, and lateral and vertical extent; flow direction, including temporal and seasonal fluctuations; flow rate; interconnection to surface water; and human-induced influences. The intent of this section is to explain the minimum characteristics necessary. Direct techniques such as installation of monitoring wells and piezometers are always necessary. Textbooks that can be consulted for additional information include Fetter (1994), Todd (1980), and Freeze and Cherry (1979).

Regulatory requirements may dictate the nature of the investigation for facility siting and ground water monitoring. For example, some regulations, such as those governing solid waste sites, mandate that an owner/operator define an uppermost aquifer system and demonstrate that it is protected adequately before a landfill can be permitted. Additionally, these regulations specify that

significant saturated zones above the uppermost aquifer system must be identified and monitored.

## PATHWAYS AND CONFINING LAYERS

Pathways for ground water and contaminant movement and zones that restrict movement must be identified and characterized. Preferential pathways typically include sands, gravels, fractured material, or coal beds. Thick, continuous layers of unfractured clay, fine silt or shale may retard flow.

The subsurface can be classified into unsaturated (vadose) and saturated (phreatic) zones. In the **unsaturated zone**, both water and air occur in the pores. In the **saturated zone**, the pores are filled with water. Ground water in the saturated zone can occur under confined or unconfined conditions. A **confined zone** is bounded by relatively impermeable layers. Water levels in wells completed in a confined zone rise above the base of an upper confining layer. These levels define an imaginary surface called the potentiometric or piezometric surface. A zone that has a water table as its upper boundary is termed **unconfined**. "Water table" is defined as a surface where hydrostatic pressure equals atmospheric pressure. In general, most water-bearing zones are not entirely confined or unconfined and often are referred to as **leaky or semi-confined**. Identifying confining conditions is important in selecting the appropriate hydraulic test for determining hydraulic conductivity and predicting ground water vulnerability. Unconfined zones are at greater risk of contamination from surface activities than confined zones.

A special case of an unconfined zone is a **perched water table**, which may develop when a relatively impervious layer of limited horizontal area (e.g., clay lens) is located between the water table and the ground surface. Ground water accumulates above this impervious layer. Perched zones may drain into an underlying zone or may be permanent. Permanent zones may serve as a supply of drinking water.

In general, identification of potential pathways and materials that may restrict flow is accomplished by evaluating drilling and subsurface sampling information, ground water level measurements, and data from hydraulic tests. In addition to the geologic criteria discussed earlier in this chapter, the field investigator should note and document the following:

- Depth to water and vertical extent of the water-bearing zone.
- Observations made during drilling, such as advancement rates and water loss.
- Depth, location, and identification of any contaminant encountered.

It also may be necessary to identify where ground water discharges to surface water via springs or baseflow to rivers, streams, or lakes. If ground water is contaminated, it may affect surface water quality over a wide area.

## FLOW DIRECTION

Since ground water flows in the direction of decreasing head, horizontal and vertical components of flow direction and gradient can be determined by acquisition and interpretation of water level data obtained from monitoring wells and piezometers. Water levels should be measured against mean sea level or a fixed reference marker to an accuracy of between 0.01 and 0.1 foot using an

appropriate device (see Chapter 10). The precision should depend on the slope of the potentiometric surface or water table and the distance between measuring points. Greater precision is necessary where the slope is gradual or wells/piezometers are close together (Dalton et al., 1991).

In newly installed wells, water levels should be allowed to stabilize for at least 24 hours after development before measurement. Additional time (e.g., 1 week) may be necessary for low-yielding wells. All measurements should be taken prior to purging and sampling and within a 24 hour period or less to insure a single "snapshot" of current conditions. Shorter intervals are necessary where a zone is affected by river stage, bank storage, impoundments, unlined ditches, pumping of production and irrigation wells, and recent precipitation. Values may need to be corrected to account for external effects. Generally, the data should represent near steady-state conditions.

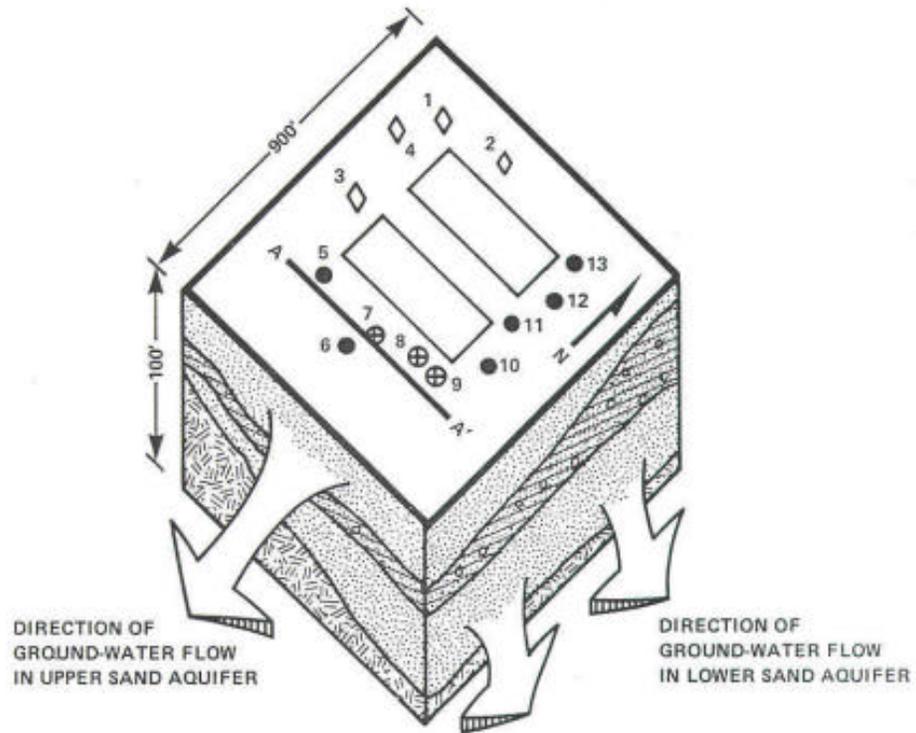
For the purpose of determining total head, piezometer and monitoring well screens should not exceed ten feet in length. The head measured in a well is the integrated average of any heads that occur over the entire length of the screened interval; therefore, care should be taken when interpreting data collected from wells or piezometers with screens greater than ten feet. It is recognized that circumstances such as natural fluctuations may necessitate longer screens; however, they should never intercept hydraulically separate zones.

Meters have been developed to measure flow direction in monitoring wells and borings. These instruments may be useful in placing wells; however, the meters generally indicate a very local situation that is subject to change. In addition, accurate measurements are dependent on choice of screen, method of installation, measurement procedures and data handling (Kerfoot, 1988). Flow meters cannot replace ground water elevation evaluations.

## **Horizontal Component**

The horizontal component of flow direction can be different for each discrete zone. Figure 3.5 shows an example of a site characterized by multiple flow paths with different horizontal components. Since ground water moves in the direction of decreasing head, the horizontal component can be determined by measuring the water level in piezometers/monitoring wells screened in a discrete water-bearing zone and constructing a contour map of the water table or potentiometric surface. The data used to develop water table maps should be obtained from piezometers or wells screened across the water table surface. Potentiometric surface maps are constructed from data gathered at the same position in the same hydrostratigraphic unit. Erroneous flow directions can be interpreted when wells are not completed in the same unit or cross more than one saturated zone.

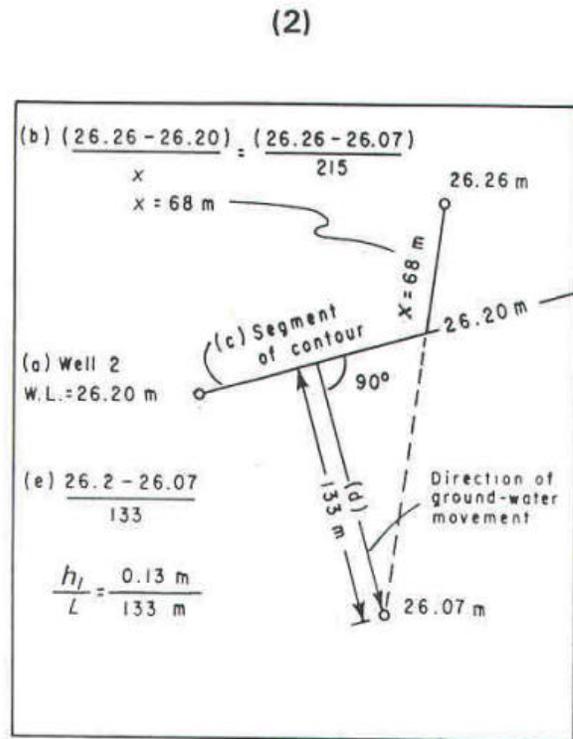
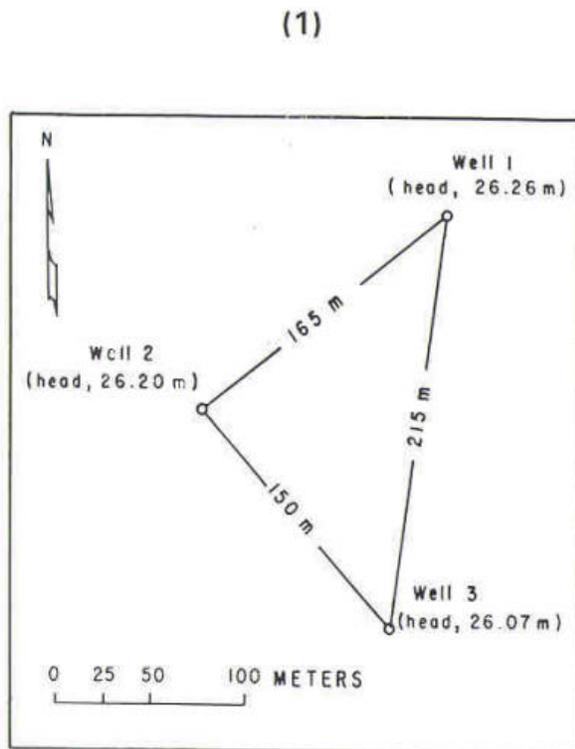
At a minimum, three measuring points are required to determine the horizontal component. The direction and gradient can be determined by conducting a three point problem (Figure 3.6). For isotropic zones, hydraulic conductivity is equal in all directions and flow is parallel to hydraulic gradient; therefore, flow lines can be constructed perpendicular to the equipotential lines if isotropism can be assumed. Anisotropic zones exhibit hydraulic conductivity that is not equal in all directions. Under such conditions, the flow lines may not be parallel, and thus may cross the



| LEGEND |                              |
|--------|------------------------------|
| ◇      | UPGRADIENT MONITORING WELL   |
| ●      | DOWNGRADIENT MONITORING WELL |
| ⊕      | MONITORING WELL CLUSTER      |
|        | SAND                         |
|        | GLACIAL TILL                 |
|        | GRANITE                      |

equipotential lines obliquely (Fetter, 1994). The terms "isotropic," "anisotropic," and "hydraulic conductivity" are discussed later in this chapter.

**Figure 3.5** Illustration of multiple ground water flow paths in the uppermost aquifer due to hydrogeologic heterogeneity (U.S. EPA, 1986d).



Both the direction of ground-water movement and the hydraulic gradient can be determined if the following data are available for three wells located in any triangular arrangement such as that shown on sketch 1:

1. The relative geographic position of the wells.
2. The distance between wells.
3. The total head at each well.

Steps in the solution are outlined below and illustrated in sketch (2):

- a. Identify the well that has the intermediate water level (that is, neither the highest head nor the lowest head).
- b. Calculate the position between the well having the highest head and the well having the lowest head at which the head is the same as that in the intermediate well.

- c. Draw a straight line between the intermediate well and the point identified in step b as being between the well having the highest head and that having the lowest head. The line represents a segment of the water level contour along which the total head is the same as that in the intermediate well.
- d. Draw a line perpendicular to the water level contour and through either the well with the highest head or the well with the lowest head. The line parallels the direction of ground water movement.
- e. Divide the difference between the head of the well and that of the contour by the distance between the well and the contour. The answer is the hydraulic gradient.

**Figure 3.6 Estimation of flow direction and gradient by a 3-point problem (Heath, 1984).**

Use of three measuring points is appropriate only if a site is relatively small and the configuration of the water table or potentiometric surface is planar (Dalton et al., 1991). Lateral variations in hydraulic conductivity, localized recharge and drainage patterns, and other factors can cause the configuration to be non-planar. For example, Figure 3.7 shows a site where leakage from a buried pipe has caused ground water mounding. Here, measurements from a three-well array would not be sufficient to detect the mound, and could result in a faulty assessment of flow direction (Dalton et al., 1991). Also, a ground water divide may be present that would not be detected with only a minimal number of measuring points. For large sites, it is recommended that at least 6 to 9 measuring points be utilized to provide a preliminary estimate of flow direction within a target area. After several sets of data are collected and analyzed, the need for additional wells/piezometers can be evaluated.

### **Vertical Component and Interconnectivity**

In addition to considering the horizontal component of flow, an investigation and/or monitoring program must accurately and directly assess the vertical component and the interconnection between saturated zones. Gradient and the relative direction of the vertical component are determined by comparing water level measurements in well/piezometer clusters. In general, interconnection can be determined by pumping a lower zone and monitoring changes in water levels measured in zones above the pumped zone. The number of wells, pumping rate, length of tests, and method of data evaluation is dependent on site conditions. The design of pumping tests and available conceptual models are discussed in Chapter 4.

Another technique to help in the determination of hydraulic connection between zones is to compare their water quality. As ground water flows, it assumes a diagnostic composition as a result of interaction with subsurface materials (Fetter, 1994). It is important to note that within each zone, natural changes in water quality also occur with increasing contact time. Interconnectivity may also be observed by correlation of water levels with recharge events and use of environmental tracers.

### **Seasonal and Temporal Effects**

Regulated entities must identify and assess factors that may result in short- or long-term variation in ground water levels and flow direction. There may be more than one mechanism operating simultaneously. Table 3.8 provides a summary of the factors, which are classified according to whether they are natural or human-induced; whether they produce fluctuations in confined or unconfined zones; and whether they are short-lived, diurnal, seasonal, or long-term. These phenomena have been discussed in detail by Freeze and Cherry (1979).

Continued monitoring and evaluation of ground water levels are necessary to detect changes in the flow regime. At a minimum, quarterly measurements should be made to assess seasonal effects. More frequent determinations may be necessary to assess diurnal, short-lived, and human-induced effects. Multiple years of data collection may be necessary to evaluate seasonal effects.

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**Figure 3.7 Estimation of ground water flow direction using a three point problem and a nine-well array. In this situation, three wells provides insufficient information** (Source: Acquisition and Interpretation of Water-Level Data by M.G. Dalton, B.E. Huntsman, and K. Bradbury, *Practical Handbook of Ground-Water Monitoring*, edited by David M. Nielsen, Copyright © 1991; by Lewis Publishers, an imprint of CRC Press, Boca Raton, Florida. With permission).

**Table 3.8 Summary of mechanisms that lead to fluctuation in ground water levels (modified from Freeze and Cherry, 1979).**

|  | Uncon-fined | Confined | Natural | Man-in-duced | Short-lived | Diurnal | Sea-sonal | Long-term | Climatic Influence |
|--|-------------|----------|---------|--------------|-------------|---------|-----------|-----------|--------------------|
| Ground water recharge (infiltration to the water table)        | X           |          | X       |              |             |         | X         |           | X                  |
| Air entrapment during ground water recharge                    | X           |          | X       |              | X           |         |           |           | X                  |
| Evapotranspiration and phreatophytic consumption               | X           |          | X       |              |             | X       | X         |           | X                  |
| Bank-storage effect near streams                               | X           |          | X       |              |             |         | X         |           | X                  |
| Tidal effects near oceans                                      | X           | X        | X       |              |             | X       |           |           |                    |
| Atmospheric pressure effects                                   | X           | X        | X       |              |             | X       |           |           | X                  |
| External loading of confined aquifers                          |             | X        |         | X            | X           |         |           |           |                    |
| Earthquakes  |             | X        | X       |              | X           |         |           |           |                    |
| Ground water pumpage   | X           | X        |         | X            |             |         |           | X         |                    |
| Deep-well injection  |             | X        |         | X            |             |         |           | X         |                    |
| Artificial recharge; leakage from ponds, lagoons and landfills | X           |          |         | X            |             |         |           | X         |                    |
| Agricultural irrigation and drainage                           | X           |          |         | X            |             |         |           | X         | X                  |
| Geotechnical drainage of open pit mines, tunnels, etc.         | X           |          |         | X            |             |         |           | X         |                    |

## FLOW RATE

In general, ground water flow rate can be determined mathematically based on site-specific parameters. The following equation, derived from Darcy's law, generally is utilized:

$$V = \frac{K \frac{dh}{dl}}{n_e}$$

where:  
V = mean ground water particle velocity (L/T)  
K = hydraulic conductivity (L/T)  
dh/dl = hydraulic gradient (L/L)  
n<sub>e</sub> = effective porosity (unitless)

As shown, velocity is proportional to hydraulic gradient and hydraulic conductivity and inversely proportional to effective porosity. Situations in which the derived equation may not apply include systems where: 1) ground water flows through materials with low hydraulic conductivity under an extremely low gradient; 2) large amounts of water pass through conduits, thus possibly causing the flow to be turbulent (Freeze and Cherry, 1979). In fractured rock, interconnected discontinuities are considered to be the main passage for fluid flow. In general, two approaches might be followed when dealing with flow through fractured rocks: continuum or discontinuum. The continuum approach assumes that the fracture mass is hydraulically equivalent to a porous medium; thus Darcy's Law as developed can be applied. If continuum conditions do not exist, the flow must be described in relation to individual fractures or fracture sets. The concept for flow in fractures is further developed in Freeze and Cherry (1979) and Domenico and Schwartz (1990). Determination of hydraulic gradient, porosity, and hydraulic conductivity is discussed below.

### Hydraulic Gradient

Hydraulic gradient is the total change in head with change in distance in the direction of flow. The gradient generally is analogous to the slope of the potentiometric or water table surface. Vertical components within a formation can be determined by comparing heads in well/piezometer clusters screened in that zone. Vertical gradients between zones can be determined if hydraulic connection exists.

A given site could exhibit different horizontal and/or vertical gradients depending on where measurements are taken. Hydraulic gradients should be provided as a range.

### Porosity/Effective Porosity

Porosity is the ratio of openings to the total volume of rock and soil. Since ground water moves and is stored within pores and fractures, porosity is important in describing flow and characterizing the quantity of contaminants that can be stored. Not all of the porosity is available for flow. Part will be occupied by static fluids being held to the soil/rock by surface tension or contained in dead end pore spaces. Effective porosity (n<sub>e</sub>) refers to the amount of interconnected pore space available for transmitting water. Effective porosity should not be confused with specific yield, total porosity, or gravity drainage. Use of any of these parameters as an estimate or substitute for n<sub>e</sub> may affect the flow velocity calculations. In some cases, however, such as for coarse-grained soils, the use of gravity-drainable porosity or specific yield may be acceptable.

Effective porosity is difficult to measure and is typically selected by experience and intuition. In some cases, a knowledge of total porosity, determined from lab tests or estimated from the literature, may be helpful. The site-specific nature of the material can be used to estimate the degree to which effective and total values differ. Tables 3.9 and 3.10 provide data that might be useful to this estimation.

For unfractured glacial till, it is recommended that 30 percent be used for  $n_e$  in velocity calculations<sup>4</sup>. While a default value of one percent has been cited for clay (U.S. EPA, 1986c), this value results in high rates that are intuitively incorrect. Primary flow through clay is known to be very low. The basis of the one percent citation is specific yield determinations (Sara, 1994); however, laboratory column breakthrough tests done by Golder Associates (1990) indicated  $n_e$  for till ranging from 0.26 to 0.35.

This range compares favorably with the value for clays reported by Rawls et al. (1983) (Table 3.9). Ohio EPA's regulatory experience indicates that use of 30 percent results in very conservative estimates of ground water movement through unfractured glacial till. In several instances, radiometric dating techniques have consistently shown flow to be significantly slower than the computed rate.

If Darcy's Law is being used to compute velocity through a fractured medium<sup>5</sup>, it should be noted that an effective porosity value that differs markedly from the total may need to be used. In these, instances,  $n_e$  may need to be established through detailed field investigations.

## Hydraulic Conductivity

Hydraulic conductivity<sup>6</sup> (K) is a coefficient of proportionality describing the ease at which water can move through a permeable medium and is often expressed in units of length per time. The K of geologic materials can vary from 1 to  $1 \times 10^{-13}$  m/s. Generally, finer-grained materials are characterized by lower values. Materials that contain a broad range of grain sizes (e.g., glacial till) typically exhibit values lower than deposits with uniform grain size (e.g., beach sands) (Sevee, 1991).

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<sup>4</sup>It should be noted that the applicability of Darcy's law to calculating primary flow velocity in fine-grained material is questionable. However, this currently is one of the best available tools to assist professionals in evaluating whether a confining unit provides protection to the underlying ground water. To further demonstrate that ground water has not/will not be affected by a potential contaminant source, other methods such as isotope dating are necessary.

<sup>5</sup>As indicated earlier in this chapter, Darcy's Law may not apply to fracture flow in some situations.

<sup>6</sup>In many engineering texts, hydraulic conductivity is also known as the coefficient of permeability; as a result, the two terms are used interchangeably (Sevee, 1991).

**Table 3.9 Porosity and Effective Porosity of Common Soils (Rawls et al., 1983)<sup>a</sup>**

| Texture         | Mean Total Porosity | Mean Effective Porosity |
|-----------------|---------------------|-------------------------|
| Sand            | 0.437               | 0.417                   |
| Loamy Sand      | 0.437               | 0.401                   |
| Sandy Loam      | 0.453               | 0.412                   |
| Loam            | 0.463               | 0.434                   |
| Silt Loam       | 0.501               | 0.486                   |
| Sandy Clay Loam | 0.398               | 0.330                   |
| Clay Loam       | 0.464               | 0.309                   |
| Silty Clay Loam | 0.471               | 0.432                   |
| Sandy Clay      | 0.430               | 0.321                   |
| Silty Clay      | 0.479               | 0.423                   |
| Clay            | 0.475               | 0.385                   |

<sup>a</sup> Based on published data for approximately 1200 soils (5,000 horizons) from 34 states.

**Table 3.10 Range of percentage of porosity for various geologic materials.**

| GEOLOGIC MATERIALS | BOUWER (1978) | TODD (1980) | FETTER (1994) | FREEZE AND CHERRY (1979) | SEVEE (1991) |
|--------------------|---------------|-------------|---------------|--------------------------|--------------|
| gravel, mixed      | 20-30         |             |               | 25-40                    | 25-40        |
| gravel, coarse     |               | 28          |               |                          |              |
| gravel, medium     |               | 32          |               |                          |              |
| gravel, fine       |               | 34          |               |                          |              |
| sand, mixed        | 25-50         |             |               | 25-50                    | 15-48        |
| sand, coarse       | 25-35         | 39          |               |                          |              |
| sand, medium       | 35-40         | 39          |               |                          |              |
| sand, fine         | 40-50         | 42          |               |                          |              |
| sand & gravel      | 10-30         |             | 20-35         |                          |              |
| silt               | 50-60         | 46          | 35-50         | 35-50                    | 35-50        |
| clay               | 50-60         | 42          | 33-60         | 40-70                    | 40-70        |
| glacial till       | 25-40         | 31-34       | 10-20         |                          |              |
| limestone          | 10-20         | 30          |               | 0-20                     | 0-20         |
| karst limestone    |               |             |               | 5-50                     | 5-50         |
| shale              |               | 6           |               | 0-10                     | 0-10         |
| sandstone          | 5-30          | 33-37       |               | 5-30                     | 5-40         |

The determination of K is important not only as a parameter for determination of flow rate, but as a means for describing and comparing different units. A saturated zone may be described as either homogenous or heterogeneous and either isotropic or anisotropic according to the variability of K in space. A zone is **homogeneous** if K is independent of location, and is **heterogeneous** if it is dependent on location. If K is independent of the direction of measurement, the zone is **isotropic**. If it varies with the direction of measurement, the zone is **anisotropic**. Anisotropy typically is the result of small-scale stratification such as bedding of sedimentary deposits and/or fractures. In bedded deposits, K is typically highest in the direction parallel to bedding and smallest perpendicular to bedding. In general, K can be several orders of magnitude higher horizontally than vertically.

Horizontal and vertical K should be determined for each discrete zone. The variation of K as a function of vertical position within each formation should be identified because such variations can create irregularities in ground water flow paths and rates.

Several techniques exist for determining the K of geologic material. These include initial estimation, laboratory determination, and field tests. In general, the field is favored over the laboratory because results represent in-situ conditions. However, laboratory analysis may be sufficient for ascertaining vertical K. The appropriate application for each technique is discussed below.

### **Estimation**

Several methods exist to estimate K from engineering and geologic descriptions and from correlations between these properties and several commonly measured soil parameters (Dawson and Istok, 1991). However, estimation should be used only initially to help determine the most appropriate field technique. Values can be estimated by comparison of material to similar materials for which a value has been established. Figure 3.8 shows typical ranges. It must be noted that estimates for a specific geologic material can vary over several orders of magnitude (Dawson and Istok, 1991).

Values for K also can be inferred from the grain-size distribution of an unconsolidated material. Hazen (1911) empirically related effective particle size to K such that:

$$K = C(D_{10})^2$$

where:

- K = hydraulic conductivity in cm/sec.
- D<sub>10</sub> = particle size (measured in mm) below which ten percent of the cumulative sample has a smaller size.
- C = constant ranging from 1 to 1.2 depending on the gradation of the sand.

This formula was developed for estimating the K of sand filters; therefore, use generally is limited to uniformly-graded sands. Other methods, such as the one developed by Fair and Hatch (1933), employ the entire grain size distribution curve. Techniques using soil index properties also have been developed (Dawson and Istok, 1991; Alyomini and Sen, 1993).

### Hydraulic Conductivity of Selected Rocks

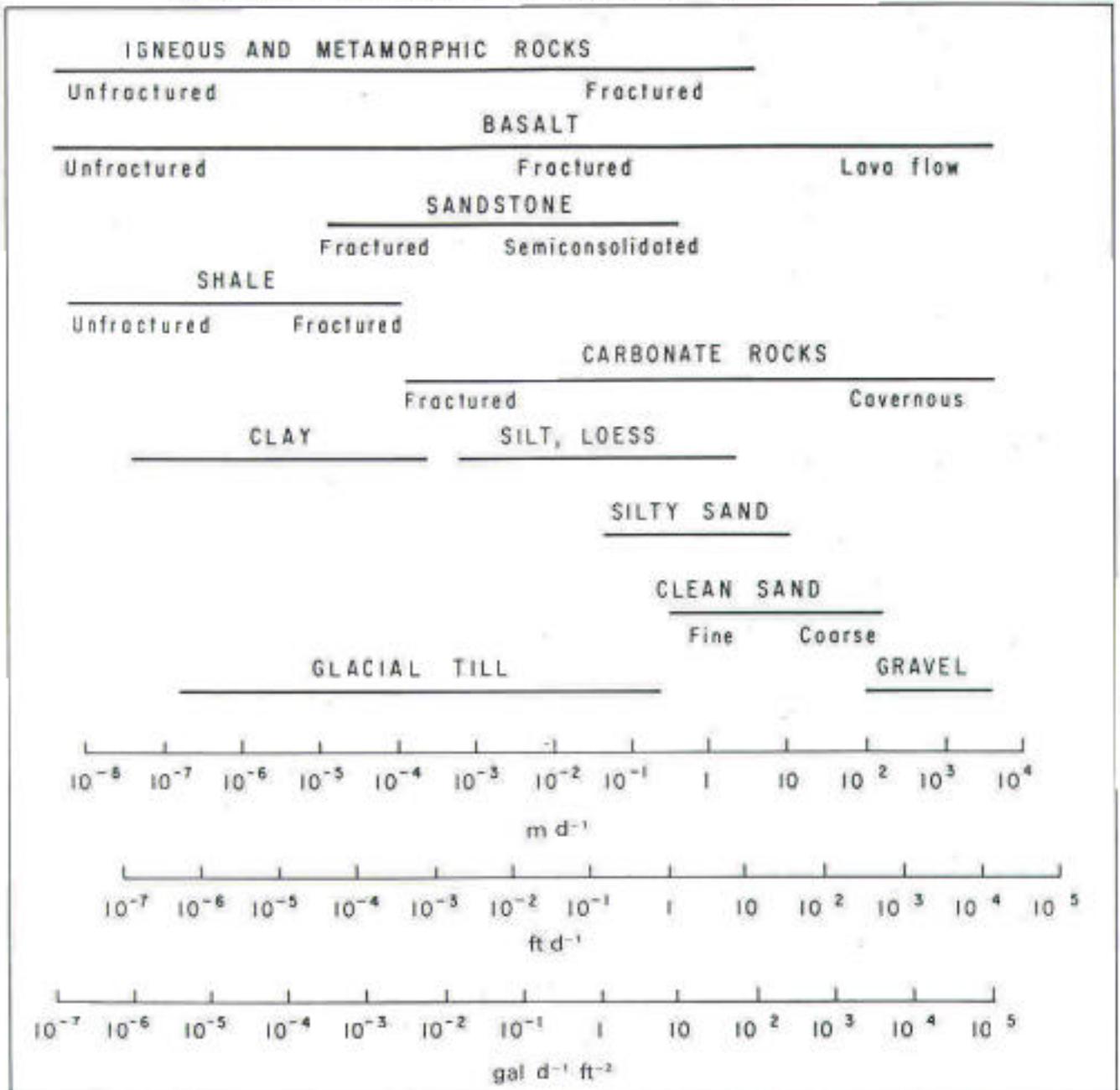


Figure 3.8 Hydraulic conductivity of selected geologic materials (Heath, 1984).

## **Laboratory Tests**

Laboratory tests are particularly useful in evaluating vertical K. In general, this parameter is used to determine the confining capabilities of a unit or the useability of materials as a liner.

Lab tests should be performed on undisturbed samples<sup>7</sup>. Unconsolidated samples should be collected with a thin wall sampler and consolidated samples should be collected by core drilling. The falling-head and constant head methods are commonly used to determine K. Both tests involve moving water through a specimen under the influence of gravity. For a **constant head test**, in-flow fluid level is maintained at a constant head and the outflow rate is measured as a function of time. This test generally is applicable for materials with K ranging from  $10^{-3}$  to  $10^{-1}$  cm/sec (Sevee, 1991). It may be used for fine-grained materials; however, test times may be prohibitively long. With the **falling-head test**, the rate of fall of water level in a tube is monitored. This method is applicable for materials with K ranging from  $10^{-7}$  to  $10^{-3}$  cm/sec (Sevee, 1991). Other lab techniques exist and are based on the same principles as falling and constant head tests. Table 3.11 summarizes the methods and their applications (Repa and Kufs, 1985).

When conducting laboratory tests, potential sources of error must be recognized. It is difficult to collect undisturbed samples during drilling, especially in cohesionless soil and fractured rock. Sample disruption can occur during transfer from the core barrel or sampling tube to the testing apparatus (Dawson and Istok, 1991). Secondary porosity features, such as fractures, bedding planes, and cavities, are seldom represented intact and in proper proportion to the rest of the sample. As a result, laboratory and field studies can produce significantly different results. Table 3.12 lists some potential sources of error and the effect they have on lab-calculated K (Repa and Kufs, 1985). If possible, remolding of samples should be avoided. Olson and Daniel (1981) provided a more detailed explanation of sources of error and methods to minimize them.

## **Field Tests**

Values for K must be determined using field methods. In-situ testing may involve removing, adding, or displacing a known volume of water from a well/piezometer or borehole and monitoring the changes in water level with time. In general, these methods can be divided into single well tests and those requiring use of a pumping or injection well in conjunction with observation wells. The results of in-situ testing are highly dependent on the design, construction, and development of the test well and if appropriate, the observation wells. Newly installed wells or piezometers should be designed and developed properly to ensure that the results reflect hydrogeologic conditions. However, it should be noted that wells designed specifically for hydraulic testing may not need to be designed as stringently as wells installed for water quality monitoring. Detailed discussions of monitoring well design and development can be found in Chapters 7 and 8. Slug and pumping tests are covered in Chapter 4.

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<sup>7</sup>Samples are collected such that disturbance to the sample is minimized. Chapter 6 describes techniques and tools for sample collection.

**Table 3.11 Laboratory methods for determining K (modified from Repa and Kufs, 1985).**

| METHOD  | APPLICATION   | MATHEMATICS                                  | REFERENCES                             |                                       |                                       |                      |  |                    |   |                                     |                               |   |  |
|---|---|--|--|---------------------------------------|---------------------------------------|----------------------|--|--------------------|---|-------------------------------------|-------------------------------|---|--|
| Constant head   | <ul style="list-style-type: none"> <li>• Best for samples with high K (i.e., coarse grained)</li> <li>• Can be used with fine grained samples but test times may be prohibitively long</li> </ul> | $K = QL_s/h_sA_s$                            | ASTM-2434-68<br>ASTM 5084-90, Method A |                                       |                                       |                      |  |                    |   |                                     |                               |   |  |
| Falling head  | <ul style="list-style-type: none"> <li>• Any soil type</li> <li>• Best suited to materials having a low K</li> </ul>  | $K = (2.3 A_p L_s / A_s t) \log (h_i / h_e)$ | ASTM 5084-90<br>Methods B&C            |                                       |                                       |                      |  |                    |   |                                     |                               |   |  |
| Constant rate of flow   | <ul style="list-style-type: none"> <li>• Any soil type</li> <li>• Best suited for fine-grained soils</li> </ul>   | $K = QL_s/h_sA_s$                            | ASTM 5084-90 Method D                  |                                       |                                       |                      |  |                    |   |                                     |                               |   |  |
| Triaxial cell   | <ul style="list-style-type: none"> <li>• Any soil type</li> <li>• Especially suited for fine-grained, compacted cohesive soils in which full fluid saturation is difficult to achieve</li> </ul>  | $K = QL_s/h_sA_s$                            | Repa and Kufs (1985)                   |                                       |                                       |                      |  |                    |   |                                     |                               |   |  |
| Pressure-chamber  | <ul style="list-style-type: none"> <li>• Any soil type</li> <li>• Remolded samples</li> </ul>   | $K = (2.3 A_p L_s / A_s t) \log (h_i / h_e)$ | Repa and Kufs (1985)                   |                                       |                                       |                      |  |                    |   |                                     |                               |   |  |
| <p>where:</p> <table> <tr> <td>t = time for head level decline (day)</td> <td><math>h_s</math> = fluid head across sample (ft)</td> </tr> <tr> <td><math>h_i</math> = initial head</td> <td><math>A_s</math> = cross-sectional area of sample</td> </tr> <tr> <td><math>h_e</math> = final head</td> <td><math>A_p</math> = cross sectional area of stand pipe (ft<sup>2</sup>)</td> </tr> <tr> <td>K = hydraulic conductivity (ft/day)</td> <td><math>L_s</math> = length of sample (ft)</td> </tr> <tr> <td>Q = outflow rate (ft<sup>3</sup>/day)</td> <td></td> </tr> </table> |   |  |  | t = time for head level decline (day) | $h_s$ = fluid head across sample (ft) | $h_i$ = initial head | $A_s$ = cross-sectional area of sample | $h_e$ = final head | $A_p$ = cross sectional area of stand pipe (ft <sup>2</sup> ) | K = hydraulic conductivity (ft/day) | $L_s$ = length of sample (ft) | Q = outflow rate (ft <sup>3</sup> /day) |  |
| t = time for head level decline (day)   | $h_s$ = fluid head across sample (ft)   |  |  |                                       |                                       |                      |  |                    |   |                                     |                               |   |  |
| $h_i$ = initial head  | $A_s$ = cross-sectional area of sample  |  |  |                                       |                                       |                      |  |                    |   |                                     |                               |   |  |
| $h_e$ = final head  | $A_p$ = cross sectional area of stand pipe (ft <sup>2</sup> )   |  |  |                                       |                                       |                      |  |                    |   |                                     |                               |   |  |
| K = hydraulic conductivity (ft/day)   | $L_s$ = length of sample (ft)   |  |  |                                       |                                       |                      |  |                    |   |                                     |                               |   |  |
| Q = outflow rate (ft <sup>3</sup> /day)   |   |  |  |                                       |                                       |                      |  |                    |   |                                     |                               |   |  |
| <p><b>Other references for laboratory K: Olson and Daniel (1981); U.S. EPA (1986e)</b></p>  |   |  |  |                                       |                                       |                      |  |                    |   |                                     |                               |   |  |

**Table 3.12. Effects of various types of errors on laboratory-measured values of K (U.S. EPA, 1986e).**

| SOURCE OF ERROR   | MEASURED K  |
|---|-------------|
| Voids formed in sample preparation  | High        |
| Smear zone formed during trimming   | Low         |
| Use of distilled water as a permeant  | Low         |
| Air in sample   | Low         |
| Growth of microorganisms  | Low         |
| Use of excessive hydraulic gradient   | Low or High |
| Use of temperatures other than the test temperature   | Varies      |
| Ignoring volume change caused by stress change (confining pressure not used)  | High        |
| Performing laboratory rather than in-situ tests   | Usually low |
| Impedance caused by the test apparatus, including the resistance of the screen or porous stone used to support the sample | Low         |

## OTHER PARAMETERS

Several other parameters may be useful for characterizing the ability of geologic materials to transmit or store ground water. Often, these parameters are used as inputs to models that assist in characterizing hydrogeology and contaminant transport.

### Transmissivity

Transmissivity is the amount of water that can be transmitted horizontally by the full saturated thickness of a zone. For confined zones, transmissivity is equal to the product of the thickness of the zone (b) and its K:

$$T = K (b)$$

This equation applies to unconfined units if b is considered to be the saturated thickness or the height of the water table above the top of an underlying confining unit. Field methods for calculating K often involve determining T and then calculating a value with the above equation.

## **Storage Coefficient, Specific Storage, And Specific Yield**

Storage coefficient (also called storativity) is a dimensionless number that represents the water that a formation releases or absorbs from storage per unit surface area per unit change in head. The storativity of a confined zone is defined as that volume of water released from (or added to) a vertical column of formation of unit horizontal cross-section per unit of decline (or rise) in the piezometric head (Bear, 1972). The storativity of a confined unit is caused by the compressibility of the water and mineral framework and is the product of the specific storage and the thickness. Specific storage is defined by Fetter (1988) as the amount of water per unit volume of a saturated formation that is stored or expelled from storage owing to the compressibility of the mineral skeleton and the pore water per unit change in head. Specific storage has the dimensions of 1/length and generally is less than .0001 foot. Storativity for confined aquifers generally is on the order of 0.005 or less. Storativity of an unconfined unit is essentially the same except that the decline is in the water table surface; however, the mechanisms causing the variation in the quantity of water stored in a column are different. With unconfined zones, water is drained out of pore space, and air is substituted as the water table drops. The water that is drained by gravity is often referred to as specific yield and the water retained against gravity is called specific retention (Bear, 1972). The specific yield of most alluvial saturated zones falls between 10 and 25% (Bear, 1972). Storativity and specific yield can be determined by pumping tests, which are described in Chapter 4.

## **Saturated Zone Yield**

Saturated zone yield generally can be defined as the maximum sustained quantity of water supplied over a period of time to a properly constructed well. The yield can be determined by conducting a pumping test.

## **ENVIRONMENTAL AND INJECTED TRACERS**

A tracer is matter or energy carried by ground water that will provide information concerning the direction and movement of water and potential contaminants that may be transported (Davis et al., 1985). Tracers can be naturally-occurring, such as heat carried by hot-spring waters; globally-produced from anthropogenic sources, such as an above-ground detonation test; or intentionally injected<sup>8</sup>, such as dyes. Naturally-occurring and globally-produced types often are referred to as environmental tracers. If sufficient information is collected, tracers may be used to determine K, porosity, dispersivity, chemical distribution coefficients, ground water flow rate, sources of recharge and ground water age.

A tracer should have a number of properties to be useful. It should be non-reactive, relatively inexpensive, and easily sampled, analyzed, and detected. Any injected tracer should be non-toxic and should be used with careful consideration of possible health considerations. Table 3.12 summarizes various tracers.

---

<sup>8</sup>If fluids are injected into the subsurface, a Class V well operating permit may be required. Ohio EPA, Division of Drinking and Ground Waters, Underground Injection Control Unit (UIC) has jurisdiction over review and issuance of these permits. Under certain conditions, it may be possible to apply for and receive an exemption from the formal permitting process for injection wells used for hydraulic testing. If you have any questions concerning Class V wells, please contact the Ohio EPA-DDAGW, UIC unit.

No ideal tracer exists. The complexities of natural systems together with the use criteria for tracers makes selection and use almost as much of an art as it is a science (U.S.EPA, 1991). The potential chemical and physical behavior of the tracer in the ground water must be understood. The type of medium and flow regime should also be considered.

Isotopes, which are atoms of the same element that differ in mass because of a difference in the number of neutrons in the nucleus, serve as valuable tracers. The naturally-occurring elements give rise to more than 1,000 stable and radioactive isotopes, commonly referred to as environmental isotopes. These can be used to identify the origin of ground water, determine its age (i.e., length of time it has been out of contact with the atmosphere), and determine if saturated zones are interconnected. This can be important when trying to determine how long it may take a potential contaminant to reach an aquifer or receptor. Isotopes that are commonly used include tritium, carbon 14, chlorine 36, and isotopes of oxygen.

It is beyond the scope of this document to detail the proper use, selection, and design of tracer tests. Two sources include Davis et al. (1985) and Alley (1993).

## **PRESENTATION OF HYDROGEOLOGIC INFORMATION**

After field investigations, the hydrogeologic data should be analyzed and interpreted. To demonstrate that a site has been adequately characterized and proper procedures have been utilized, the data, methodologies and interpretations should be presented in a report. Components of the report should include, but should not be limited to, a written description, raw data, maps, cross sections, and methodology. Any applicable regulations/rules should be consulted to determine if specific content and format are required.

### **WRITTEN DESCRIPTION**

A narrative description of the geology and nature and occurrence of ground water should include, at a minimum:

- An evaluation of regional hydrogeology that includes depth to bedrock, characteristics of the major stratigraphic units, average yield of water wells within a one mile radius (logs for wells within one mile also should be submitted<sup>9</sup>), approximate direction of ground water flow, identification and estimation of the amount of recharge and discharge, geomorphology, and structural geology.
- An accurate classification and description of the consolidated and unconsolidated materials at the site from the ground surface down to the base of the lowest saturated zone of concern. This may include:
  - Hydraulic conductivity (vertical and horizontal).

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<sup>9</sup>The radial distance may be specified by program requirements. For example, some CERCLA projects may need a 4 mile radius.

- Rock and soil types.
- Thickness and lateral extent of units.
- Porosity/effective porosity and bulk density.
- Moisture content.
- The attenuation capacity and mechanism of natural earth materials (such as ion exchange capacity, organic carbon content, mineral content, soil sorptive capacity, storage capacity, pH).
- A site-specific description of structural geology and geomorphology.
- A site-specific description of the occurrence of ground water at the site, including:
  - Identification of saturated zones, including depth and lateral and vertical extent.
  - Identification of zones of high K that may act as preferential pathways.
  - Identification of zones of low K that may act as barriers to contaminants.
  - Ground water flow direction and rates (including sample calculations).
  - Effects of stratification on saturated and unsaturated flow.
  - Description of the interconnection between saturated zones and surface water.
  - Description of recharge and discharge areas.
  - Fluctuations in ground water levels and their effects on flow direction.
- Description of the relationship of the proposed/existing waste management unit to ground water occurrence and site geology.

## RAW DATA

All raw data collected during the hydrogeologic investigation should be included in the report. This should include, but not be limited to:

- **Boring/Geologic Logs:** Logs should be provided for all borings. They should be complete technical records of conditions encountered and should include results of laboratory analyses, field identifications, descriptive text, and graphics. Depths/heights should be recorded in fractions (tenths). Logs should be uniform and legible for potential reproduction and submission and should contain, at a minimum, the following information:
  - Site name and site-specific coordinates.
  - The name of the responsible party, the driller, and the on-site
  - Method of drilling.
  - Boring identification number and coordinates.
  - Date started, date completed, and date abandoned or converted into
  - Depth of boring.
  - Surface elevation based on Mean Sea Level (MSL) or fixed reference

- Method and location of all in-situ sampling.
  - Condition of samples, percent recovery, blow counts, moisture content,
  - Materials classification, both field and laboratory.
  - Depth to water, water-bearing zones and laboratory permeability
  - Color and/or stains.
  - Presence of structural features, such as fractures, solution cavities, or
  - Drilling observations, such as loss of circulation, rig chatter, and
- **Well Construction Logs:** Construction logs should be provided for all wells and piezometers used to obtain water level measurements and ground water samples. Information that should be included is listed in Chapter 7. Logs for all wells installed during a hydrogeologic investigation must be submitted to the ODNR, Division of Water. Figure 3.10 shows the prescribed form.
  - **Ground Water Elevation Measurements:** All ground water elevations should be submitted in tabulated form.
  - **Field Test Data:** Raw data from in-situ hydraulic tests should be submitted with a report. General information that should be submitted is provided in Chapter 4.

## CROSS SECTIONS

An adequate number of cross-sections should be provided. Various orientations (e.g., in direction of ground water flow and orthogonal to ground water flow) should be used. Each cross-section should depict, at a minimum:

- Depth, thickness, classification, and hydraulic characteristics of each unit.
- Water table and/or potentiometric surface.
- Structures such as zones of fracturing or channeling that influence water movement.
- Zones of higher K that may influence ground water flow.
- Zones of lower K that may restrict and/or attenuate ground water flow.
- Location and depth of each boring and/or monitoring well screen.
- Orientation of cross-section and horizontal and vertical scales.
- Location of proposed or existing waste management areas.
- Legend.

## MAPS

The following maps may assist in demonstrating site hydrogeology:

- A **surface topography map** depicting (at a minimum) streams, wetlands, depressions, and springs. The map should be constructed by a qualified professional and should provide contour intervals at a level of detail appropriate for the investigation (e.g., two-foot intervals). The map should depict the location of all borings, monitoring wells, and cross-sections. Employment of a conventional or photogrammetric survey company that develops topographic maps by obtaining aerial data often is necessary. Aerial data can

be supplemented by data obtained from stereoscopic maps, wetland inventory maps, U.S.G.S. topographic maps, etc.

- A **detailed facility map** depicting anthropogenic features, including property lines (with owners of adjacent properties clearly marked), location of all potential contaminant disposal areas, buildings, and utility lines.
- **Ground water elevation contour maps** for each zone of concern, with actual measurements at each well/piezometer. Contour lines within the area represented by the data should be represented with a solid line. Any interpretation outside the area should be represented with a dotted or dashed line. An explanation of flow direction and a justification of the extrapolation of flow outside the area defined by the data points should be included in the narrative portion of the report. Flow direction also should be depicted on the contour maps.

## **METHODOLOGY**

The methodology used to evaluate site hydrogeology should be described. This includes, but may not be limited to:

- Number, location, and depth of borings and monitoring wells or piezometers.
- Information on well and piezometer construction and development.
- The procedures and methods used to characterize soil and rock samples.
- The procedures and rationale used to define saturated zones and potential confining units.
- A description and rationale for use of indirect methods such as geophysics.

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**TECHNICAL GUIDANCE MANUAL FOR HYDROGEOLOGIC  
INVESTIGATIONS AND GROUND WATER MONITORING**

**CHAPTER 4  
SLUG AND PUMPING TESTS**

**February 1995**

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## CHAPTER 4

### SLUG AND PUMPING TESTS

Slug and pumping tests are used to determine in-situ properties of water-bearing formations and define the overall hydrogeologic regime. Such tests can determine transmissivity (T), hydraulic conductivity (K), storativity (S), connection between saturated zones, identification of boundary conditions, and the cone of influence of a pumping well in a ground water extraction system. To enable proper test design, it is important to define objectives and understand site hydrogeology as much as possible. Methods, instruments, and operating procedures should be specified in a workplan. The results of tests, methods, and any departures from the work plan that were necessary during implementation should be documented in a report.

This chapter covers various types of tests, including single well and multiple well. Their advantages and disadvantages and the minimum criteria that should be considered prior to, during, and after implementation are summarized. It is beyond the scope of this document to address all details on test design and analysis; therefore, additional sources have been referenced.

#### SINGLE WELL TESTS

A single well test involves pumping, displacing, or adding water and measuring changes in water levels in the well. This type of test allows a rapid and economical calculation of K and T of the zone of interest at a single location. Single well tests also can determine response criteria for observation wells in multiple well pumping tests.

Single well tests should be conducted in properly designed and developed wells or piezometers. If development is inadequate, the presence of drilling mud filter cake (use of mud is not recommended) or the smearing of fine-grained material along the borehole wall may result in data that indicate an artificially low K. This may lead to underestimation of contaminant migration potential. Drilling methods, well design and installation, and well development are covered in Chapters 6, 7 and 8, respectively. The various types of tests are discussed briefly below. Additional information can be found in documents by Black (1978), Chirlin (1990), Dawson and Istok (1991), Kruseman and de Ridder (1991), and Lohman (1972).

#### SLUG TESTS

A slug test involves the abrupt removal, addition, or displacement of a known volume of water and the subsequent monitoring of changes in water level as equilibrium conditions return. The measurements are recorded and analyzed by one or more methods. The rate of water level change is a function of the K of the formation and the geometry of the well or screened interval.

Slug tests generally are conducted in formations that exhibit low K. They may not be appropriate in fractured rock or formations with T greater than 250 m<sup>2</sup>/day (2, 690 ft<sup>2</sup>/day) (Kruseman and de Ridder, 1991); however, in some instances, a vacuum or slug test conducted with a pressure transducer or electronic data logger may be warranted.

Hydraulic properties determined by slug tests are representative only of the material in the immediate vicinity of the well; therefore, slug tests should not be considered a substitute for conventional multiple well tests. Due to the localized nature of hydraulic response, the test may be affected by the properties of the well filter pack. Therefore, the results should be compared to known values for similar geologic media to determine if they are reasonable.

If slug tests are used, the designer should consider the amount of displaced water, design of the well, number of tests, method and frequency of water level measurements, and the method used to analyze the data.

### **Design of Well**

Well depth, length of screen, screen slot size and length, and distribution of the filter pack must be known and based on site-specific boring information in order for a well to be used as a valid observation point. For example, equations used in data analysis make use of the radii of the well and borehole. The nature of the materials comprising the screened interval (i.e., thickness, grain size, and porosity of the filter pack) also must be known.

### **Number of Tests**

Properties determined from slug tests at a single location are not very useful for site characterization unless they are compared with data from tests in other wells installed in the same zone. When conducted in large number, slug tests are valuable for determining subsurface heterogeneity and isotropy. The appropriate number depends on site hydrogeologic complexity.

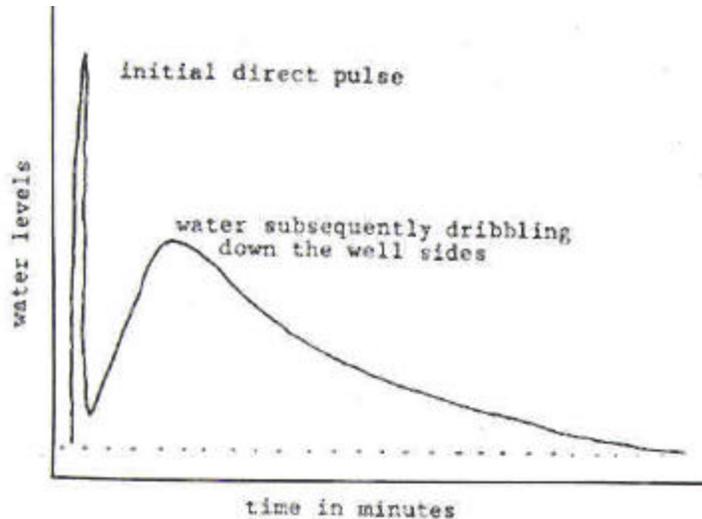
### **Test Performance and Data Collection**

Data collection should include establishment of water level trends prior to and following the application of the slug. Pre-test measurements should be made until any changes have stabilized and should be taken for a period of time, at least as long as the expected recovery period. Water level measurements in low-permeability zones may be taken with manual devices. Automatic data loggers should be used for tests of high permeability zones. Slug tests should be continued until at least 85-90 percent of the initial pre-test measurement is obtained (U.S. EPA, 1986).

Whenever possible, water should either be removed by bailing or it should be displaced by submerging a solid body. According to Black (1978), an addition of water invariably arrives as an initial direct pulse followed by a subsequent charge that runs down the sides of a well. This may result in a response that is not instantaneous, which may subsequently influence the data (Figure 4.1). An advantage of displacement is that it allows for collection and analysis of both slug injection and slug withdrawal data. However, slug injection tests should not be conducted in wells where the screened interval intercepts the water table.

The volume of water removed or displaced should be large enough to insure that build-up or drawdown can be measured adequately, but it should not result in significant changes in

saturated zone thickness (Dawson and Istok, 1991). It should be large enough to change water level by 10 to 50 centimeters (Kruseman and de Ridder, 1991). Field procedures for slug tests are also described in ASTM D 4044-91 (1992).



**Figure 4.1 Results of a slug test with addition of water. Water arrives as an initial direct pulse followed by a subsequent charge that runs down the sides of the well**  
 (Source: Adapted from Black, 1978).

### **Modified Slug Tests**

In addition to removal or displacement of water, a change in static water level can be accomplished by pressurizing a well with air or water or by creating a vacuum. Packers are often used to seal the zone to be tested.

### ***Packer Tests Within A Stable Borehole***

Horizontal K for consolidated rock can be determined by a packer test conducted in a stable borehole (Sevee, 1991). A single packer system can be used when testing between a packer and the bottom of the borehole (Figure 4.2A). Two packer systems can be utilized in a completed borehole at any position or interval (Figure 4.2B). A packer is inflated using water or gas. Water should be injected for a given length of time to test the packed-off zone.

### ***Pressure Tests***

A pulse or a pressure test may be appropriate in formations where K can be assumed to be lower than  $10^{-7}$  cm/sec. In a pulse test, an increment of pressure is applied into a packed zone. The decay of pressure is monitored over a period of time using pressure transducers with electronic data loggers or strip-chart recorders. The rate of decay is related to the K and S of the formation being tested. This test generally is applied in rock formations characterized by low K. Compensation must be made for skin effects<sup>1</sup> and packer adjustments during the test. An understanding of the presence and orientation of fractures is necessary to select an appropriate type curve to analyze test data (Sevee, 1991).

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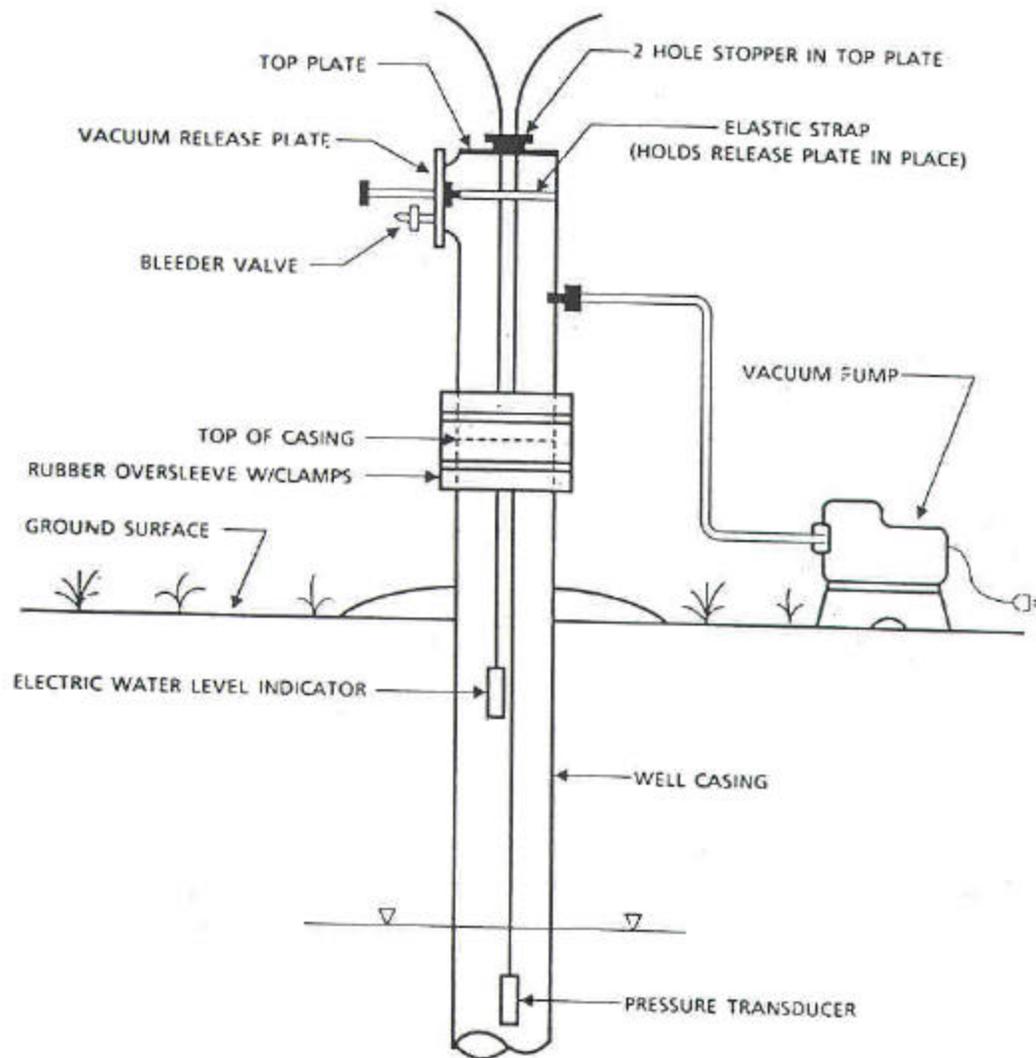
<sup>1</sup>Skin effects result from locally increasing the K near the well by opening fractures (positive skin) or decreasing the K (negative skin) by filling voids or coating borehole walls with drilling cuttings (Sevee, 1991).

## ***Vacuum Tests***

According to Orient et al. (1987), vacuum tests can be used to evaluate the K of glacial deposits and compare favorably to more conventional methods. Figure 4.3 shows typical test design. In general, water level is raised by inducing vacuum conditions. Once it reaches the desired height and sufficient time has been allowed for the formation to return to its previous hydrostatic equilibrium, the vacuum is broken and the recovery is monitored. The data is evaluated using the same techniques that are used to evaluate conventional slug test data.

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**Figure 4.2 In-Situ packer testing. A - Single packer system, test conducted during drilling. B - Double packer system, test conducted after borehole is complete** (Source: Design and Installation of Ground Water Monitoring Wells by D.M. Nielsen and R. Schalla, *Practical Handbook of Ground Water Monitoring*, edited by David M. Nielsen, Copyright©1991 by permission.) Lewis Publishers, an imprint of CRC Press, Boca Raton, Florida. With permission.)



**Figure 4.3 Vacuum testing setup** (Source: Vacuum and Pressure Test Methods for Estimating Hydraulic Conductivity by J.P. Orient, A. Nazar and R.C. Rice. Ground Water Monitoring Review. Volume 7, No. 1, Page 50 (Figure 5). 1987. Reprinted from Ground Water Monitoring Review with permission from the National Ground Water Association. Copyright 1987.)

## Analysis of Slug Test Data

Mathematical models for slug test data analysis are summarized in Table 4.1. Models have been developed to deal with confined, unconfined, partial penetration, and skin effects. Calculation of K for a fully screened zone is achieved by dividing T by the entire thickness of the zone. A test of a partially penetrating well yields a T value that is only indicative of that portion of the zone that is penetrated by the well screen. Results from slug tests should not be "over-interpreted". The values obtained are for the geologic material immediately surrounding the well intake, which invariably has been altered to some degree by the installation process.

## SINGLE WELL PUMPING TESTS

A single well pumping test involves pumping at a constant or variable rate and measuring changes in water levels during pumping and recovery. Such tests are used to determine T and K when water level recovery is too rapid for slug tests and no observation wells or piezometers are available.

A simplistic single well test consists of pumping at a constant rate and measuring drawdown. When the water level has stabilized, steady flow conditions can be assumed and the following variation of the Theim equation can be used for estimating T (modified from Boonstra and de Ridder, 1981):

$$T = \frac{43.08 Q}{S_w}$$

where: Q = the constant well discharge in feet<sup>3</sup>/day.  
S<sub>w</sub> = the stabilized drawdown inside the well at steady flow in feet.  
T = the transmissivity.

The equation can be applied to data for both confined and unconfined zones; however, for unconfined zones, drawdown (s<sub>w</sub>) must be corrected to s<sub>w</sub>' = s<sub>w</sub> - (s<sub>w</sub><sup>2</sup>/2D), where D is the saturated zone thickness in feet. Appreciable error can be made in calculating for T using this equation, especially if well construction is unknown or inaccurate or if the screen is partially clogged (Boonstra and de Ridder, 1981). The equation, T = KD can be utilized to determine K.

The drawdown in a pumped well is influenced by well loss and well-bore storage. Well loss is responsible for drawdown being greater than expected from theoretical calculations and can be classified as linear or non-linear. Linear loss is caused by compaction and/or plugging of subsurface material during well construction and installation and head loss in the filter pack and screen. Non-linear loss includes head loss from friction within the screen and suction pipe. Since well-bore storage is large when compared to an equal volume of formation material, it must be considered when analyzing drawdown data from single well pumping tests (Kruseman and de Ridder, 1991). However, Papadopoulos and Cooper (1967) observed that the influence of well-bore storage on drawdown decreases with time (t) and becomes negligible at t > 25r<sub>c</sub><sup>2</sup>, where r<sub>c</sub> is the radius of the unscreened part of the well where the water level is changing. The effects of well-bore storage on early-time drawdown data can be determined by a log-log plot of drawdown (s<sub>w</sub>) versus time (t). Borehole storage effects exist if the early-time drawdown data plots as a unit-slope straight line (Kruseman and de Ridder, 1991).

**Table 4.1 Analysis methods for slug tests.**

| <b>GENERAL ASSUMPTIONS</b>   |                      |                |                     |                        |  |  |             |
|--|----------------------|----------------|---------------------|------------------------|--|--|-------------|
| <ol style="list-style-type: none"> <li>1. The aquifer has an apparently infinite areal extent.</li> <li>2. The zone is homogeneous and of uniform thickness over the area influenced by the test (except when noted in application column).</li> <li>3. Prior to the test, the water table or piezometric surface is (nearly) horizontal over the area influenced and extends infinitely in the radial direction.</li> <li>4. The head in the well is changed instantaneously at time <math>t_0 = 0</math>.</li> <li>5. The inertia of the water column in the well and the linear and non-linear well losses are negligible (i.e., well installation and development process are assumed to have not changed the hydraulic characteristics of the formation).</li> <li>6. The well diameter is finite; hence storage in the well cannot be neglected.</li> <li>7. Ground water density and viscosity are constant.</li> <li>8. No phases other than water (such as gasoline) are assumed to be present in the well or saturated portion of the aquifer.</li> <li>9. Ground water flow can be described by Darcy's Law.</li> <li>10. Water is assumed to flow horizontally.</li> </ol> |                      |                |                     |                        |  |  |             |
| METHOD   | APPLICATION          |                |                     | ADDITIONAL ASSUMPTIONS | PROCEDURE/ANALYSIS   | REMARKS  |             |
|  | "Aquifer" Type       | Flow Condition | Can account for     |                        |  |  |             |
|  |                      |                | Partial Penetration |                        |  |  | Anisotropic |
| Cooper et al. (1967) (a,b)   | Confined             | Transient      | No                  | No                     | - The rate at which the water flows from the well into the aquifer (or vice versa) is equal to the rate at which the volume of water stored in the well changes as the head in the well falls or rises | - Conventional**<br>- Type curve analysis<br><br>- Also described in ASTM D4104-91 (1992)  |             |
| Bouwer and Rice (1976)<br>Bouwer (1989) (a,b)  | Unconfined or leaky* | Steady state   | Yes                 | No                     | - Aquifer is incompressible<br><br>- Buildup of the water table is small compared to aquifer thickness   | - Conventional**<br><br>- Calculations based on modified Theim equation and geometric parameters<br><br>- Can be used to estimate the K of leaky aquifers that receive water from the upper-semi confining layer through recharge or compression |             |

**Table 4.1 (continued): Analysis Methods of Slug tests.**

| METHOD                               | APPLICATION             |                |                     |             | ADDITIONAL ASSUMPTIONS   | PROCEDURE/ANALYSIS   | REMARKS  |
|--------------------------------------|-------------------------|----------------|---------------------|-------------|--|--|--|
|                                      | "Aquifer" Type          | Flow Condition | Can account for     |             |  |  |  |
|                                      |                         |                | Partial Penetration | Anisotropic |  |  |  |
| Hvorslev (1951) (a)                  | Confined or Unconfined* | Transient      | Yes                 | Yes         | - The injection well is considered to be a slot (line source) with infinitesimal width   | - Conventional<br><br>- Analytical equations and calculations of hydraulic equation based on test conditions                 | - Differences of 0.3X to 0.5X can be observed when comparing the K calculated from other methods<br><br>- In some cases can be applied to unconfined aquifers, Fetter (1988) |
| Bredehoeft and Papadopulos (1980)    | Confined                | Transient      |                     | Yes         |  | - Modified<br>- Measure decay of head change by pressurizing a volume of water in the well<br>- Type curves<br>- Type curves | - Low to extremely low K (i.e. silts, clays, shales)   |
| Uffink (1984) (Oscillation Test) (b) | Confined                | Transient      |                     | No          | -Inertia of water column is not negligible, the head change in the well at $t > t_0$ can be described as an exponentially damped cyclic fluctuation<br>- Storativity (s) and the skin factor are already known or can be estimated | - Modified<br>- Stress zone by lowering water table by compressed air. Calculate K by Hvorslev method.                       |  |

\* see remarks

\*\* conventional refers to either injecting or withdrawing or displacing using a solid slug

a Described in Dawson and Istok (1991)

b Described in Kruseman and de Ridder (1991)

A step-drawdown test can be conducted to account for well loss. This test involves pumping at a constant rate until drawdown has stabilized. The rate of pumping is then increased. This process should be repeated through a minimum of three steps. Methods for analyzing the data have been summarized by Kruseman and de Ridder (1991).

Table 4.2 presents several methods for analyzing the drawdown data for constant discharge, variable discharge, and step-discharge single well tests. Analysis of recovery test data (residual drawdown) is invaluable with a single well pumping test. Methods for analysis are straight line methods, which are the same as for conventional pumping tests. However, with single well tests, one must account for the effects of well-bore storage when evaluating recovery (Kruseman and de Ridder, 1991). Available methods to analyze recovery are discussed in the Multiple Well Pumping Tests section of this chapter.

## **MULTIPLE WELL PUMPING TESTS**

A multiple well test is implemented by pumping a well continuously and measuring water level changes in both the pumped and observation wells during pumping or subsequent recovery. Properly designed and conducted multiple well tests can be used to define the overall hydrogeologic regime of the area being investigated, including T, S and/or specific yield of a zone. They also can help design municipal well fields, predict rates of ground water flow, determine interconnectivity between saturated zones, and design a remediation system.

Two basic types are constant discharge and variable discharge. The former is performed by pumping at a constant rate for the duration of the test, while the latter is distinguished by changes in rate. Measurements obtained from the pumping well generally are less desirable for calculating hydraulic properties because of the irregularities induced from the operation of the pump and well bore storage. Obtaining data from observation well(s) allows for characterization of the pumped zone over a larger area.

Test design and data analysis are dependent on the characteristics of the zone tested, the desired/required information, and available funds. Design and analysis are summarized below. References suggested for more detailed information include Lohman (1972), Walton (1987), Dawson and Istok (1991), and Kruseman and de Ridder (1991).

## **PRELIMINARY STUDIES**

Prior to initiating a test, the following data should be gathered:

- The geologic characteristics of the subsurface that may influence ground water flow.
- The type of water-bearing zone and its lateral and vertical extent.
- The depth, thickness, and lateral extent of any confining beds.
- Location of recharge and discharge boundaries.
- Horizontal and vertical flow components (e.g., direction, gradient)
- Location, construction, and zone of completion of any existing wells in the area.
- Location and effects of any pumping wells.
- Approximate values and spatial variation of formation T and S.
- Determination of seasonal ground water fluctuations and any regional water level trends.

**Table 4.2 Single well pumping tests.**

**GENERAL ASSUMPTIONS**

1. The aquifer is infinite in areal extent.
2. The aquifer is homogeneous, isotropic, and of uniform thickness over the area influenced by the test.
3. Prior to pumping, the piezometric surface is horizontal, or nearly so, over the area to be influenced by the test.
4. The well penetrates the entire thickness of the aquifer and, thus, receives water by horizontal flow.
5. The water removed from storage in the aquifer is discharged instantaneously with decline of head.
6. Non-linear well losses are negligible.

**The following assumptions/conditions apply to leaky confined aquifers.**

1. The aquitard is infinite in areal extent.
2. The aquitard is homogeneous, isotropic and of uniform thickness.
3. The water supplied by leakage from the aquitard is discharged instantaneously with decline in head.

| METHOD                                   | APPLICATION                |                | ADDITIONAL ASSUMPTIONS/CONDITIONS   | ANALYSIS/PROCEDURE   | REMARKS  |
|--|----------------------------|----------------|---|--|--|
|  | "Aquifer" Type             | Flow Condition |   |  |  |
| Papadopulos and Cooper (1967) (a & b)    | Confined                   | Transient      | The well diameter cannot be considered infinitesimal, hence, storage in well cannot be neglected              | Constant discharge<br><br>Equations take storage capacity of well into account<br><br>Type curves, data curve, log/log | - Early time data does not adequately reflect aquifer characteristics<br>- May be difficult to match the data curve with appropriate type curves because of similarities of curves |
| Rushton and Singh (1983) (b)             | Confined                   | Transient      | The well diameter cannot be considered infinitesimal, hence storage in well cannot be neglected               | Constant discharge<br><br>Type curve fitting, data curve semi-log  | More sensitive curve fitting than Papadopulos and Cooper method  |
| Birsoy and Summers(1980) (b)             | Confined                   | Transient      | Storativity is known or can be estimated with reasonable accuracy   | Variable discharge (aquifer is pumped stepwise or is intermittently pumped at constant discharge)                      |  |
| Hurr-Worthington (Worthington, 1981) (b) | Confined or leaky confined | Transient      | Storage in well cannot be neglected.<br><br>Storativity is known or can be estimated with reasonable accuracy | Constant discharge<br><br>Modified Theis Equation  |  |

**Table 4.2 (Continued): Single well pumping tests.**

| METHOD                           | APPLICATION                |                | ADDITIONAL ASSUMPTIONS/CONDITIONS   | ANALYSIS/PROCEDURE  | REMARKS  |
|----------------------------------|----------------------------|----------------|---|---|--|
|                                  | "Aquifer" Type             | Flow Condition |   |   |  |
| Jacob's Straight Line Method (b) | Confined or leaky confined | Transient      | <p>For confined,</p> $t < 25 \frac{r_c^2}{KD}$ <p>if net effect of well borestorage can be neglected.</p> <p>For leaky, <math>25 \frac{r_c^2}{KD} &lt; t &lt; \frac{cS}{20}</math></p> <p>as long as the influence of leakage is negligible. <math>t &lt; \frac{cS}{20}</math></p>                      | <p>Constant discharge</p> <p>T determined by drawdown differences</p> | <p>Sensitive to minor variations in discharge rate</p> <p>May be able to account for partial penetration if late-time data is used</p> |
| Hantush (1959b) (b)              | Leaky confined/artesian    | Transient      | <p>Flow through aquitard is vertical</p> <p>Aquitard is incompressible (i.e. changes in aquitard storage are negligible)</p> <p>At the beginning of the test (t=0), the water level in the well is lowered instantly, at t&gt;0, the drawdown in the well is constant and its discharge is variable</p> | <p>Variable discharge</p> <p>Type curve matching</p>                  |  |
| Jacob and Lohman (1952)(b)       | Confined/artesian          | Transient      | <p>At the beginning of the test (t=0), water levels screened in the artesian aquifer are lowered instantaneously.</p> <p>At t&gt;0, the drawdown is constant and discharge is variable</p> <p>Uw &lt;0.01</p>   | <p>Variable discharge (drawdown is constant)</p>                      | <p>If value of the effective radius is not known then storativity cannot be determined</p>   |

a Described in Dawson and Istok (1991), b Described in Kruseman and deRidder (1991)

t = time since start of pumping, KD =transmissivity of the aquifer, r<sub>c</sub> = radius of the unscreend part of the well where water level is changing, c = hydraulic resistance of the aquitard, S = storativity, Uw = equation function

This preliminary information can assist in the proper design of the test and the choice of a conceptual model. Test design also can be facilitated by preliminary conceptual modeling efforts that predict the outcome of the test beforehand (Walton, 1987). This serves two purposes. First, it describes the aquifer so that an appropriate data analysis method is evident. Secondly, it suggests deficiencies in observation well locations.

Costs frequently are reduced by using existing wells rather than installing new ones; however, few existing configurations are suitable. Evaluation of existing wells to identify ones that are potentially useable is the first step in design (Stallman, 1983). Single well tests should be conducted on the existing wells to determine whether they will respond appropriately.

## **PUMPING TEST DESIGN**

As indicated, the design of a pumping test is dependent on the hydrogeologic environment and the purpose of the test. The designer must determine pumping well location and design, pumping rate, pump selection, location and depth of observation wells, test duration, discharge rate measurements and devices, interval and method of water level measurements, and method of analyzing data.

### **Pumping Well Location**

A pumping well should be located far enough away from hydraulic boundaries to permit recognition of drawdown trends before boundary conditions influence the drawdown data (Sevee, 1991). To minimize the effect of stream, river or lake bed infiltration, it should be located at a distance equal to or exceeding the aquifer thickness from the possible boundary (Walton, 1987). However, if the intent is to induce recharge, then the pumping well should be located as close to the boundary as possible (Sevee, 1991). The appropriate depth should be determined from exploratory boreholes or logs from nearby wells.

### **Pumping Well Design**

The design of a pumping well is dependent on the hydrogeologic environment, the choice of conceptual model, and economics. Components that must be considered include diameter, length and depth of the screened interval, and screen slot configuration.

A general rule is to screen the well over at least 80 percent of the aquifer thickness. This makes it possible to obtain about 90 percent or more of the maximum yield that could be obtained if the entire aquifer were screened, and also allows horizontal flow toward the well to be assumed, which is an assumption that underlies almost all well-flow equations. Pumping wells completed in thick zones often have intake lengths less than 80 percent of the thickness. These wells are considered partially-penetrating (Kruseman and deRidder, 1991), and pumping would be expected to induce vertical flow components. As a result, corrections to the drawdown data may be necessary. Corrections are discussed later in this chapter.

The diameter of a pumping well is dependent on the conceptual model and the estimated hydraulic properties. It must accommodate the pump, assure hydraulic efficiency, and allow measurement of depth to water before, during and after pumping. Table 4.3 recommends casing diameters

based on pumping rates; however, the final selection should be based on consultation with the pump manufacturer.

The screen slot size and filter pack material should be based on the grain size distribution of the zone being pumped. The screen should be factory-slotted or perforated over no more than 30 to 40 percent of its circumference to keep entrance velocity less than 3 cm/sec (Kruseman and de Ridder, 1991). At this velocity, friction losses in the screen are small and may be considered negligible. Slots should be long and narrow or continuous. The screen should be factory-produced. Slots produced manually are not appropriate under any circumstances.

**Table 4.3 Recommended pumping well diameter for various pumping rates. (Dawson and Istok, 1991, after Driscoll, 1986).**

| <b>PUMPING RATE</b>                    |  | <b>DIAMETER</b>    |                    |
|--|--|--------------------|--------------------|
| <b><i>gal</i></b><br><b><i>min</i></b> | <b><i>m</i><sup>3</sup></b><br><b><i>day</i></b> | <b><i>(in)</i></b> | <b><i>(mm)</i></b> |
| <100                                   | <545   | 6                  | 152                |
| 75-175                                 | 409-954  | 8                  | 203                |
| 150-350                                | 818-1910   | 10                 | 254                |
| 300-700                                | 1640-3820  | 12                 | 305                |
| 500-1000                               | 2730-5450  | 14                 | 365                |
| 800-1800                               | 4360-9810  | 16                 | 406                |
| 1200-3000                              | 6540-16400                                       | 20                 | 508                |

### **Pumping Rate**

Insufficient pumping rates may result in underestimation of the hydraulic parameters of both the zone tested and confining layers. Likewise, excessive rates for too short a duration may lead to calculation of erroneously large hydraulic properties. The rate(s) should be sufficient to ensure that the aquifer is stressed and that drawdown can be measured accurately. The water table in an unconfined zone should not be lowered by more than 25 percent. This is the largest drawdown that can be corrected and analyzed with an analytical solution of the ground water flow equation (Dawson and Istok, 1991). The pumping rate for tests conducted in confined zones should not readily dewater the pumping well.

Well efficiency and an appropriate pumping rate for a constant discharge test can be determined by conducting a step-drawdown test. A step test involves pumping a single well at a low constant rate until the drawdown within the well has stabilized. The rate is then increased to a higher constant discharge until the water level has stabilized once more. At a minimum, to insure that an appropriate rate can be determined from the data, three successively greater rates of equal duration should be utilized. The duration of each step generally should be at least 2 hours; however, the required time is dependent on aquifer characteristics. References detailing the mechanics of a step test include Kruseman and de Ridder (1991), Driscoll (1986), and Dawson and Istok (1991).

Other methods that may be useful to estimate an appropriate pumping rate for a constant head test include: 1) using an empirical formula to predict well specific capacity, and 2) predicting drawdown using analytical solutions. These methods are described by Dawson and Istok (1991). It should be noted that these techniques predict discharge rates that can be utilized to determine hydraulic parameters and should not be utilized to estimate an appropriate rate for capturing a contaminant plume.

### **Pump Selection**

The pump and power supply must be capable of operating continuously at an appropriate constant discharge rate for at least the expected duration of the test. Pumps powered by electric motors produce the most constant discharge (Stallman, 1983).

### **Observation Well Number**

The appropriate number of observation wells depends on the goals of the test, hydrogeologic complexity, the degree of accuracy needed, and economics. Though it is always best to have as many wells as conditions permit, at least three should be employed in the pumping zone (Kruseman and de Ridder, 1991). If two or more are available, data can be analyzed by both drawdown versus time and drawdown versus distance relationships. Using both and observing how wells respond in various locations provides greater assurance that: 1) the calculated hydraulic properties are representative of the zone being pumped over a large area, and 2) any heterogeneities that may affect the flow of ground water and contaminants have been identified. In areas in where several complex boundaries exist, additional wells may be needed to allow proper interpretation of the test data (Sevee, 1991).

### **Observation Well Design**

In general, observation wells need to be constructed with an appropriate filter pack, screen slot size, and annular seal, and must be developed properly. Practices for design and development of observation wells can be similar to those for monitoring wells (see Chapters 7 & 8). The observation wells/piezometers must be of sufficient diameter to accommodate the measuring device, but should not be so large that the drawdown cannot be measured.

### **Observation Well Depth**

Fully-penetrating wells are desirable. The open portion of an observation well generally should be placed vertically opposite the intake of the pumping well. When testing heterogeneous zones, it is recommended that an observation well be installed in each permeable layer. Additional wells should be placed in the aquitards to determine leakage and interconnectivity (Kruseman and de Ridder, 1991).

### **Observation Well Location**

Observation well location is dependent on the type of aquifer, estimated transmissivity, duration of the test, discharge rate, length of the pumping well screen, whether the aquifer is stratified or

fractured, and anticipated boundary conditions. Placing observation wells 10 to 100 meters (33 to 328 feet) from the pumping well is generally adequate for determining hydraulic parameters. For thick or stratified, confined zones, the distance should be greater (Kruseman and de Ridder, 1991). It also is recommended that additional observation wells be located outside the zone of influence of the pumping well to monitor possible natural changes in head.

In general, observation wells completed in a confined zone can be spaced further from the pumping well than those completed in an unconfined aquifer. The decline in the piezometric surface of confined zones spreads rapidly because the release of water from storage is entirely due to compressibility of water and the aquifer material. Water movement in unconfined zones is principally from draining of pores, which results in a slower expansion.

Under isotropic conditions, the distribution of the observation wells around the pumping well can be arbitrary. However, an even distribution is desirable so that drawdown measurements are representative of the largest volume of aquifer possible (Dawson and Istok, 1991). If feasible, at least three wells should be logarithmically spaced to provide at least one logarithmic cycle of distance-drawdown data (Walton, 1987). If anisotropic conditions exist or are suspected, then a single row of observation wells is not sufficient to estimate the directional dependence of transmissivity. A minimum of 3 observation wells, none of which are on the same radial arc, is required to separate the anisotropic behavior.

The length of the pumping well screen can have a strong influence on the distance of the observation wells from the pumping well. Partially-penetrating pumping wells will induce vertical flow, which is most noticeable near the well (Figure 4.4). As a result, water level measurements taken from these wells need to be corrected; however, the effects of vertical flow become more negligible at increasing distances from the pumping well. For partially-penetrating pumping wells, corrections to the drawdown data may not be necessary if the following relation holds true (Sevee, 1991; and Dawson and Istok, 1991):

$$M.D. \geq 1.5 D \sqrt{\frac{K_H}{K_V}}$$

M.D. = minimum distance between pumping well and observation well.

$D$  = thickness of the aquifer.

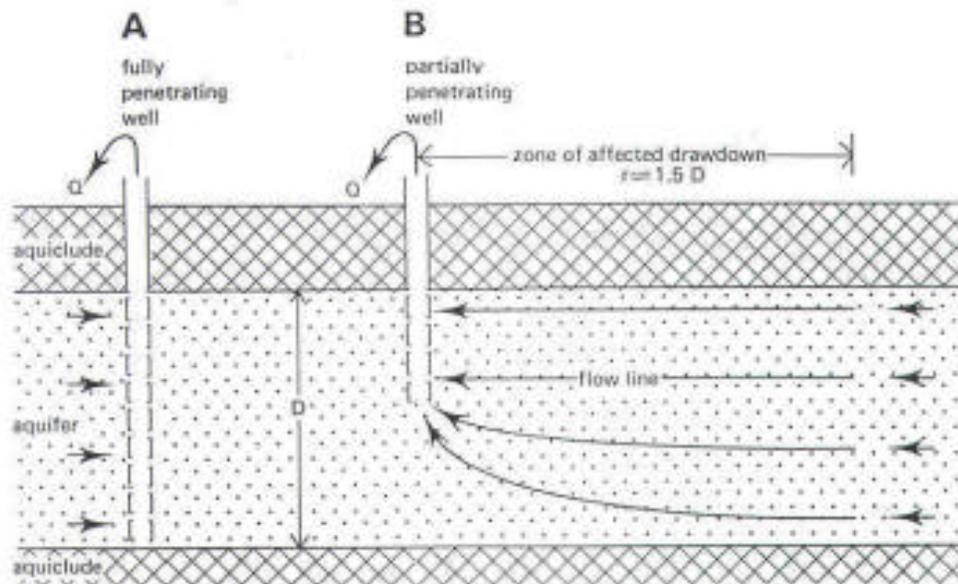
$K_H$  = horizontal K.

$K_V$  = vertical K.

Drawdown measured in observation wells located less than the minimum distance should be corrected. Typically, horizontal K is ten times greater than vertical K. If this ratio is used, then the minimum distance becomes  $1.5D/10$ . It should be noted that partially-penetrating wells located at or greater than the minimum distance may be too far away to show drawdown.

Anticipated boundary conditions (e.g., an impervious zone or a recharging river) also can affect the placement of observation wells. Wells can be placed to either minimize the effect of the boundary or more precisely locate the discontinuity (Dawson and Istok, 1991). According to Walton (1987), to minimize the effect of the boundary on distance-drawdown data, wells should be placed along a line through the pumping well and parallel to the boundary. Observation wells also should be

placed on a line perpendicular to the boundary. If more than one boundary is suspected or known, the wells should be located so that the effects on drawdown data encountered by the first boundary have stabilized prior to encountering the second boundary (Sevee, 1991).



**4.4 (A) Flow to a fully penetrating well. (B) Flow to a partially penetrating well.** (Source: *Analysis and Evaluation of Pumping Test* by G. P. Kruseman and N.A. de Ridder, Copyright © 1991 by International Institute for Land Reclamation and Improvement, publication 47, 377 pp. Printed with permission).

### Duration of Pumping

It is difficult to predict how long a pumping test should be conducted. The duration depends on the hydrogeologic setting, boundary conditions, and degree of accuracy desired. Economic factors and time constraints also may be influential; however, economizing the period of pumping is not recommended. The cost of continuing a test is low compared to total costs, particularly when the wells have been specially constructed and positioned for test purposes (Kruseman and de Ridder, 1991).

Pumping tests commonly last from five hours to five days (Walton, 1962). Though not absolutely necessary, it is recommended that tests be continued until the cone of depression has stabilized and does not expand as pumping continues. Such a steady state or equilibrium can occur within a few hours to weeks or never. According to Kruseman and de Ridder (1991), the average time to reach steady state in leaky aquifers is 15 to 20 hours. A test of a confined aquifer should last a minimum of 24 hours. Three days or more should be allowed for tests conducted in unconfined aquifers because of the slow expansion of the cone of depression. The duration necessary to define the hydraulic parameters depends on the regional and local geologic/hydrogeologic setting. Plotting drawdown data during tests often reveals anomalies and the presence of suspected or unknown boundaries, and assists in determining test duration.

## Discharge Rate Measurement

Variation in discharge rates produces aberrations in drawdown that are difficult to treat in data analysis. Engines, even those equipped with automatic speed controls, can produce variations up to 20 to 25 percent over the course of a day. The rate should never vary by more than five percent (Osborn, 1993). In order to obtain reliable data, discharge should be monitored and adjustments made as needed.

The frequency of measurements is dependent on the pump, engine power characteristics, the well, and the zone tested. Discharge from electric pumps should be measured and adjusted (if necessary) at 5, 10, 20, 30, 60 minutes, and hourly thereafter. Other types of pumps may require more frequent attention; however, no "rule of thumb" can be set because of the wide variation in equipment response (Stallman, 1983).

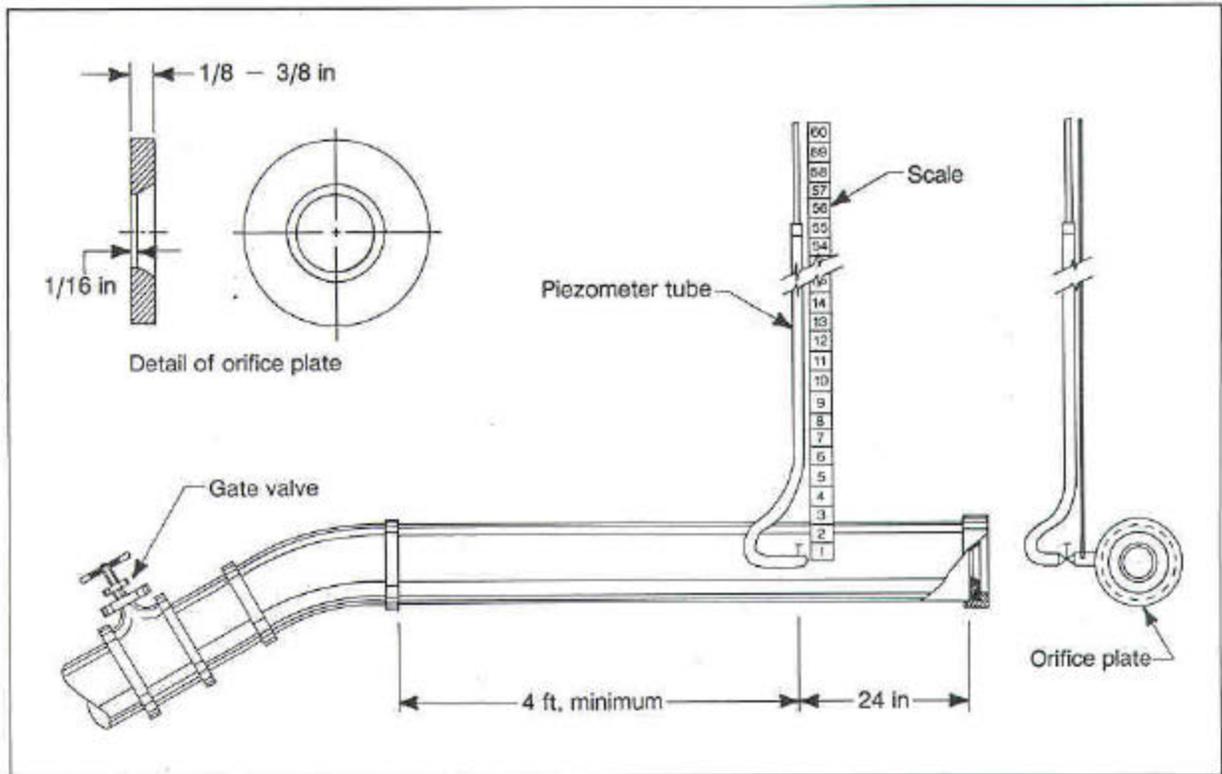
## Discharge Measuring Devices

Some discharge measurement techniques are more accurate than others and some allow for a convenient means of adjusting rate. A **commercial water meter** of appropriate capacity can be utilized. It should be connected to the discharge pipe in a way that ensures accurate readings. A disadvantage is the unavoidable delay in obtaining values at the start of the test, when pumping rate is being adjusted to the desired level (Driscoll, 1986). When discharge is low, the rate can be measured as a function of time to fill a **container of known volume**. The **orifice weir** is commonly used to measure discharge from high capacity pumps. A manometer is fitted into the discharge pipe. The water level in the manometer represents the pressure in the pipe when the water flows through the orifice. Figure 4.5 shows a diagram of a typical circular orifice weir. Details on orifice design and interpretation of results can be found in Driscoll (1986). Finally, discharge rate can be obtained by water level measurements taken from **weirs and flumes**. The rate of flow is determined within known constriction dimensions placed in the discharge channel originating at the well head (Driscoll, 1986).

## Interval of Water Level Measurements

### ***Pretest Measurements***

Prior to the start of tests, water level data should be collected from the pumping and observation wells to determine existing trends for all zones to be monitored. The pumping phase should begin only if identified and recorded trends are expected to remain constant. As a general rule, the period of observation should be at least twice the length of the estimated time of pumping (Stallman, 1983). Water levels should be measured and recorded hourly for all zones. In addition, the barometric pressure should be monitored, at least hourly, to determine the barometric efficiency of saturated zone(s), which may be useful in correcting the drawdown data. Barometric efficiency is discussed later in this chapter.



**Figure 4.5 Construction diagram of a circular orifice weir commonly used for measuring rates of a high capacity pump. (Source: *Ground Water and Wells* by E.G. Driscoll. Copyright , © 1986; Johnson screens. Printed with permission).**

### ***Measurements During Pumping***

The appropriate time interval for water level measurements varies from frequent at the beginning of a test, when water-levels are changing rapidly, to long at the end of the test, when change is slow. Typical intervals for the pumping well and observation wells located close to the pumping well are given in Tables 4.4 and 4.5, respectively. Though specified intervals need not be followed rigidly, each logarithmic cycle of time should contain at least 10 data points spread through the cycle (Stallman, 1983). Frequent readings are essential during the first hour since the rate of change is faster. For wells further away and those located in zones above or below the pumping zone, the frequent measurements recommended by Table 4.5 for the first few minutes of the pumping tests are less important (Kruseman and de Ridder, 1991).

**Table 4.4 Range of interval between water-level measurements in the pumping well (Kruseman and de Ridder, 1991).**

| TIME SINCE START OF PUMPING TIME INTERVAL |             |
|---|-------------|
| 0 to 5 minutes                            | 0.5 minutes |
| 2 to 60 minutes                           | 5 minutes   |
| 60 to 120 minutes                         | 20 minutes  |
| 120 to shutdown of the pump               | 60 minutes  |

**Table 4.5 Range of intervals between water-level measurements in observation wells (Kruseman and de Ridder, 1991).**

| TIME SINCE START OF PUMPING    | TIME INTERVAL      |
|--------------------------------|--------------------|
| 0 to 2 minutes                 | approx. 10 seconds |
| 2 to 5 minutes                 | 30 seconds         |
| 5 to 15 minutes                | 1 minute           |
| 50 to 100 minutes              | 5 minutes          |
| 100 minutes to 5 hours         | 30 minutes         |
| 5 hours to 48 hours            | 60 minutes         |
| 48 hours to 6 days             | 3 times a day      |
| 6 days to shutdown of the pump | 1 time a day       |

According to Stallman (1983), it is not necessary to measure water levels in all wells simultaneously, but it is highly desirable to achieve nearly uniform separation of plotted drawdowns on a logarithmic scale. All watches used should be synchronized before the test is started, and provisions made to notify all participants at the instant the test is initiated.

### ***Measurements During Recovery***

After pumping is completed, water level recovery should be monitored with the same frequency used during pumping.

### **Water Level Measurement Devices**

The most accurate recording of water level changes is made with fully automatic microcomputer-controlled systems that use pressure or acoustic transducers for continuous measurements. Water levels can also be determined by hand, but the instant of each reading must be recorded with a chronometer. Measurements can be performed with floating steel tape equipped with a standard pointer, electronic sounder, or wet-tape method. For observation wells close to the pumped well, automatic recorders programmed for frequent measurements are most convenient because water level change is rapid during the first hour of the test. For detailed descriptions of automatic recorders, mechanical and electric sounders, and other tools, see Driscoll (1986), Dalton et al. (1991), and ASTM D4750-87 (1992). Chapter 10 of this document contains a summary of manual devices.

The measurement procedure should be standardized and calibrated prior to the start of the test. Transducers should be calibrated by a direct method, and the calibration should be checked at the conclusion of the recovery test.

### **Discharge of Pumped Water**

Water extracted during a pumping test must be discharged properly and in accordance with any applicable laws and regulations. At sites with contaminated ground water, the discharge may need to be containerized and sampled to assess the presence of contaminants and, if necessary, treated and/or disposed at an appropriate permitted facility.

It is not the intent of this document to define Agency policy on disposal of pumped water. In general, the water should be evaluated to determine if it is characteristically a waste. If the ground water has been contaminated by a listed hazardous waste, the ground water is considered to "contain" that waste, and must therefore be managed as such. Disposal must be at a permitted hazardous waste facility. Treatment must be in a wastewater treatment system that is appropriate for the waste and meets the definitions contained in OAC rule 3745-50-10.

If containerization is not necessary, then pumped water must be discharged in a manner that prevents recharge into any zone being monitored during the test. At a minimum, the water should be discharged 100 to 200 meters from the pumped well. This is particularly important when testing unconfined zones. At no time should the discharge water be injected back into the subsurface. A permit for discharge via stream or storm sewer may be required (contact the Division of Surface Water, Ohio EPA).

### **Decontamination of Equipment**

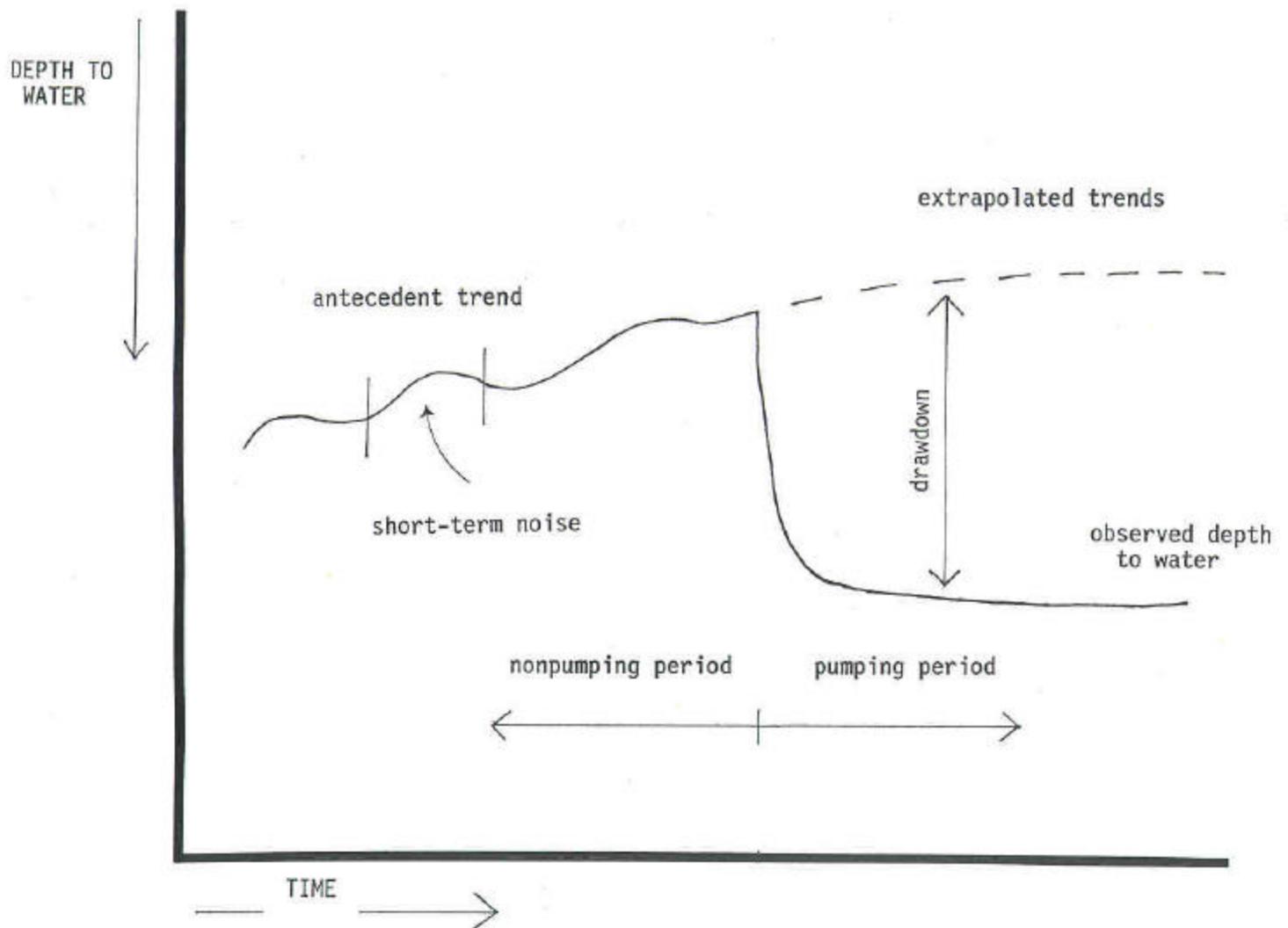
Decontamination of equipment is important throughout an in-situ test. Contact of contaminated equipment with ground water (or a well) may cause a measuring point to be unsuitable for water quality investigations. Details on appropriate methods can be found in Chapter 10.

### **CORRECTION TO DRAWDOWN DATA**

Prior to using the drawdown data collected from a pumping test, it may be necessary to correct for either external sources or effects induced by the test. Barometric pressure changes, tidal or river fluctuations, natural recharge and discharge, and unique situations (e.g., a heavy rainfall) may all exert an influence. In confined and leaky aquifers, changes in hydraulic head may be due to influences of tidal or river-level fluctuations, surface loading, or changes in atmospheric pressure.

Diurnal fluctuations in water levels can occur in unconfined aquifers due to the differences between night and day evapotranspiration. Corrections to measurements may be needed for unconfined aquifer data due to a decrease in saturated thickness caused by the pumping test. Also, corrections may be necessary if the pumping well only partially penetrates the zone tested. By identifying pre-test water level trends in zone(s) of interest, long and short-term variations can be eliminated from the data if their impacts are significant during the pumping phase (Figure 4.6).

In order to determine if corrections are necessary, measurements should be taken during the test in observation wells unaffected by the pumping. Hydrographs of the pumping and observation wells covering a sufficient period of pre-test and post-recovery periods can help determine if the data needs to be corrected and also to correct the drawdown data. If the same constant water level is observed during the pre-testing and post-recovery periods, it can safely be assumed that no external events exerted an influence (Kruseman and de Ridder, 1991).



**Figure 4.6 Hydrograph for hypothetical observation well showing definition of drawdown (adapted from Stallman, 1983).**

## Barometric Pressure

Data for confined and leaky zones needs to be corrected for the amount of rise in water levels resulting from a decrease in atmospheric pressure and/or the amount of fall resulting from an increase. To make the correction, the barometric efficiency (BE) of the zone needs to be determined. The BE can be calculated by the following equation [Dawson and Istok (1991) and Kruseman and de Ridder (1991)]:

$$BE = \frac{Mh}{Mk_a / \bar{\alpha}_w} \times 100\%$$

where:  $Mh$  = change of head in the observation well.  
 $(Mk_a / \bar{\alpha}_w)$  = change in atmospheric pressure expressed as a height of water.  
 $k_a$  = change in atmospheric pressure.  
 $\bar{\alpha}_w$  = specific weight of water.

If the change in hydraulic head is plotted versus the change in pressure (measured column height) and a best-fit straight line is drawn, then the slope of the line is the BE. From changes in atmospheric pressure observed during the test and the BE, the change in water level due to changes in barometric pressure can be calculated and the drawdown data can be corrected. When artesian zones are tested, barometric pressure (to a sensitivity of +/- 0.01 inch of mercury) should be recorded continuously throughout the testing period. Barometric efficiency typically ranges between 0.20 and 0.75 (Kruseman and de Ridder, 1991).

## Saturated Thickness

The saturated thickness of an unconfined zone decreases during pumping tests; however, most conceptual models are based on the assumption that it remains constant. This assumption can be accepted if the saturated thickness does not decrease more than 25 percent. If the decrease is greater than 25 percent, then the drawdown data should be corrected prior to analysis (Dawson and Istok, 1991).

According to Jacob (1944), data for unconfined zones can be corrected for saturated thickness change with the following equation:

$$s_{\text{corrected}} = s - s^2/2m$$

where:  $s_{\text{corrected}}$  = corrected drawdown.

$s$  = observed drawdown.

$m$  = initial saturated thickness.

However, this correction is based on the Dupuit-Forchheimer assumption (ground water flows horizontally and hydraulic gradient is equal to the slope of the water table). Neuman (1975) showed that this assumption is not valid for an unconfined aquifer until the later portion of the test when the drawdown matches the Theis type curve. Therefore, the correction is not recommended with early and intermediate data (Dawson and Istok, 1991).

## Unique Fluctuations

Data cannot be corrected for unique events such as a heavy rain or sudden fall or rise of a nearby river that is hydraulically connected to the zone tested. However, in favorable circumstances, some allowances can be made for the resulting fluctuations by extrapolating data from a controlled piezometer outside the zone of influence. In most cases, the data collected is rendered worthless and the test has to be repeated when the situation returns to normal (Kruseman and de Ridder, 1991). It is also important to understand the effects of nearby industrial or municipal pumping wells prior to conducting a pumping test.

## Partially-Penetrating Wells

In some cases, a saturated zone is so thick that it is not justifiable to install a fully-penetrating well, and the aquifer must be pumped by a partially-penetrating well. Partial-penetration causes vertical flow in the vicinity of the well, which results in additional head loss. As indicated earlier, this effect decreases with increasing distance from the pumping well and no correction is necessary if the observation well is at a distance greater than  $1.5 D / K_H / K_V$ . Various methods have been developed to correct data for the effects of partially-penetrating wells. These were discussed in detail by Kruseman and de Ridder (1991). Table 4.6 lists the methods and their general applications.

## ANALYSIS OF MULTIPLE WELL PUMPING TEST DATA

Many conceptual models exist for interpreting multiple well pumping test data. The hydraulic properties computed by a particular method can only be considered correct if the assumptions included in the conceptual model on which the method is based are valid for the particular system being tested. Because the computed values depend on the choice of conceptual model used to analyze the data, the selection of an appropriate model is the single most important step in analysis (Dawson and Istok, 1991).

It is beyond the scope of this document to detail or discuss all conceptual models. Tables 4.7 through 4.11 can be used for a preliminary selection. In addition, the ASTM Method D4043-91 (1992) provides a decision tree for the selection of an aquifer test method and ASTM Methods D4106-91 (1992) and D4105-91 (1992) offer information on determining hydraulic parameters. Additional references are provided in the tables that should serve as a guide for choice and use of conceptual models. It should be noted that additional models may exist that are not listed here. Any model utilized must be shown to be appropriate for site conditions.

Data collected during a pumping test are subject to a variety of circumstances that may be recognized in the field or may not be apparent until data analysis has begun. In either case, all information (including field observations) must be examined during data correlation and analysis.

**Table 4.6 Corrections for partially penetrating effects (information derived from Kruseman & de Ridder, 1991.)**

| <i>METHOD</i>  | <i>APPLICATION</i>   | <i>ORIGINAL SOURCE</i>    |
|--|--|---------------------------|
| Huisman Method I   | - confined aquifer<br>- steady state                                 | Anonymous, 1964           |
| Huisman Method II  | - confined<br>- unsteady state<br>- time of pumping relatively short | Hantush (1961 a, 1961 b)  |
| Hantush Modification of Theis Method                                   | - confined<br>- unsteady state<br>- time of pumping relatively short | Hantush (1961 a, 1961 b)  |
| Hantush, Modification of Jacob Method                                  | - confined<br>- unsteady state<br>- time of pumping relatively long  | Hantush (1961 b)          |
| Weeks', "Modification of Walton and the Hantush Curve Fitting Methods" | - leaky aquifers<br>- steady state flow                              | Weeks (1969)              |
| Streltsova's Curve Fitting Method                                      | - unconfined<br>- anisotropic<br>- unsteady state                    | Streltsova (1974)         |
| Neuman's Curve-Fitting Method  | - unconfined<br>- anisotropic  | Neuman (1974, 1975, 1979) |

## RECOVERY TESTS

Recovery tests (also called residual drawdown tests) involve measuring water level rise after the pump is shut down. These tests provide an independent check on the transmissivity determined from a pumping test. Results of a recovery test conducted on confined and leaky confined zones can be more reliable than pumping test results because recovery occurs at a constant rate that is not influenced by the erratic fluctuations that can be characteristic of pumping rate. Hysteresis effects must be accounted for when evaluating recovery data collected from unconfined aquifers. Table 4.12 provides methods for analyzing recovery data.

**Table 4.7 Multiple-Well, Constant Discharge Pumping Tests, Unconfined Aquifer.**

**GENERAL ASSUMPTIONS**

1. The aquifer is unconfined. The aquifer is bounded below by an aquiclude.
2. All layers are horizontal and extend infinitely in the radial extent.
3. The aquifer is homogeneous, isotropic (unless noted) and of uniform thickness over the area influenced by the test.
4. Prior to pumping, the water table is horizontal over the area that will be influenced by the test.
5. Ground water density and viscosity are constant.
6. Ground water flow can be described by Darcy's Law.
7. Head losses through well screen and pump intake are negligible.
8. The aquifer is compressible and completely elastic.
9. The aquifer has been pumped long enough that equilibrium has been reached (drawdown is not changing with time).
10. Drawdown is small compared to the saturated thickness of the aquifer (i.e., no more than 25 percent).
11. Pumping and observation wells are screened over the entire saturated thickness and receives water from the entire aquifer (unless noted).
12. Ground water flow above the water table is negligible.

| METHOD   | CAN ACCOUNT FOR |                     |                        | ADDITIONAL ASSUMPTIONS AND CONDITIONS   | ANALYSIS/ PROCEDURES | REMARKS  |
|--|-----------------|---------------------|------------------------|---|----------------------|--|
|  | Flow Conditions | Partial Penetration | Other                  |   |                      |  |
| Neuman's Curve Fitting Method (Neuman, 1972) (a,b) | Transient       | No                  | anisotropic conditions | <p>The influence of the unsaturated zone upon drawdowns of the aquifer is negligible</p> <p>The diameters of the pumped and observation wells are small, i.e., storage in them can be neglected</p> <p>The ratio of the specific yield versus the elastic early-time storativity is greater than 10, i.e.,</p> $\frac{S_y}{S_A} > 10$ | Curve fitting method | Theory should be valid for piezometers with short screens provided that the drawdowns are averaged over the aquifer (Van der Kamp, 1985) |

**Table 4.7 (continued). Multiple-well, constant discharge pumping tests, unconfined aquifers.**

| METHOD  | CAN ACCOUNT FOR |                     |                                       | ADDITIONAL ASSUMPTIONS AND CONDITIONS  | ANALYSIS/ PROCEDURES  | REMARKS   |
|---|-----------------|---------------------|---------------------------------------|--|---|---|
|   | Flow Conditions | Partial Penetration | Other                                 |  |   |   |
| Thiem-Dupuit's Method, (Thiem, 1906)<br><br>(b) | Steady state    | No                  |                                       | Velocity of flow is proportional to the tangent of the hydraulic gradient instead of the sine as it is in reality<br><br>Flow is horizontal and uniform everywhere in a vertical section through the well axis<br><br>The aquifer has been pumping long enough that equilibrium has been reached | Plot drawdown versus time and substitute values into analytical equations | Steady state will only be achieved after long pumping time<br><br>Does not give accurate description of drawdown near the well<br><br>Assumptions ignore the existence of a seepage face at the well and the influence of the vertical velocity component |
| Boulton and Streltsova (1976)<br>a              | Transient       | Yes                 | storage in the well<br><br>Anisotropy |  | Type curve fitting  | The affects of well storage on drawdown can be neglected if either<br><br>$t > \frac{2.5 \times 10^{-3} r_c^2}{\hat{O}}$ or<br>$r > 3.00 r_w$<br>Other models may be more applicable.   |
| Neuman (1974) a                                 | Transient       | Yes                 | Anisotropy                            |  | Type curve fitting  |   |

a Described in Dawson and Istok, 1991

b Described in Kruseman and de Ridder, 1991

t = time,  $\hat{O}$  = transmissivity, r = radial distance from the pumping well,  $r_w$  = effective radius of the pumping well,  $r_c$  = inside radius of the pumping well within the range of water fluctuations

**Table 4.8 Multiple-well, constant-discharge pumping tests, confined aquifers.**

**GENERAL ASSUMPTIONS**

1. The aquifer is confined. The aquifer is bounded above and below by aquicludes.
2. The aquifer is homogeneous, isotropic (unless noted in special conditions) and of uniform thickness over the area influenced by the test.
3. All layers are horizontal and extend infinitely in the radial extent.
4. Prior to pumping, the piezometric surface is horizontal and extends infinitely in the radial direction.
5. Ground water density and viscosity are constant.
6. Ground water can be described by Darcy's Law.
7. Head losses through well screen and pump intake are negligible.
8. Ground water flow is horizontal and is directed radially to the well.
9. Pumping well and observation wells are screened over the entire thickness of the aquifer.

**Additional assumptions for unsteady state flow.**

10. The water removed from storage is discharged instantaneously with decline of head.
11. The diameter of the well is small, i.e., the storage in the well can be neglected.

| METHOD                 | APPLICATION    |                     | ADDITIONAL ASSUMPTIONS AND CONDITIONS | ANALYSIS/ PROCEDURES  | REMARKS  |       |
|------------------------|----------------|---------------------|---------------------------------------|---|--|-------|
|                        | Flow Condition | CAN ACCOUNT FOR     |                                       |   |  |       |
|                        |                | Partial Penetration |                                       |   |  | Other |
| Thiem (1906)<br>(a, b) | Steady state   | No                  |                                       | The aquifer has been pumped long enough that equilibrium has been reached (drawdown is not changed with time) | Drawdown versus time plotted on semi-log paper and substitution of values into analytical equations.<br><br>Drawdown is influenced by well losses, screen and pump intake                          |       |
| Theis (1935)<br>(a,b)  | Transient      | No                  |                                       | The aquifer is compressible and completely elastic  | Type curve analysis<br><br>Because there may be a time lag between pressure decline and release of stored water, early drawdown data may not closely represent theoretical drawdown data           |       |
| Hantush (1964)<br>(b)  | Transient      | Yes                 | Anisotropy in the horizontal plane    | No vertical flow at the top and bottom of the aquifer   | Solutions involve type curve analysis or inflection point method<br><br>Inflection point method can be used when the horizontal and vertical hydraulic conductivities can be reasonably estimated. |       |

**Table 4.8 (continued): Multiple-well tests, constant discharge pumping tests, confined aquifers.**

| METHOD   | APPLICATION    |                     | ADDITIONAL ASSUMPTIONS AND CONDITIONS | ANALYSIS/ PROCEDURES  | REMARKS  |       |
|--|----------------|---------------------|---------------------------------------|---|--|-------|
|  | Flow Condition | CAN ACCOUNT FOR     |                                       |   |  |       |
|  |                | Partial Penetration |                                       |   |  | Other |
| Jacob's Method (Cooper and Jacob, 1946)<br>(b) | Transient      | No                  |                                       | $u < 0.01$ where<br>$u = r^2 \frac{S}{4KDt}$  | Based on Theis Equation, straight line method based on drawdown versus time on semi-log paper<br><br>Can also be applied to single well pump tests<br><br>Condition that u values are small usually is satisfied at moderate distances from the well within a hour or so.<br><br>at $u < 0.05$ or $0.10$ , error introduced is 2 and 5% respectively |       |
| Weeks (1969)<br>(b)                            | Transient      | Yes                 | Anisotropy in the vertical plane      | $t > \frac{SD}{2K_v}$ <p>Must have at least two piezometers, one which is at a distance of at least</p> $r > 2D \sqrt{\frac{K_h}{K_v}}$ | Apply methods for fully penetrating wells to determine T and S, then determine $K_h$ & $K_v$ by data plots and substitutions into equations<br><br>Similar procedure can be applied to leaky aquifers  |       |
| Papadopulos (1965)<br>(a)                      | Transient      | No                  | Anisotropy in horizontal plane        |   | Curve fitting<br><br>Two dimensional coordinate system<br>Min. of three observation wells  |       |
| Papadopulos and Cooper (1967)<br>(a)           | Transient      | No                  | Well Storage                          |   | Curve fitting<br><br>Pumping rate is the sum of the ground water entering in the pumping well from the aquifer and the rate of decrease of water stored in well casing.  |       |

| METHOD   | APPLICATION    |                     | ADDITIONAL ASSUMPTIONS AND CONDITIONS | ANALYSIS/ PROCEDURES  | REMARKS  |       |
|--|----------------|---------------------|---------------------------------------|---|--|-------|
|  | Flow Condition | CAN ACCOUNT FOR     |                                       |   |  |       |
|  |                | Partial Penetration |                                       |   |  | Other |
| Neuman's Extension of Papadopoulos (Neuman et al., 1984) (b) | Transient      | No                  | Anisotropy in the horizontal plane    | Aquifer is penetrated by at least three wells, which are not on the same ray.<br><br>Requires drawdown data from at least 3 wells on different rays from the pumping well<br><br>Requires two pumping tests conducted in sequence | More reliable results can be obtained by conducting 3 pumping tests.   |       |
| Hantush (1966) (b)   | Transient      | No                  | Anisotropy in the horizontal plane    | Use of Theis (1906) or Cooper and Jacob (1946)<br><br>Substitution into various equations   | If the principal direction of anisotropy is known, drawdown data from two piezometers on different rays is sufficient. If not, 3 wells on different rays will be needed. |       |
| Hantush and Thomas (1966) (b)                                | Transient      | No                  | Anisotropy in the horizontal plane    | Apply methods for confined isotropic aquifers to the data for each ray of piezometers<br><br>Calculation of T in the major and minor directions of anisotropy involves substitution   |  |       |

a Described in Dawson and Istok (1991)

b Described in Kruseman and de Ridder (1991)

S = Storativity, K = hydraulic conductivity, D = thickness of saturated zone, r = distance to observation well, t = time since start of pumping

**Table 4.9 Multiple-well, Constant discharge pumping tests, leaky aquifers.**

| <b>GENERAL ASSUMPTIONS</b>   |  |  |  |  |  |  |
|--|--|--|--|--|--|--|
| 1. The aquifer is leaky.<br>2. The aquifer and aquitard have seemingly infinite and areal extent.<br>3. The aquifer and aquitard are homogeneous, isotropic (unless noted), and of uniform thickness over the area influenced by the test.<br>4. Prior to pumping, the piezometric surface and the water table are horizontal over the area that will be influenced by the test.<br>5. The well penetrates the entire thickness of the aquifer and thus receives water by horizontal flow (unless noted).<br>6. The flow in the aquitard is vertical.<br>7. The drawdown in the unpumped aquifer (or aquitard) is negligible.<br>8. Ground water flow can be described by Darcy's Law. |  |  |  |  |  |  |
| <b>Additional assumptions for transient conditions:</b>  |  |  |  |  |  |  |
| 9. Water removed from storage in the aquifer and the water supplied by leakage from the aquitard is discharged instantaneously with decline of head.   |  |  |  |  |  |  |
| 10. The diameter of the well is very small, i.e., the storage in the well can be neglected.  |  |  |  |  |  |  |

| METHOD                      | CAN ACCOUNT FOR |                     |  | ADDITIONAL ASSUMPTIONS AND CONDITIONS  | ANALYSIS/PROCEDURES   | REMARKS   |
|-----------------------------|-----------------|---------------------|--|--|---|---|
|                             | Flow Conditions | Partial Penetration | Other  |  |   |   |
| DeGlee (1930 & 1951)<br>(b) | steady state    | No                  |  | $L > 3D$ : where L represents a leakage factor and D is the saturated thickness of the aquifer                         | Substitution into equations   |   |
| Hantush (1960)<br>(b)       | Transient       | No                  | Takes into account storage changes in the aquitard | The aquitard is compressible, i.e., the changes in the aquitard storage are appreciable<br><br>$t < S \frac{D^2}{10K}$ | Type curve analysis<br><br>Generally is Theis equation plus an error function | Only the early-time drawdown should be used to satisfy the assumption that the drawdown in the aquitard is negligible |

**Table 4.9 (continued): Multiple-well, constant discharge pumping tests, leaking aquifers.**

| METHOD                                | CAN ACCOUNT FOR |                     |       | ADDITIONAL ASSUMPTIONS AND CONDITIONS   | ANALYSIS/PROCEDURES   | REMARKS   |
|---------------------------------------|-----------------|---------------------|-------|---|---|---|
|                                       | Flow Conditions | Partial Penetration | Other |   |   |   |
| Hantush-Inflection Point (1956) (a,b) | Transient       | No                  |       | <p>The aquitard is incompressible, i.e., changes in aquitard storage are negligible</p> <p>It must be possible to extrapolate the steady-state drawdown for each observation well</p>                 | Plotting drawdown versus time on semi-log paper, substitution of values into equation | <p>Accuracy depends on accuracy of extrapolating the maximum drawdown</p> <p>Two different methods, one requires one piezometer, and the other requires data from two piezometers</p>   |
| Hantush-Jacob (1955) (b)              | Steady state    | No                  |       | <p>aquitard is incompressible</p> <p><math>L &gt; 3D</math></p> <p><math>r/L \neq 0.05</math></p> <p>L = leakage factor<br/>r = distance from pumping well<br/>D = saturated thickness of aquifer</p> | Best fit straight line, substitution into equation                                    | <p>Results are an approximation because method only can be used for values of <math>r/L \leq 0.05</math> which is a restrictive limiting condition</p> <p>If errors in hydraulic parameters are to be less than 7%, <math>r/L</math> should be less than 0.16</p> |
| Lai and Su (1974) (a,b)               | Transient       | No                  |       | The aquitard is incompressible, i.e., changes in aquitard storage are negligible  | Type - curve fitting method   |   |

**Table 4.9 (continued): Multiple-well, constant discharge pumping tests, leaking aquifers.**

| METHOD                           | CAN ACCOUNT FOR |                     |  | ADDITIONAL ASSUMPTIONS AND CONDITIONS   | ANALYSIS/PROCEDURES  | REMARKS  |
|----------------------------------|-----------------|---------------------|--|---|--|--|
|                                  | Flow Conditions | Partial Penetration | Other  |   |  |  |
| Neuman-Witherspoon (1972)<br>(b) | Transient       | No                  | Determines the hydraulic characteristics of the aquitard | The aquitard is compressible i.e., changes in aquitard storage are appreciable<br><br>The radial distance from the well to the piezometer should be small (<100m) | Substitution of values into Neuman Witherspoon equations (derived from Hantush-Jacob Equation) | Need to calculate for transmissivity using one of the other methods for leaky aquifers   |
| Hantush-Jacob (1955)<br>(a)      | Transient       | No                  |  | Ground water flow in the aquitard is vertical<br><br>Aquitard is bounded above by aquitard and an unconfined aquifer and bounded below by an aquiclude            | Curve fitting and substitution of values into equation   | Drawdown in the source bed can be neglected when<br><br>$t < \frac{S'(D')^2}{10DK'}$ or<br><br>KD of source bed is >100 KD of aquifer  |
| Walton (1962)<br>(b)             | Transient       | No                  |  | - The aquitard is incompressible, i.e., changes in aquitard storage are negligible  | - Type curve fitting   | - To obtain the unique fitting position of the data plot with one of the type curves, enough of the observation data should fall within the period when leakage effects are negligible |

**Table 4.9 (continued): Multiple-well, constant discharge pumping tests, leaking aquifers.**

| METHOD                | CAN ACCOUNT FOR |                     |                                   | ADDITIONAL ASSUMPTIONS AND CONDITIONS   | ANALYSIS/PROCEDURES   | REMARKS   |
|-----------------------|-----------------|---------------------|-----------------------------------|---|---|---|
|                       | Flow Conditions | Partial Penetration | Other                             |   |   |   |
| Hantush (1966)<br>(b) | Transient       | No                  | Anisotropic in horizontal plane   |   | Substitution into equations   | - Similar to Hantush's methods for confined aquifers except initial step uses methods to calculate the hydraulic parameters |
| Weeks (1969) (b)      | Transient       | Yes                 | Anisotropic in the vertical plane | <ul style="list-style-type: none"> <li>- Large values of pumping time:<br/> <math display="block">t &gt; \frac{SD}{2K_v}</math> </li> <li>- Drawdown data from at least two piezometers, with one piezometer at a distance greater than<br/> <math display="block">2D \sqrt{\frac{K_h}{K_v}}</math> </li> </ul> -Aquitard is incompressible | - Apply methods for leaky confined aquifers, to determine transmissivity and storativity, then determine $K_h$ and $K_v$ from data plots and substitutions into equations | - Similar process can be conducted for confined aquifer   |

a Described in Dawson and Istok, 1991

b Described in Kruseman and de Ridder, 1991

t = time since start of pumping, S' = aquitard storativity, D'= saturated thickness of aquitard, D = saturated thickness of the aquifer, K'= hydraulic conductivity of aquitard

**Table 4.10 Pumping tests, variable discharge.**

| METHOD*                                | APPLICATION  | ASSUMPTIONS  | PROCEDURE  | REMARKS                       |
|--|--|--|--|-------------------------------|
| Birsoy and Summers (1980)              | -Confined<br>- Transient<br>- Aquifer pumped step-wise or intermittently at variable rates | - General assumptions for confined aquifers<br>$\frac{r^2 S}{4KD} \times \frac{1}{B_{t(n)}(t - t_n)} < 0.01$   | Analytical solution<br><br>Apply the principle of superposition to Jacob's approximation rates | Tedious process               |
| Aron and Scott (1965)                  | -Confined<br><br>-Transient<br><br>Discharge rate decreases                                | - Same general assumptions as above<br><br>- Discharge rate decreases with time sharpest decrease occurring soon after the start of pumping  | Curve fitting and analytical solutions   | Analogous to the Jacob Method |
| Hantush (1964)                         | - Confined<br><br>- Transient  | - Standard assumptions for confined aquifers<br><br>- At the start of the tests, the water level in the free flowing well drops instantaneously. At $t > 0$ drawdown is constant and its discharge rate is variable                                    | - Type curve analysis  |                               |
| Hantush-DeGlee Method (Hantush, 1959b) | - Leaky aquifers<br><br>- Transient<br><br>- Fully penetrating well                        | - Standard assumptions for leaky aquifers (see leaky section)<br><br>- $L > 3D$<br><br>- At the start of the tests, the water level in the free flowing well drops instantaneously. At $t > 0$ drawdown is constant and its discharge rate is variable | DeGlee's method using Hantush Equation   |                               |

\* Methods described in Kruseman and de Ridder (1991).

R = distance of piezometer from pumping well, S = storativity, D = thickness of aquifer, K = hydraulic conductivity,  $B_{u(n)}$  is a time function, and L = leakage factor

**Table 4.11 Methods of analysis for pumping tests with special conditions.**

| <b>CONDITION</b>   | <b>FLOW</b>    | <b>AQUIFER TYPE</b>    | <b>MODELS &amp; SOURCES<sup>2</sup></b>             |
|--|----------------|------------------------|---|
| One or more recharge boundaries  | Steady State   | Confined or Unconfined | Dietz (1943)  |
| One or more straight recharge boundaries   | Unsteady State | Confined or Unconfined | Stallman (in Ferris et al., 1962)                   |
| One recharge boundary  | Unsteady State | Confined or Unconfined | Hantush (1959a)                                     |
| Aquifer bounded by two fully penetrating boundaries  | Unsteady State | Leaky or Confined      | Vandenberg (1976 and 1977)                          |
| Wedge shaped aquifer   | Unsteady State | Confined               | Hantush (1962)                                      |
| Water table slopes   | Steady State   | Unconfined             | Culmination Point Method (Huisman, 1972)            |
|  | Unsteady State | Unconfined             | Hantush (1964)                                      |
| Two layered aquifer, unrestricted cross flow<br>Pumping well does not penetrate entire thickness | Unsteady State | Confined               | Javandel-Witherspoon (1983)                         |
| Leaky two-layered aquifer, separated by aquitard with cross-flow across aquitard                 | Steady State   | Leaky                  | Bruggeman (1966)                                    |
| Large diameter well  | Unsteady State | Confined               | Papadopoulos (1967), Papadopoulos and Cooper (1967) |
| Large diameter well  | Unsteady State | Unconfined             | Boulton and Streltsova, (1976)                      |

<sup>2</sup> Methods are described in Kruseman and de Ridder, 1991.

**Table 4.12 Recovery test methods (discussed in Kruseman and de Ridder, 1991).**

| <b>METHOD</b>          | <b>APPLICATION</b>  | <b>SOURCE</b>                           |
|------------------------|---|---|
| Theis Recovery Methods | c Confined<br>c Unsteady state<br>c Recovery after constant discharge       | c Theis (1935)                          |
|                        | c Leaky<br>c Unsteady state<br>c Recovery after constant discharge          | c Vandenberg (1975)<br>c Hantush (1964) |
|                        | c Unconfined<br>c Recovery after constant discharge<br>c Late recovery data | c Neuman (1975)                         |
|                        | c Unconfined<br>c Recovery after constant drawdown                          | c Rushton and Rathod (1980)             |
| Birsoy and Summers     | c Unconfined<br>c Recovery after variable discharge                         | c Birsoy and Summers (1980)             |

### **PRESENTATION OF DATA**

The specifics of an in-situ test should be described in a report to demonstrate that the test was conducted properly and that the data and interpretations are representative of site conditions. Work plans should be submitted prior to conducting tests to ensure that the results will be relevant to regulatory and program goals.

### **SINGLE WELL TESTS**

At a minimum, the following should be specified in a workplan for a single well or slug test:

- Preliminary evaluation of hydraulic conductivity (i.e., data used to plan the test).
- Design or proposed design of the well (e.g., depth and length of screen and filter pack).
- Proposed amount and method to displace the water, such as:
  - Dimension and weight of slug.
  - Composition of slug.
  - Manner in which the slug will be lowered and raised from the well.
  - Use of packers, and manner in which pressure will be delivered to packed-off zone.
  - Chemical quality of water to be added.
- Proposed frequency of water level measurements.
- Proposed number and location of tests.
- Proposed method of analysis.

To provide adequate documentation that the test was conducted and interpreted correctly, the following should be provided in a report:

- The design and implementation of the test (workplan content items as specified above).
- All raw data (including type curves, if used).
- Sample calculations.
- Any field conditions or problems noted during the test that may influence the results.
- An evaluation and interpretation of the data (relating it to overall site conditions).

## **MULTIPLE WELL PUMPING TESTS**

At a minimum, the following should be provided in a workplan for a conventional multiple well pumping test:

- Preliminary evaluation of hydrogeologic conditions, including all data used to plan and design the test.
- Proposed test and rationale for design, including but not limited to:
  - Geologic zone into which the pumping well is completed (i.e. areal extent, thickness, lateral and vertical extent).
  - Pumping well construction (justification should be provided if the well screen is partially penetrating).
  - Duration of pumping.
  - Rate of pumping and method for determination.
  - Location of all proposed observation wells.
  - Geologic zone(s) to be monitored (including depths, thickness, spatial relationship to the pumped zone).
  - Observation well construction.
  - Method of water level measurements (for each well).
  - Methods for gathering data used to correct drawdown and establishment of existing trends in water levels.
  - Method of data analysis.
  - Procedures for the discharge of pumped water.

After completion of a pumping test, the following should be included in a report to document that the test was conducted and interpreted correctly:

- Specific design of the test (workplan content items as specified above), including modifications from the planned configuration and rationale for any deviations.
- Date and time pumping began and ended.
- Raw data, including water level measurements, time of measurement in minutes after pumping started or ended, drawdown, pumping rates, etc. All data should be expressed in consistent units.
- Data plots and type curves, if used. All graphs and data plots should be labeled clearly.
- Calculations.
- Comments noting any external events (e.g., change in weather patterns, passage of train or heavy machinery).
- Data plots, graphs, and equations used to determine drawdown corrections.
- Data analysis method, including assumptions, limitations and references.
- Interpretation of the data using both results of the test and other available hydrogeologic information.

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**TECHNICAL GUIDANCE MANUAL FOR HYDROGEOLOGIC  
INVESTIGATIONS AND GROUND WATER MONITORING**

**CHAPTER 5  
MONITOR WELL PLACEMENT**

**February 1995**

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## CHAPTER 5

### MONITORING WELL PLACEMENT

Ground water quality at potential pollution sources can best be evaluated by chemical analysis of ground water samples collected from properly installed and constructed monitoring wells. The proper placement of monitoring wells is necessary to: 1) determine flow direction, 2) detect the release of contaminants from a suspected or known source, and 3) determine the extent of contamination. For purposes of this document, the term, "monitoring well placement", refers to the areal location of a well and the depth and the length of its screen. To detect contaminants, placement must be such that potential pathways are intercepted.

#### FACTORS DICTATING POTENTIAL CONTAMINANT PATHWAYS

Factors that should be considered to determine pathways include hydrogeologic/geologic characteristics, contaminant characteristics, and anthropogenic influences. The configuration and size of contaminant plumes and/or number of pathways at a site are composites of these factors.

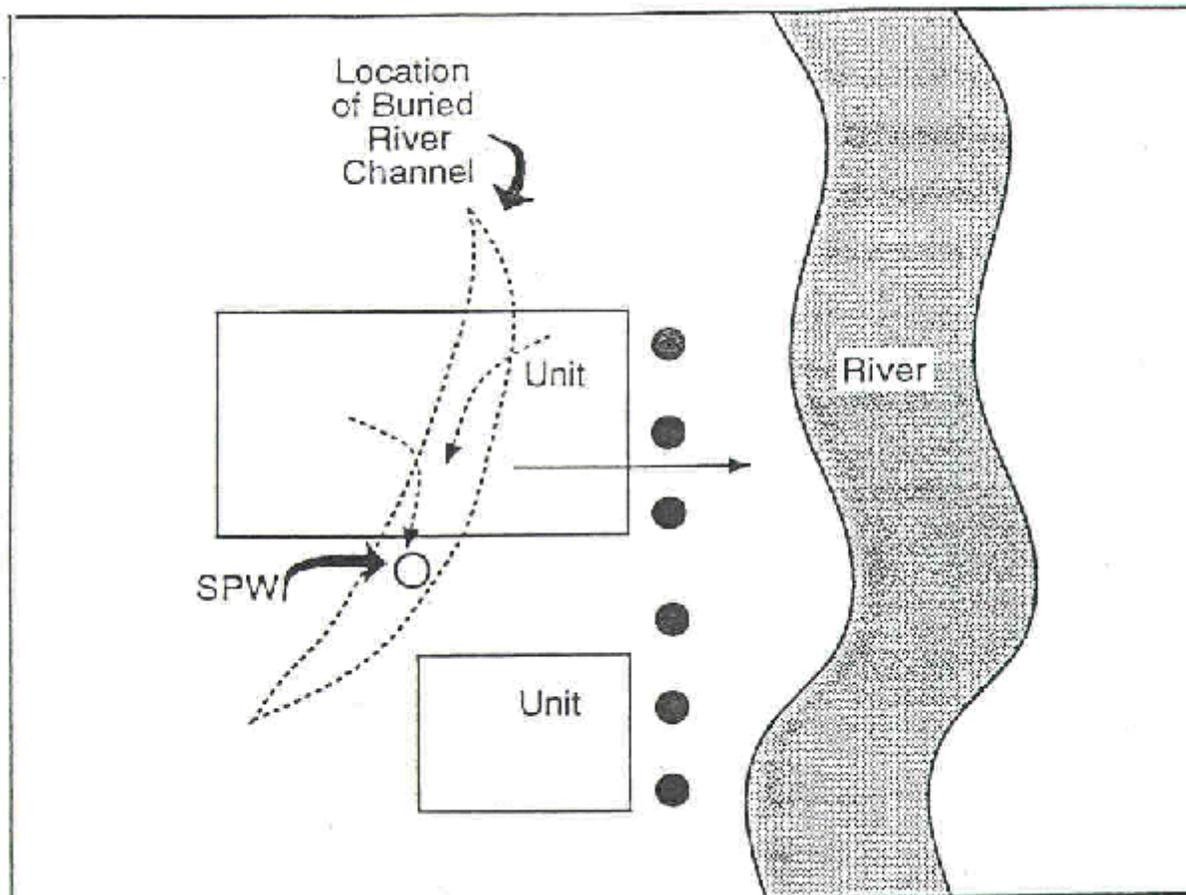
#### SITE HYDROGEOLOGY

Understanding the principles of ground water movement (flow rate, direction, and gradient) through various types of geologic materials plays a key role in developing strategies for identifying likely contaminant migration routes. Therefore, a detailed site-specific investigation should be conducted before establishing a monitoring well network. If the distribution and characteristics of materials are not defined, the zones requiring monitoring may be identified incorrectly, and releases may remain undetected. The components of a hydrogeologic investigation are outlined in Chapter 3.

Preferential pathways include zones that are fractured or have relatively high matrix hydraulic conductivity (K). The distribution of these materials can play a significant role in dictating contaminant movement. The presence of conductive zones within less conductive zones can create multiple paths of migration from a source. For example, Figure 5.1 shows a buried river channel. The regional and general, local ground water flow is toward the river; however, beneath a portion of the site, ground water is directed along the buried channel. Figure 5.2 demonstrates how water and contaminants may migrate horizontally across a perched water zone and then vertically through the unsaturated zone, transmitting contaminants to an underlying water-bearing zone over a pathway that is circuitous and not easily identified. Figure 5.3 demonstrates how complex flow patterns can occur due to fracturing. Regional/and local flow is to the south. However, the orientation, density and connectivity of fractures may initially direct ground water and contaminants in a southeastern direction, then southwest.

Ground water moves at rates both greater and less than the average linear velocity. This is due to: 1) fluids moving faster through the center of the pores than along the edges, 2) fluids travelling shorter pathways and/or splitting or branching to the sides, and 3) fluids travelling faster through larger pores than through smaller pores (Fetter, 1994). Because the invading solute-containing water does not travel at the same velocity, mixing occurs along flow paths. This mixing is called

mechanical dispersion and results in distribution of the solute at the advancing edge of flow (Fetter, 1993). The mixing that occurs in the direction of flow is called longitudinal dispersion. Spreading normal to the direction of flow from splitting and branching out to the sides is called transverse dispersion.



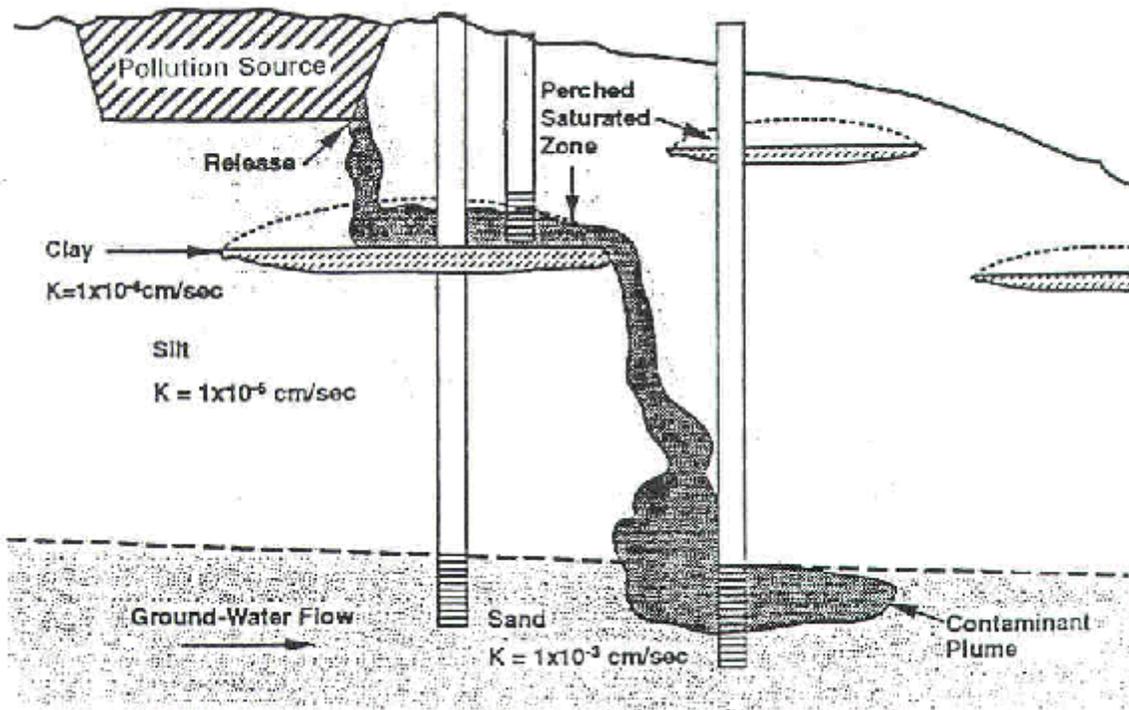
• Down gradient detection wells

• Down gradient well in buried channel

○ Preferential pathway of contaminant migration into the buried river channel

→ Local ground-water flow direction

**Figure 5.1** Geologic setting where ground water flow is affected by a buried river channel. Ground water flow is regionally/locally directed toward the river; however over a portion of the site, the ground water is directed along a buried valley (Source: Modified from U.S. EPA, 1993a).



**Figure 5.2** Contaminants and fluids migrate horizontally across a perched zone, then vertically to a water-bearing zone (Source: Modified from USEPA, 1993a).

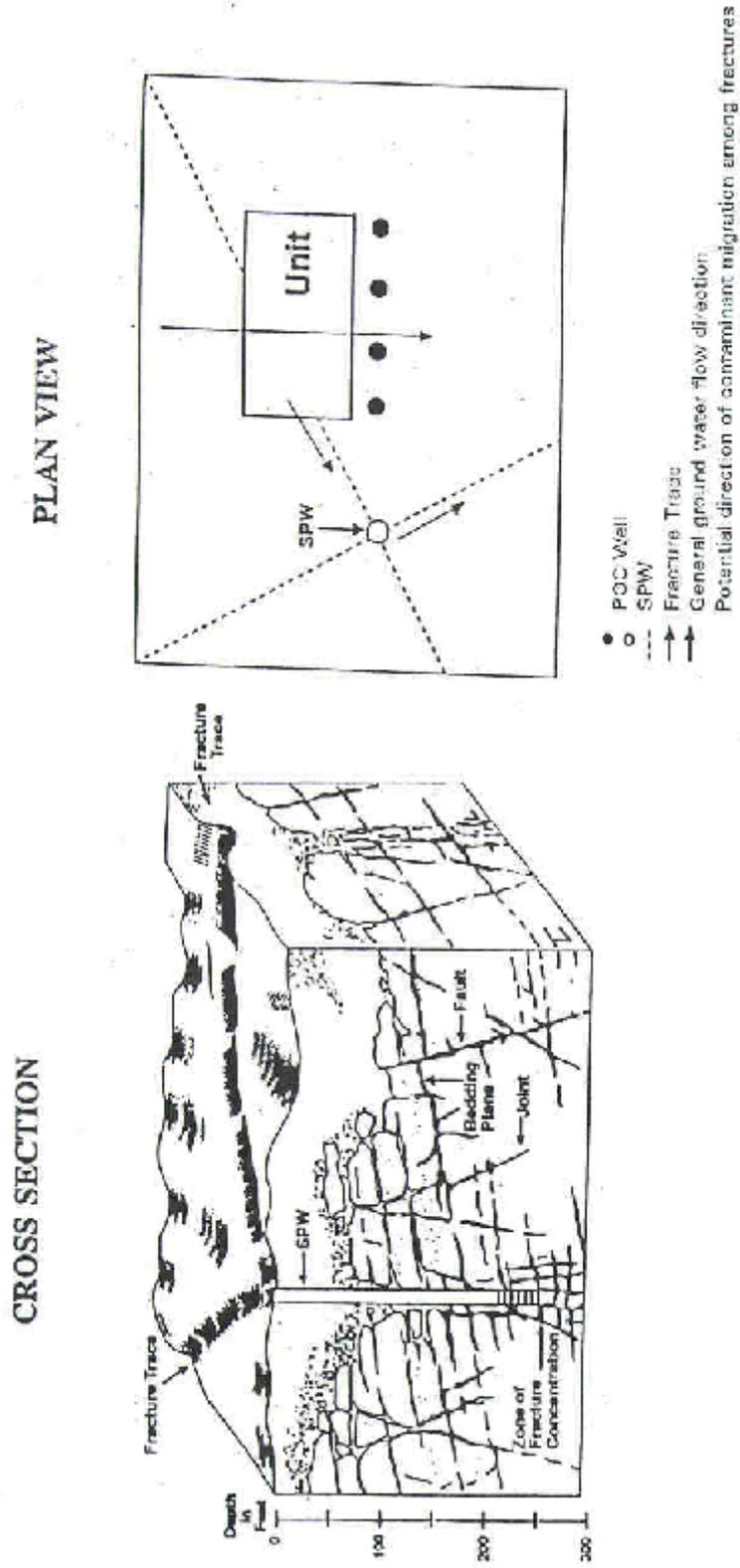


Figure 5.3 Complex fracturing creating multiple pathways for contaminant migration (U.S. EPA, 1993a)

Diffusion is the process by which ionic and molecular species dissolved in the water move from areas of higher concentration (i.e., chemical activity) to areas of lower concentration. The processes of mechanical dispersion and molecular diffusion cannot be distinguished in a ground water flow system and often are referred to collectively as hydrodynamic dispersion (Fetter, 1994). Depending on the degree of dispersion, a contaminant may form a wide or a narrow plume. Hydrodynamic dispersion phenomena also may cause contaminants to arrive at a given location significantly ahead of the arrival time expected solely from an average flow rate. General textbooks by Freeze and Cherry (1979), Fetter (1994), Luckner and Schestakow (1991), Domenico and Schwartz (1990), and Fetter (1993) should be consulted for additional information on hydrodynamic dispersion.

Colloidal transport may result in higher levels of contaminants being present than would be predicted by the mass solute transport equation. Colloids are particles with diameters less than 10  $\mu\text{m}$  and include dissolved organic macromolecules, microorganisms, microemulsions of nonaqueous phase organic liquids, mineral precipitates, weathered material, precipitates of transuranic elements such as plutonium, and rock and mineral fragments (McCarthy, 1990). Colloids may be small enough to move through the pores of an aquifer. They can sorb inorganic and organic contaminants and stabilize them, thus creating a second mobile phase.

Colloids may have a velocity greater than the average linear velocity (Enfield and Bengtsson, 1988). This is due to the size-exclusion effect, which occurs when molecules or ions are so large that they cannot travel through the smaller pores. As result, they are restricted to the large pores in which the ground water velocity is greater than average. This effect is much more prevalent in fine-grained materials that have some pores small enough to exclude some molecules (Fetter, 1993).

## CONTAMINANT PROPERTIES

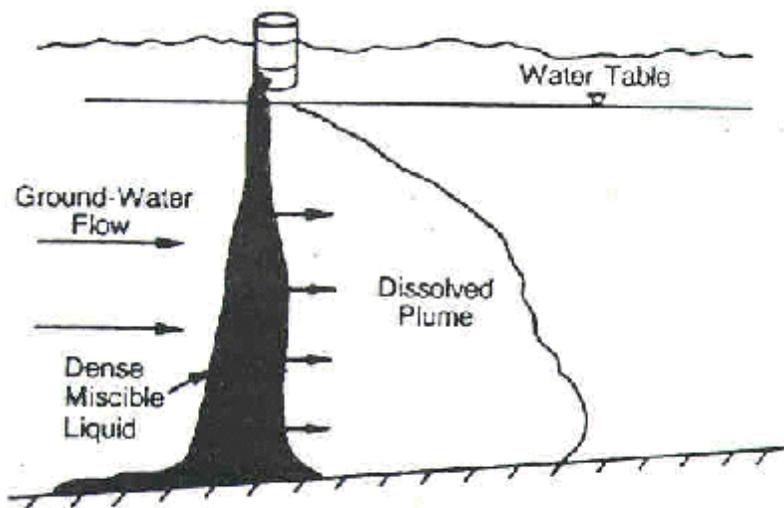
Fate and transport of contaminants are functions of their characteristics, including, but not limited to, relative solubility, density, viscosity, and potential for sorption, reaction and degradation. Multiple plumes can form if a combination of contaminants with different properties is present.

**Relative solubility** controls whether a contaminant exists in ground water primarily as a dissolved (soluble) or free liquid phase (insoluble). Movement of the dissolved phase is generally in the direction of ground water flow and is governed primarily by the processes of advection-dispersion and biological/chemical attenuation. **Fluid density** is defined as the mass of fluid per unit volume ( $\text{g}/\text{cm}^3$ ). If a contaminant is more dense than ground water, it tends to sink and may accumulate as a dense non-aqueous phase liquid (DNAPL). Conversely, a contaminant less dense tends to remain in the upper portions of saturated zones as a light non-aqueous phase liquid (LNAPL). Most LNAPLs are hydrocarbon oils and fuels and most DNAPLs are highly chlorinated compounds such as carbon tetrachloride, tetrachloroethene and PCBs (U.S. EPA, 1993a).

The density of a contaminant, in conjunction with its relative solubility, affects the shape and disposition of the dissolved and free phase plume(s). Individual contaminants can be classified based on relative solubility and density as: 1) low density and relatively soluble, 2) high density and relatively soluble, 3) low density and relatively insoluble, or 4) high density and relatively insoluble.

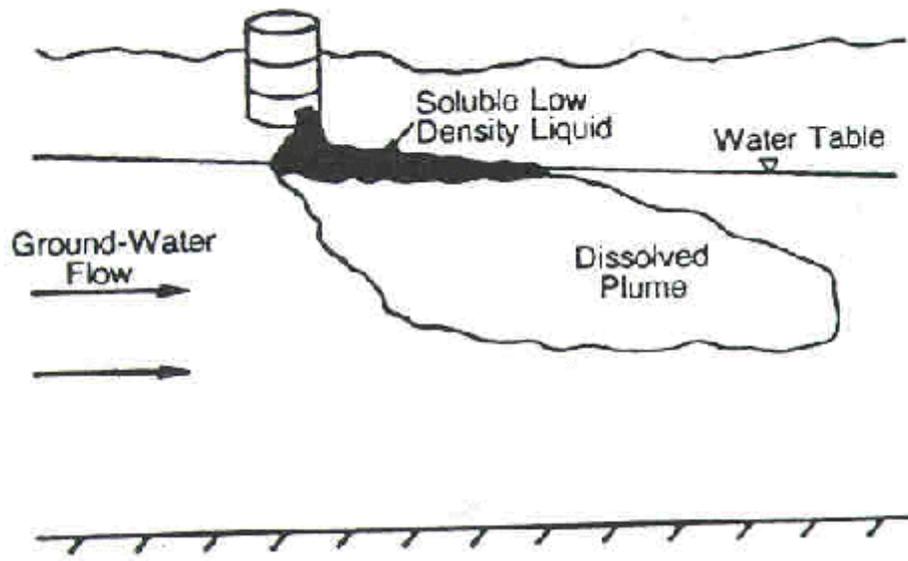
Relatively soluble contaminants are generally mobile in the subsurface and can form a large dissolved plume with a relatively small free phase plume. If a contaminant is a dense, soluble liquid, the plumes that form may cover the entire thickness of the saturated zone (Figure 5.4). Likewise, if a contaminant is soluble but of low density, the major portion of the plume will be limited to the upper portions of the saturated zone (Figure 5.5). The depth of the dissolved phase would be dependent on the vertical flow component.

Relatively insoluble liquids can exist as large free liquid plumes with a relatively small dissolved plume. DNAPLs tend to migrate vertically and coalesce at the surface of a confining layer, their movement dictated by its dip. In some cases, DNAPLs may migrate in a direction that does not correspond to the direction of ground water flow (Figure 5.6). LNAPLs generally migrate on top of the capillary fringe/water table and have an underlying halo of dissolved substance (Figure 5.7). Identifying whether or not a compound exists as DNAPL or LNAPL can be complicated by the substance in which it is dissolved. For example, free phase PCBs may be denser than water, but PCBs in oil can be transported as an LNAPL. Additional information on NAPL migration is provided in documents by U.S. EPA (1993) and Huling and Weaver (1991).

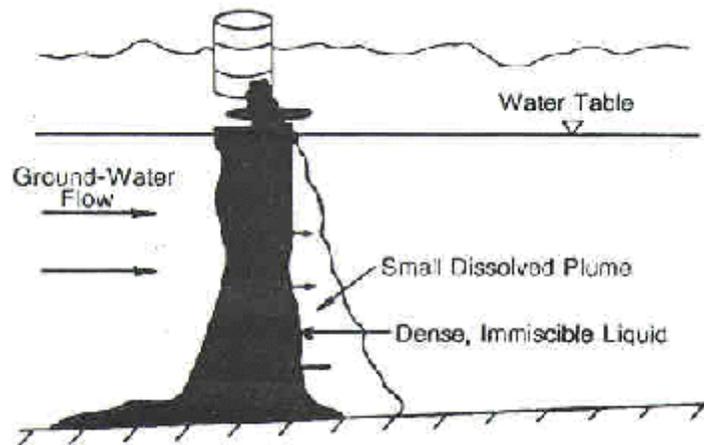


**Figure 5.4**

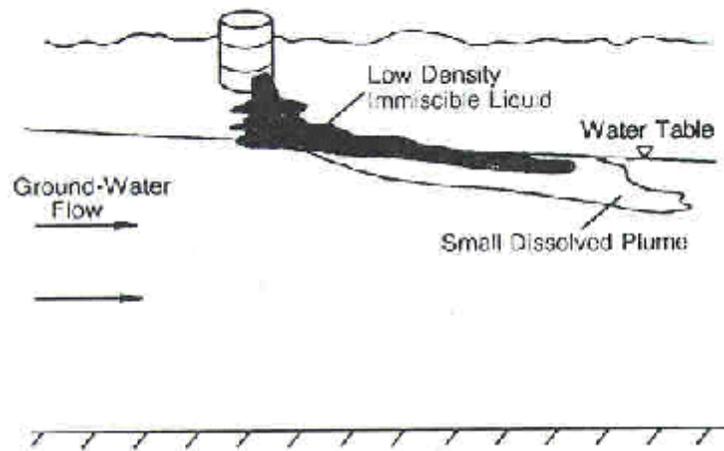
**Migration of a dense, soluble contaminant in the subsurface (Aller et al., 1991).**



**Figure 5.5** Migration of a low density, soluble contaminant in the subsurface (Aller et al., 1991).



**Figure 5.6** Migration of a dense, non-aqueous phase liquid in the subsurface (Aller et al., 1991).



**Figure 5.7 Migration of a low density, non-aqueous phase liquid in the subsurface (Aller et al., 1991)**

**Kinematic viscosity** of a non-aqueous phase liquid (NAPL) provides an indication of the potential for the compound (in its pure form) to percolate through the subsurface. Kinematic viscosity is the ratio of dynamic viscosity to density. **Dynamic viscosity** provides an indication of the ease with which a compound (in its pure form) will flow. Lower kinematic viscosity results in greater tendency to penetrate a porous media. In general, mobility can be rated high if the value is less than 0.4 centistokes (cs), moderate if between 0.4 and 0.8 cs, and low if greater than 0.8 cs (U.S. EPA, 1992).

The kinematic viscosity of water is approximately 1 cs. The relative viscosity of a NAPL indicates how fast it penetrates the subsurface relative to water. For example, tetrachloroethene, 1,1,1-trichloroethane, methylene chloride, chloroform, and carbon tetrachloride (low kinematic viscosity) flow 1.5 to 3 times as fast as water, while light heating oil, diesel fuel, jet fuel, and crude oil (high kinematic viscosity) flow 2 to 10 times slower than water (Schwille, 1981, 1988; Huling and Weaver, 1991). The relative permeability of a material can be one or more orders of magnitude higher when low viscosity fluids are moving through it than for water moving through the same material. A low viscosity LNAPL such as gasoline tends to spread on the capillary fringe/water table surface more readily than would a LNAPL of high viscosity. A DNAPL more viscous than water tends to move more slowly than the average linear velocity of ground water.

**Sorption** processes include adsorption, chemisorption, absorption and ion exchange. It is not the intent of this document to define or separate these phenomena. Sorption reactions between solutes and the geologic matrix can retard the movement of a "reactive" solute. From a practical viewpoint, the important aspect is the removal of the solute from solution, irrespective of the process (Fetter, 1993). For example, many heavy metals (e.g., cadmium, lead, and mercury) are adsorbed readily onto particle surfaces or trapped by clays through ion exchange. Adsorption of metals generally increases with increasing pH, although exceptions occur. Synthetic organic compounds in solution can be adsorbed by the organic carbon in soil.

The rate and extent of adsorption depends on the characteristics of the adsorbing agent and the chemicals and the phases in which the chemicals exist. The process by which a contaminant that was originally in solution becomes distributed between the solution and the solid phase is called partitioning. The partitioning coefficient ( $K_d$ ) is used to evaluate the effect of sorption on the retardation of an organic chemical compared with the rate of movement of ground water. The expression:

$$R = 1 + rK_d/n,$$

where  $R$  is the retardation factor that quantitatively expresses the ratio of velocity of water to velocity of the chemical,  $r$  is the bulk density and  $n$  is the porosity of the subsurface material, defines  $K_d$ .

Other parameters that may be useful in predicting extent of adsorption of an organic constituent include the octanol-water partitioning coefficient ( $K_{ow}$ ) and the organic carbon absorption coefficient ( $K_{oc}$ ). The higher the value of  $K_{ow}$  and  $K_{oc}$ , the greater the tendency for adsorption to soils containing appreciable amounts of organic carbon.

***Chemical reactions and biological and chemical degradation*** of a contaminant may form new compounds. For example, trichloroethene degrades to dichloroethene and subsequently to vinyl chloride. The properties of both the original contaminant and its degradation products must be considered. Degradation in the subsurface may not always be predictable merely from the known behavior of compounds. Verification by direct experimentation, such as bench or pilot studies, may be necessary. Also, studies have demonstrated that certain organic and acidic liquid wastes can cause desiccation cracks in clays, which can lead to increases in permeability (Brown, 1988).

## **ANTHROPOGENIC INFLUENCES**

Anthropogenic (human-made) influences can alter ground water flow direction and thus dictate contaminant pathways. Pumping wells, artificial recharge, irrigation, and changes in land use patterns (e.g., paving and construction) can also alter flow beneath a pollution source either on a continuous or intermittent basis. Other structures that can be important include, but are not limited to, infiltration galleries, storm sewers, sanitary sewers, utility lines, underground piping, and drainage tiles.

## **DESIGN OF A MONITORING WELL NETWORK**

The objective of pollution source monitoring is to evaluate ground water occurring in potential contaminant pathways and any specific zone required for regulatory purposes. For each pathway monitored, well placement should allow comparison of downgradient to background quality. The installation of an adequate network of wells generally is an iterative process. The network should be evaluated on a continuing basis as site and waste characteristics become better defined.

Design must also be based on consideration of safety, system maintenance considerations, property boundaries, accessibility, site operations, and vehicle traffic. For example, it may be difficult to locate wells due to traffic patterns, buildings, and neighboring facilities or residences. It

may be unsafe to install wells near overhead and buried electrical lines and pipe lines. An additional concern is the number, spacing, and orientation of potential pollution sources. U.S. EPA (1993a)<sup>1</sup> summarized the criteria necessary to determine whether "waste management units" need to be monitored as multiple or individual units .

Components of well placement that must be considered are number, areal location (horizontal placement), and depth and length of intakes (vertical placement). The designer must consider both vertical and horizontal placement simultaneously to develop a three-dimensional system. The following guidance cannot be applied without a sufficient understanding of the factors that dictate contaminant pathways (discussed in previous section). The importance of understanding hydrogeologic conditions and waste characteristics cannot be overemphasized (Barcelona et al., 1985).

## **NUMBER OF WELLS**

The number of wells needed is dependent on the goals of the monitoring program (which may be dictated by regulatory requirements) and site conditions. A network designed merely to investigate whether contamination has occurred (detection monitoring) may be less extensive than one installed to determine the rate and extent of contaminant migration (assessment monitoring) or to monitor remedial activities. Additionally, regulatory requirements may specify a minimum number of detection wells. However, the minimum is generally insufficient for large regulated units and when multiple or thick pathways are present.

## **VERTICAL PLACEMENT**

Vertical placement of monitoring wells should be based on the depth and thickness of pathways. Components of vertical placement include the depth and length of well screens.

### **Depth of Screens**

At a minimum, wells should be screened in the first potential pathway encountered and any zone that may be required by regulation. Depth-series water sampling during drilling may assist in determining optimum screen depth.

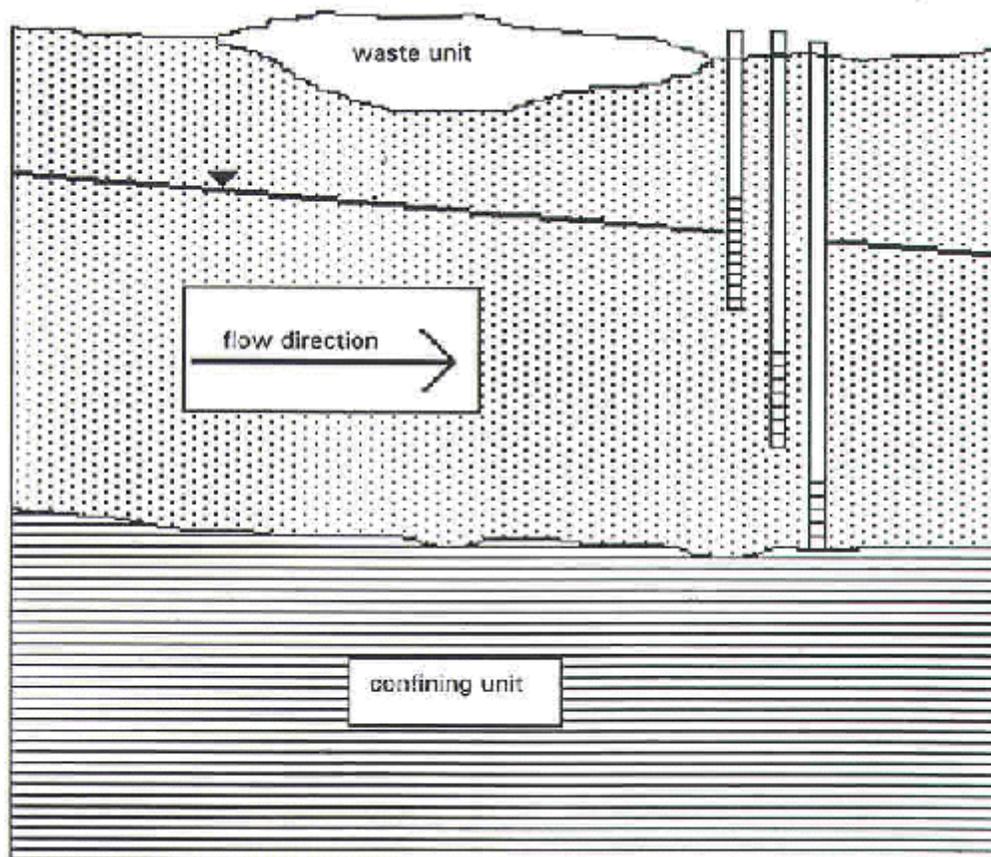
If a pathway is thick (greater than 10 feet), multiple wells installed to various depths at each location may be necessary to sample discrete vertical segments (see Chapter 7). This can allow determination of the vertical distribution of ground water contamination and flow. Installation of wells that monitor the top, middle and bottom portions of a saturated zone may be necessary (Figure 5.8). Multiple wells at the same location also may be necessary if multiple, discrete saturated zones that could act as pathways are present (Figure 5.9). Care should be taken during drilling to avoid ground water mixing between saturated zones (see Chapter 6).

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<sup>1</sup>This document (U.S. EPA, 1993a) was developed for RCRA-permitted facilities. However, technical issues addressed may be appropriate to all types of pollution source monitoring investigations.

When installing wells to detect ground water contamination by LNAPLs, it is essential that screens are placed across the water table interface and are completed at a depth and length sufficient to compensate for seasonal level fluctuations. Deeper wells may be necessary to determine the vertical extent of contamination if a significant dissolved portion is present. DNAPLs may exhibit overall vertical migration even if horizontal ground water flow predominates; therefore, at a minimum, screens need to be placed at or near the bottom of a saturated zone or just above a confining layer (Figure 5.8, well c). Multiple wells completed at different depths may be required if both LNAPLs and DNAPLs are present.

If detection monitoring has documented the presence of ground water contamination and potential exists for contaminants to occur at deeper levels, additional wells with screens at deeper horizons should be installed to allow assessment of the vertical extent of migration



**Figure 5.8 Clustering of wells due to thickness of the saturated unit.**

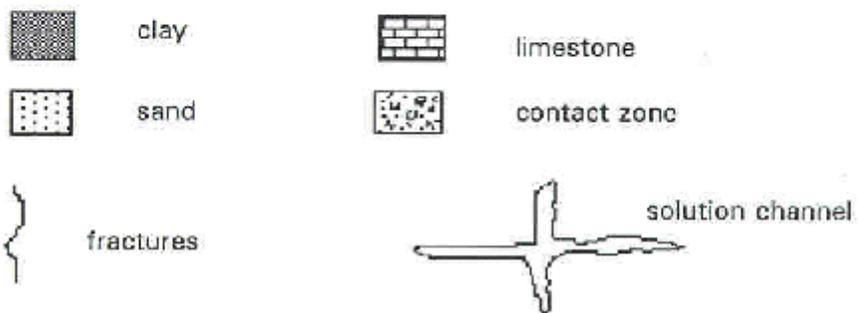
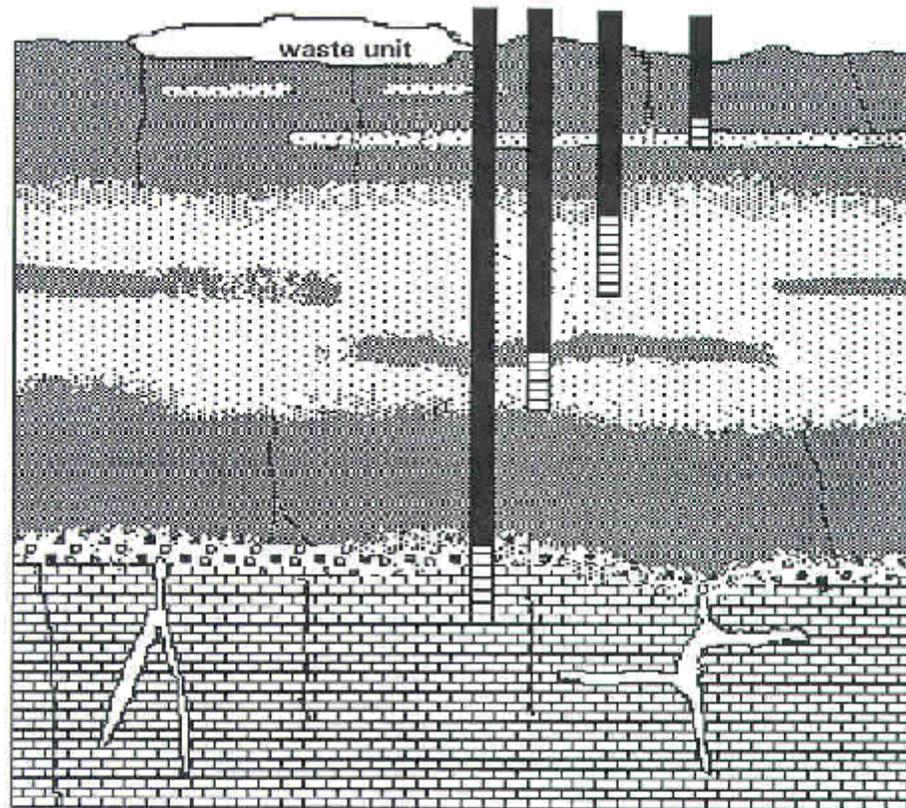


Figure 5.9 Cross-section showing a well cluster.

## **Length of Screens**

In general, it is recommended that screen lengths should not exceed ten feet; however, the complexity of hydrogeologic conditions or the intended use of wells may dictate that longer (or shorter) screens are necessary. For example, variable formations necessitate shorter screens that allow discrete portions to be sampled. If a screen crosses through several alternating zones of high and low K, each zone contributes a different volumetric flow to the total yield. If only one zone is contaminated, a sample obtained from such a well will not be representative of the contaminated zone due to sample dilution. Screens crossing several zones would also provide inaccurate data for flow direction and rate. Additionally, these wells may act as conduits for contaminant migration.

Though screen length may be dependent on the thickness of the saturated zone, it is not synonymous. Screen lengths shorter than the saturated thickness may be necessary when monitoring homogeneous zones because the behavior of the contaminant may cause it to be concentrated at a particular depth, and long screens may dilute samples. Likewise, longer screens may be necessary if a fluctuating water table occurs and the contaminant of concern is lighter than water and floats on the water table surface.

## **HORIZONTAL PLACEMENT OF DOWNGRADIENT WELLS**

Horizontal placement of downgradient monitoring wells should be based on the number and spatial distribution of potential contaminant pathways. The components of horizontal placement include location relative to the pollution source and spacing. The designer should also consider potential receptors such as water supply wells, springs, and surface waters that are downgradient of the pollution source.

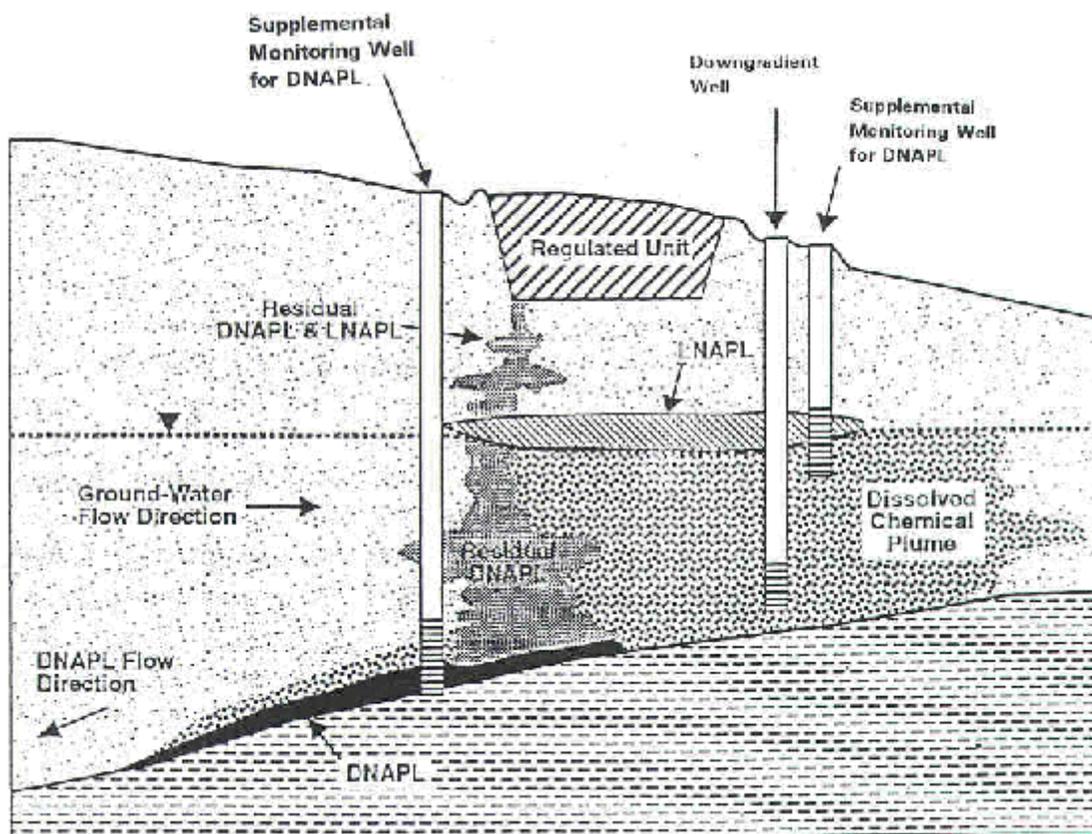
### **Placement Relative to Pollution Source**

To identify proper locations for ground water sampling, the direction of ground water flow should be determined in all potential contaminant migration pathways. Methods for determining flow direction are discussed in Chapter 3. Knowledge of flow direction is necessary to ensure that wells intended to intercept potentially contaminated ground water are placed hydraulically downgradient of the potential source. To determine if a release has occurred, the downgradient wells should be located laterally along the edge of, or as close as practicable to, the source and have intakes placed to intersect likely pathways. Placing wells through waste management units should be avoided; however, this is sometimes necessary in order to determine if contaminants are present. In this case, special well construction procedures must be followed in order to prevent downward movement of waste constituents. In addition, Ohio Revised Code section 3734.02(H) requires authorization from the Director of the Ohio EPA to engage in filling, grading, excavating, building, drilling, or mining on land where a hazardous or solid waste facility has been operated.

In situations where a potential source is topographically higher than the surrounding landscape or where a surface impoundment is located in an area where there is a shallow water table, mounding may occur. In these situations, it may be necessary to place downgradient wells entirely around the source.

In instances where a potential exists for a DNAPL to sink vertically and accumulate at the interface of a lower impermeable boundary, it may be necessary to place wells intended to detect contamination at a location upgradient from the pollution source. The dense fluid moves in response to gravity and/or the dip of confining layers and, therefore, may migrate in a direction that is different from the ground water flow direction (Figure 5.10). A knowledge of the slope of the confining layer may be needed in order to locate and monitor the dense phase. It should be noted that, if a dense phase is also soluble in water, a dissolved plume will form and move in the direction of ground water flow (Aller et al., 1991). If a DNAPL is soluble, then a detection monitoring system may only need to enable a comparison of downgradient and background ground water samples.

If detection monitoring has documented the presence of ground water contamination, additional wells should be added at increasing distances away from the source area. The wells should be sampled to assess the horizontal extent of contaminant migration.



**Figure 5.10. Migration of a DNAPL along the dip of a confining layer (modified from U.S. EPA, 1993a).**

## Spacing

Spacing refers to the distance between adjacent wells that monitor one zone. Generally, the more complex the hydrogeology, the less the spacing should be. Monitored zones that exhibit horizontal heterogeneity in material type may necessitate closer or variable spacing. Close spacing may be necessary when a pollution source is underlain by gravelly sand because of the greater potential for rapidly moving, narrow plumes to form. Conversely, zones characterized by low K and high diffusivities (such as a clay-silt) develop wider plumes and larger spacing may be sufficient. Other characteristics that may require wells to be closely spaced include location in or near recharge zones, steep or variable hydraulic gradients, high flow velocity, and variable flow direction.

The placement of wells in fractured bedrock or bedrock containing solution channels may be difficult. Fractured rock contains numerous zones that may act as discrete pathways for contaminant migration. Monitoring wells often must intersect these zones to be able to provide water or detect contaminants (Chapter 3 addresses methods to locate fractures).

Close spacing of wells may be warranted if characterizing leaks of synthetic liners. Such leaks may result in a more narrow plume than leaks from an unlined pond. Also, closer spacing may be necessary in areas that are characterized by buried pipes, utility lines, or trenches where point source leaks may occur (U.S. EPA, 1986).

## BACKGROUND MONITORING WELL(S) PLACEMENT

Background monitoring wells generally are placed hydraulically upgradient of the pollution source. The wells must provide samples that are unaffected by facility operations and representative of background ground water quality. Sampling must be sufficient to account for hydrogeologic heterogeneity and seasonal, temporal, and spatial changes in background water quality.

### Location

It is important that background wells are completed in the same stratigraphic horizons as downgradient wells to allow for representative comparisons. Screen length should be selected using the same criteria described earlier in this chapter for downgradient wells. It is also important to locate at a distance from the potential pollution source greater than the radii of hydraulic influence so that the wells will not receive contaminants during development or purging.

It may not always be possible or desirable to locate background wells hydraulically upgradient from the source. Situations that may affect the location of background wells include:

- Waste sources that are topographically higher than the surrounding landscape may be characterized by ground water flow radially away from the source due to mounding. Surface impoundments located in an area of shallow ground water also may cause mounding.
- In some instances, the unit being monitored downgradient may pinch out in the upgradient direction.

- If other activities have affected ground water quality upgradient of the pollution source, the contamination may bias the quality comparison.
- Flow direction can vary seasonally or in response to the influence of nearby surface water or ground water pumping. Due to the changes, no location is clearly upgradient under all conditions.
- The pollution source is situated adjacent to the facility property boundary such that the upgradient flow direction would dictate a background well to be located off-property.
- Upgradient locations are inaccessible due to an obstacle (e.g., other pollution sources, buildings, utilities, etc.).

In these situations, background wells do not need to be upgradient as long as it is demonstrated that 1) they are situated beyond the influence of the pollution source, 2) they are completed in the same zone as the downgradient wells, and 3) the samples provided are representative of background ground water quality. In the case of radial flow, the background wells should be located in an area considered upgradient of the predisposal flow trends.

### **Number**

Dependent upon the complexity of hydrogeologic conditions and the number, location, and size of the pollution source, more than one background well may be necessary. Some general situations that may warrant more are as follows:

- The pollution source is very large.
- Multiple potential pollution sources are present.
- The hydrogeologic setting is characterized by distinctly different hydraulic zones.
- Background ground water quality varies spatially or seasonally.

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**TECHNICAL GUIDANCE MANUAL FOR HYDROGEOLOGIC  
INVESTIGATIONS AND GROUND WATER MONITORING**

**CHAPTER 6  
DRILLING AND SUBSURFACE SAMPLING**

**February 1995**

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## CHAPTER 6

### DRILLING AND SUBSURFACE SAMPLING

Drilling and sampling of boreholes represent important components of virtually all hydrogeologic investigations and ground water monitoring programs. Drilling should cause as little disturbance of the subsurface as possible. Methods should be incorporated for identification of saturated zones and sampling of formation materials to characterize the subsurface and, subsequently, allow for proper monitoring well installation. Appropriate quality assurance/quality control (QA/QC) procedures, including equipment decontamination and measures to prevent cross-contamination of subsurface zones, must be implemented. The following sections discuss drilling, subsurface sampling, and QA/QC.

#### FACTORS AFFECTING CHOICE OF DRILLING METHOD

The choice of drilling method must be based on expected performance when hydrogeologic conditions, contaminant type and presence, and the nature and scope of the investigation are considered. Additional factors that should be considered include site access and equipment availability.

#### HYDROGEOLOGIC CONDITIONS

For most sites, hydrogeology is the most important factor in drilling method selection. If work is just beginning, initial literature and data searches for the surrounding area should be conducted to obtain a general knowledge of the local geology and the occurrence of ground water. If borings have been performed on or near the site, available logs may prove valuable.

Geologic conditions affecting the choice of methods include:

- **Material Consolidation:** Some methods can penetrate unconsolidated materials quite efficiently, but cannot penetrate rock.
- **Material Cohesiveness:** When drilling through cohesive material, an open borehole can be maintained and a well can be installed directly. However, when penetrating less stable and collapsing formations, the method must allow casing or the drill string to be used to maintain the borehole.
- **Thickness of Formation:** If thin, intermittent sand lenses are of interest, methods offer differing capabilities of allowing their identification. Most, however, can allow detection of a thick, high-yield zone.
- **Presence of Fractures:** Fractures in rock and porous, unconsolidated material may cause lost circulation of fluids and hinder penetration. Where this is a problem, casing may have to be advanced closely behind the bit. Therefore, the chosen method should be one that permits casing installation during drilling (Davis et al., 1991).

- **Presence of Cobbles and Boulders:** The presence of cobbles and boulders can hinder advancement of a bit. Where cobbles and boulders are present, a method should be chosen that can penetrate the materials effectively.
- **Heaving Sands:** Some equipment may be limited in its ability to drill below the water table, particularly in loose granular soils. With some methods, sand or gravel can flow into the drill stem, making sample retrieval and well installation difficult. Special equipment may need to be used.

Aller et al. (1991) developed an extensive rating system to determine applicable drilling methods for various generic geologic situations. Methods were rated for versatility, sample reliability, relative cost, availability, relative time required for well installation and development, ability to preserve natural conditions, ability to install particular well diameters, and relative ease of well completion and development. This system can help narrow the choices to those most applicable to site conditions.

## CONTAMINANT TYPE AND PRESENCE

Characteristics of contamination that can affect the choice of drilling method include:

- **Contaminant Phase:** If contaminants are present in the gaseous phase, the method should be able to contain the contaminants, minimize losses to the atmosphere, and reduce any explosive potential. If free product is present, methods should be utilized to determine when it is encountered. In certain situations, type and amount of contamination can be anticipated. Appropriate planning is necessary.
- **Potential for Cross-Contamination:** If a well must be installed to monitor a zone of unknown ground water quality that underlies a contaminated zone, adequate precautions must be taken to prevent cross-contamination. Generally, the portion of the borehole opposite an upper water-bearing zone should be drilled, cased, and grouted separately. A smaller diameter borehole then should be completed through the grouted casing into the underlying zone. This process is often referred to as "telescoping", and should prevent migration of contaminants from the upper zone into the lower zone. Hackett (1987) provided specific details for this technique when hollow-stem augers are used.
- **Concentration of Contaminants:** When high concentrations of contaminants exist, extra precautions for equipment decontamination and disposal of fluids (if used) and cuttings should be considered. Fluid and cuttings may need to be disposed as hazardous waste. Thus, waste minimization may be a major concern for method selection.

## NATURE AND SCOPE OF INVESTIGATION

The drilling method should allow for identification of subsurface geology and water-producing zones based on the nature and scope of the investigation. Factors that can dictate method selection include:

- **Monitoring Well Depth and Diameter:** The method must be able to meet the depth and diameter requirements of proposed monitoring wells. Casing typically ranges from two to four inches in diameter. Wells that will be pumped for aquifer tests or remediation may need to be at least 4 inches in diameter to allow access for pumps and to provide adequate yield. Sufficient space must be present in boreholes to allow adequate installation of seals and filter packs.
- **Knowledge of Site Hydrogeology:** If little or no background information is available, it may be desirable to perform a small scale hydraulic test on selected zones or obtain ground water samples for contaminant analysis. The ability to collect samples during drilling varies according to the method used and the ability to pump the zone of interest. In some cases, a screened drill string may be employed. In other cases, a well point or in-situ sampler (e.g., a hydropunch) can be driven ahead of the borehole base (see Chapter 11). The driven tool is then pumped to remove fine sediment and provide a sample. After sampling, the device is retrieved and drilling is resumed. These tools may be used with any method that allows easy access to the borehole bottom. However, they should only be used as a screening tool. A well point never should be used as a permanent monitoring well.

## OTHER FACTORS

Physical features alone potentially can influence the choice of drilling method. Moving large equipment over rough or muddy terrain or into tight spaces between physical obstructions often is required. Overhead powerlines or structures common around industrial areas may hinder rig movement. Equipment availability also must be considered. Regional geology and demand play a major role in determining equipment availability.

## DRILLING METHODS

The following discussion provides a general description of recommended drilling methods for monitoring well installation. These include hollow-stem auger, cable tool, and rotary techniques. Again, site conditions should dictate the selection. One (or a combination) should be adequate to satisfy most situations.

### HOLLOW-STEM AUGER

Hollow-stem augers are readily available in Ohio, and are recommended for penetrating unconsolidated materials. Auger rigs generally are the smallest, lightest and most maneuverable (Davis et al., 1991). Each section or flight is typically 5 feet in length. A head is attached to the first flight and cuttings are rotated to the surface as the borehole is advanced (Figure 6.1). A pilot bit (or center bit) can be held at the base of the first flight with drill rods to prevent cuttings from entering. When the bit is removed, formation samples can be obtained through the auger using split-spoon or thin-wall samplers. Generally, the introduction of fluids is not needed; therefore, ground water quality alteration usually is avoided. Hackett (1987, 1988) has written a detailed review on procedures for using hollow-stem augers.

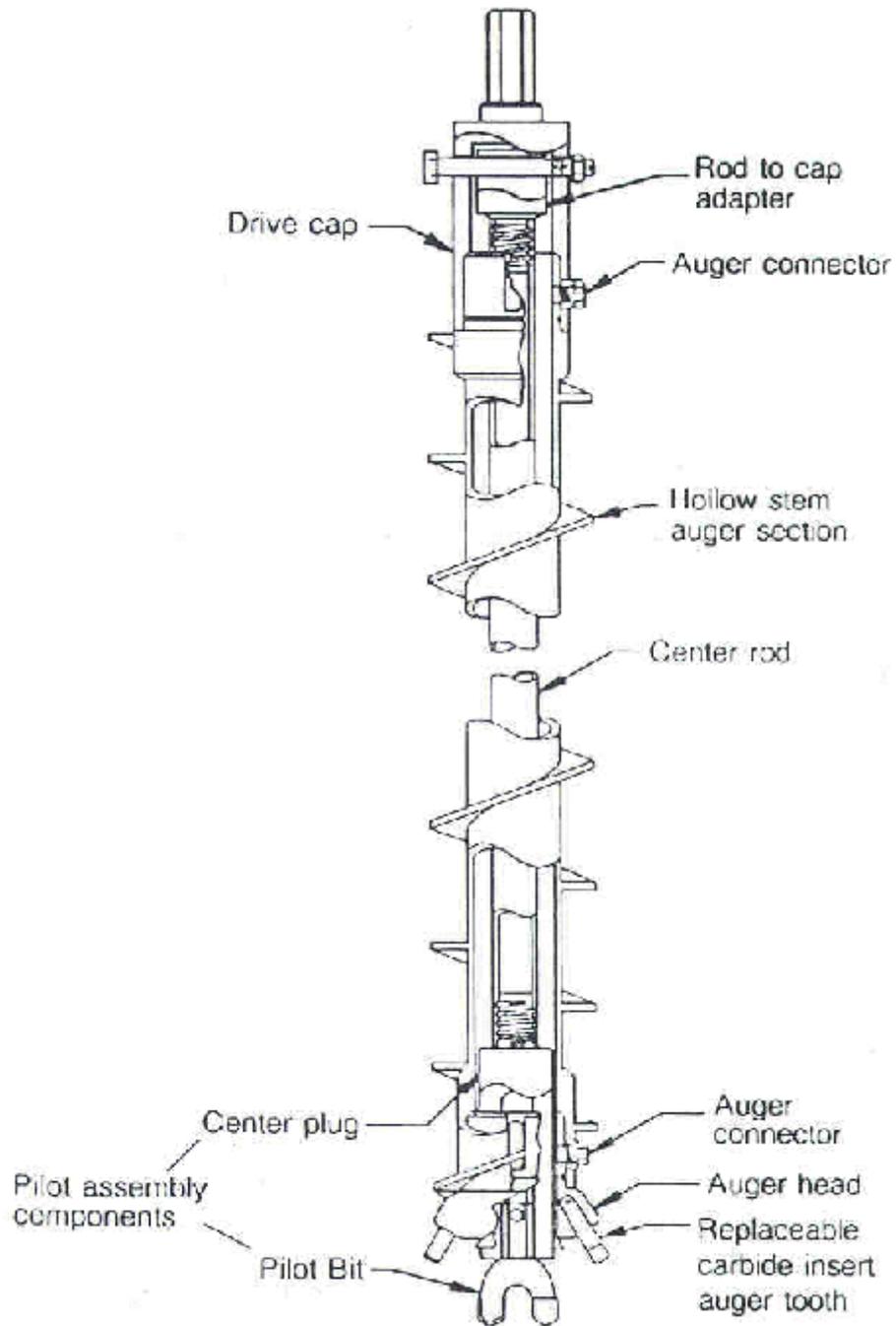
One of the major advantages of hollow-stem augers is that they allow for well installation directly through the auger into non-cohesive material. Table 6.1 shows auger sizes typically available. The inside diameter of the hollow-stem is generally used to specify size, not the diameter of the hole drilled. Appropriate clearance should be available to provide effective space for materials placement. If space is insufficient, bridging of the materials may bind the casing and auger together, resulting in the extraction of the well as the auger is removed (Hackett, 1988). Additionally, insertion of a tremie pipe may be difficult.

The most widely available size is 3.25-inch (6.25-inch outside diameter, including the flights), which has been used to install 2-inch (2.378 outside diameter) monitoring wells; however, this allows limited access. It is doubtful that materials can be placed adequately at depths below 15 feet considering the relatively small amount of clearance offered. The minimum size that should be used for installation of 2-inch diameter casing is 4.25 inches; however, larger augers may be necessary. U.S. EPA (1986a) recommended that the inner diameter of the auger be 3 to 5 inches greater than the outer diameter of the casing.

The depth capability of hollow-stem augering is dependent on site geology and the size of the rig and stem. In general, greater depths can be reached when penetrating clays than when penetrating sands; however, clays may cause the auger to bind, which limits depths. The size of the rig and stem affects the downward pressure and torque on the stem. Greater depths may be reached by smaller augers. Depths of 200 + feet can be reached utilizing a 4.25-inch hollow-stem auger, whereas 10.25-inch augers can reach a maximum depth of approximately 75 feet.

Hollow-stem augering presents some disadvantages. It cannot penetrate cobbles and boulders nor most rock formations. In some cases, obstructions can be pushed aside by spinning the augers in-place. When this is not successful, replacing the pilot assembly with a small tri-cone bit may allow penetration. Additionally, carbide-tipped cutting teeth have been developed for the upper portions of weathered bedrock, which may be useful when the unconsolidated/bedrock interface is the zone of interest.

Although augering generally allows for adequate identification of water-producing zones, the technique may cause clay and silt to smear on the borehole wall, preventing the identification of low yield zones and hindering well development. This smearing may be beneficial if it serves to impede vertical ground water movement, which reduces the potential for cross-contamination between subsurface zones. However, the possibility of this circumstance occurring is unpredictable



**Figure 6.1** Components of hollow-stem auger (Source: Aller et al., 1991; after Central Mine Equipment, 1987).

**Table 6.1 Typical auger sizes available for monitoring well drilling (in Aller et al., 1991).**

| <b>HOLLOW-STEM AUGER WITH SLIP FIT, BOX AND PIN CONNECTIONS (Central Mine Equipment Company, 1987)</b> |                                     |   |
|--|-------------------------------------|---|
| <b>Hollow-Stem Inside Diameter (inches)</b>  | <b>Flighting Diameter (inches)*</b> | <b>Auger Head Cutting Diameter (inches)</b> |
| 2 1/4  | 5 5/8                               | 6 1/4                                       |
| 2 3/4  | 6 1/8                               | 6 3/4                                       |
| 3 1/4  | 6 5/8                               | 7 1/4                                       |
| 3 3/4  | 7 1/8                               | 7 3/4                                       |
| 4 1/4  | 7 5/8                               | 8 1/4                                       |
| 6 1/4  | 9 5/8                               | 10 1/4                                      |
| 8 1/4  | 11 5/8                              | 12 1/2                                      |
| <b>HOLLOW-STEM AUGER WITH THREADED CONNECTIONS (Mobile Drilling Company, 1982)</b>                     |                                     |   |
| <b>Hollow-Stem Inside Diameter (inches)</b>  | <b>Flighting Diameter (inches)*</b> | <b>Auger Head Cutting Diameter (inches)</b> |
| 2 1/2  | 6 1/4                               | 8   |
| 3 3/8  | 8 1/4                               | 9   |
| 4  | 8 1/2                               | 11  |
| 6  | 11                                  | 13 1/4                                      |
| *NOTE: Auger flighting diameters should be considered minimum manufacturing dimensions.                |                                     |   |

The use of hollow-stem augers may be hindered by "heaving sands," which occur when a confined, saturated sand unit is encountered. Infiltration of the sand and water into the augers causes them to bind. Common strategies to alleviate this include (Aller et al., 1991):

- Water may be added to maintain a positive downward pressure to offset the pressure of the formation.
- Drilling muds can be added to further offset the pressure.
- The lower portion of the auger may be perforated to allow formation water to enter. This will equalize the hydraulic pressure and prevent entrance of sediments. Screened augers (Taylor and Serafini, 1988) have been developed for this purpose, although strength and structural integrity is lost.
- The pilot bit can be kept in place or a knock-out plug or winged clam can be added to the base of the hollow-stem to prevent infiltration.

The most common approach is to add water to the hollow-stem (Aller et al., 1991). If this is done, only clean, potable water of known chemical quality should be used. Drilling muds are not recommended because the quality of water samples and the integrity of the formation matrix may be affected. Screened augers may be viable. The pilot bit, knock-out plug or winged clam may not be useful when formation samples are needed because the removal of these devices to sample will result in the entrance of sand. The knock-out plug may be useful if prior site characterization eliminates the need for the collection of formation samples.

## **CABLE TOOL**

The cable tool is the oldest drilling method and is readily available throughout Ohio. A heavy string is dropped repeatedly to penetrate the subsurface. The bit crushes rock and causes loosening and mixing in unconsolidated formations (Driscoll, 1986). When penetrating unconsolidated materials, outer casing must follow the bit closely as the boring is advanced to prevent caving. The outer casing often is driven ahead of the hole bottom to prevent cross-contamination. The cuttings are removed periodically with a bailer.

Cable tools drill a wide variety of hole diameters to almost unlimited depths. Individual water-bearing zones and changes in formation often are more easily identified with cable tool drilling than with other methods (e.g., smearing along sidewalls generally is less severe and thinner than with hollow-stem augering). Representative samples can be collected by driving tools (e.g., split-spoon) ahead of the hole bottom. Well installation and development are relatively easy to perform when this drilling method is used. Additionally, the method typically produces a low volume of fluids and cuttings that need disposal (Davis et al., 1991).

Disadvantages of cable tool include: 1) The rate of penetration is very slow, with rates of 10 to 20 feet per day common (Davis et al., 1991); 2) Problems with "heaving" sands are possible, just as with the hollow-stem auger; 3) When drilling through unsaturated materials, water must be added to form a slurry so cuttings can be bailed; and 4) The driven outer steel casing is not adequate for monitoring well design. The undesirable effects of the presence of the steel casing can be avoided by installing an inner casing of the proper composition. The driven casing is retracted by driving it upward or raising it with hydraulic jacks; however, it may be difficult to remove long strings without special equipment.

For most site conditions and investigative goals, the cable tool is an acceptable alternative to hollow-stem augering. Its ability to penetrate both rock and unconsolidated formations with the limited introduction of fluids make it an excellent option. In general, cable tool drilling is recommended for installation of large diameter wells (6-10 inch well casing) to all depths in unconsolidated and unsaturated conditions. It also is an adequate substitute where hollow-stem augering is not feasible (i.e., deep wells in unconsolidated formations, or drilling through cobbles and boulders). Cable tools may be used to penetrate rock, but slow rates may limit the feasibility.

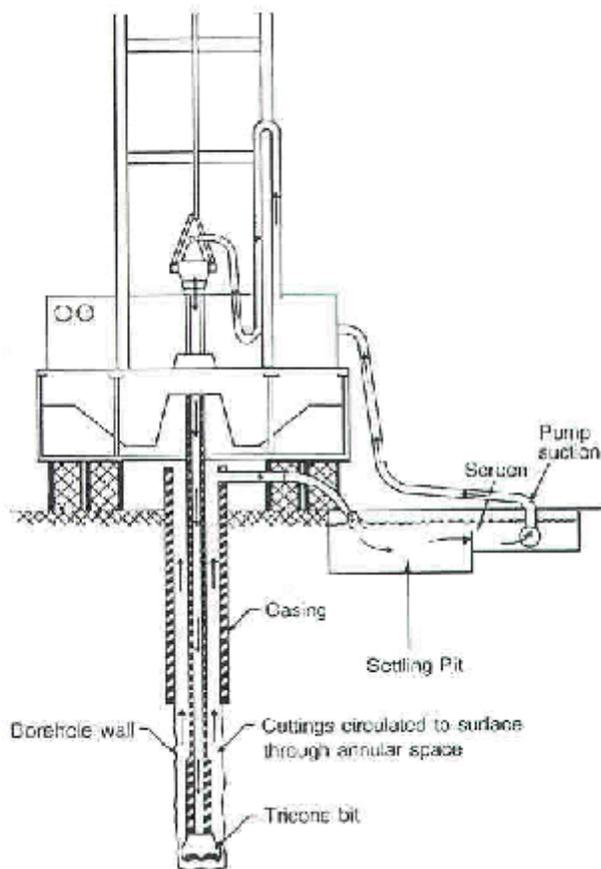
## **DIRECT ROTARY**

Direct rotary drilling is known for the speed at which it allows penetration. A bit is rotated against the sides of the borehole. Circulation of fluids (i.e., water, mud, or air) (Figure 6.2) lubricates and

cools the bit, removes cuttings, and maintains and seals the borehole wall. The fluid and cuttings return to the surface between the drill pipe and borehole wall.

Several types of bits may be utilized, including drag, roller cone, and tricone. Drag bits are used to penetrate unconsolidated and semi-consolidated deposits. Roller cone bits are preferred when drilling through consolidated rock. Tricone bits are effective for every type of formation (Driscoll, 1986).

In-situ samples may be taken by using a bit with an opening through which sampling tools can fit. However, circulation must be broken to collect samples. Though samples can be obtained directly from the stream of circulated fluid by placing a collection device in the discharge flow, their quantity is insufficient.



**Figure 6.2** Diagram of a direct rotary circulation system(Source: Aller et al, 1991; after National Water Well Association of Australia, 1984).

## **Water Rotary**

Water rotary is effective for penetrating most hydrogeologic environments (U.S. EPA, 1992); however, it is recommended only where the water will have limited effects on the formation matrix and ground water chemistry. Clean, potable water of known chemical quality transported from off-site should be used. This method works best when penetrating rock formations where a stable borehole can be maintained.

Use of water rotary is limited because the water may mix and/or react with formation water and hamper the identification of water bearing zones. In addition, the water cannot maintain the borehole wall or prevent the in-flow of fluids from unconsolidated formations, nor can it prevent cross-contamination. It may be desirable to drive casing during drilling. Another option is to complete a multiple-cased well where each section is grouted and successively smaller diameter holes and casing are completed. Heaving sands may cause a problem unless proper pressure can be maintained in the borehole water column.

## **Air Rotary**

Air rotary involves forcing air down the drill string to cool the bit and remove cuttings through the annulus (Aller et al., 1991). No muds are used that "cake" onto the borehole wall, although water and/or foams often are added to improve penetration rates (foam should not be used). Air removes cuttings effectively and maintains a clean borehole wall, thus allowing for a greater ease in well completion and development. This method can provide a wide range of borehole diameters and is readily available throughout Ohio.

Air rotary is best justified for penetrating rock (competent or fractured). Its use in unconsolidated formations is limited due to potential borehole instability. Hollow-stem augers are often used to drill through the unconsolidated deposits, while the air rotary technique is used to complete boreholes into the bedrock.

The identification of thick water-bearing zones is relatively easy, but the identification of thin zones within dry formations can be difficult due to the pressure of the air, its drying effects, and sorption of moisture by the cuttings. Where thin zones are anticipated, drilling should be slowed or stopped to allow any ground water to enter the borehole. This method will work only for the uppermost zones because shallow infiltration hinders the detection of lower zones. Increased grain size of cuttings also may aid in the identification of water-bearing zones. Cuttings are typically very fine-grained and abraded. As water is encountered (or added), grain size increases.

A disadvantage of air rotary is that compressors often introduce hydrocarbon-related contaminants to the borehole. As a result, in-line filters must be installed and checked regularly for clogging. Additionally, control and containment of cuttings at contaminated sites may be difficult. Added safety precautions should be considered due to the abundance of dust, mists and potential volatilization of organic compounds.

Down-hole hammer bits often are substituted for the roller cone bit to speed penetration through very hard, abrasive rock (Aller et al., 1991). However, because oil is required in the air stream to lubricate the hammer bit, this technique is not recommended.

The potential for cross-contamination is great due to the lack of casing to seal off specific zones. Therefore, air rotary techniques should not be used when upper layers are contaminated. Another concern is the effect on formation geochemistry and water quality due to the introduction of air. Air can change redox state and also may enhance biodegradation and volatilization. Through time and proper well development, these effects eventually may disappear. It is important that knowledge of the local geochemistry and potential contaminants be obtained and weighed into the determination of whether the method is appropriate.

### **Air Rotary With Casing Driver**

A casing driver can be used with air rotary as the bit advances. This allows unconsolidated formations to be penetrated because the driven casing prevents borehole collapse (Aller et al., 1991). Moreover, the casing can prevent cross-contamination between water-bearing zones. Normally, the bit is advanced 6 to 12 inches ahead of the casing. It also is possible to advance the casing ahead of the bit and use the drill to clean out the casing. This technique may be necessary for caving and slumping formations and can minimize air contact with the formation.

Air rotary with a casing driver is most applicable for penetrating unconsolidated formations where gravel and boulders exist and air introduction is acceptable. It also may be useful for drilling through unconsolidated formations to depths that the hollow-stem auger cannot attain, although increased friction may hinder penetration below 200 feet in dry, unconsolidated materials (Davis et al, 1991). Telescoped boreholes and casing may help overcome this problem.

Air rotary with a casing driver can be used when both rock and unconsolidated formations must be penetrated. The driver is used to complete a cased borehole through the unconsolidated materials and strict air rotary methods are used once rock is encountered. When completing a monitoring well, the surface casing can be driven upward to expose the well intake once the screen and casing have been installed. The filter pack and annular seal are installed as the driven casing is retracted. Woessner (1987) provided additional information on the air rotary with casing driver method.

### **Mud Rotary**

Mud rotary is common in the oil and water well industry. Typically, bentonite-based mud is added to maintain positive pressure and the borehole walls. The introduction of mud generally "cakes" the formation with fine material that must be extracted during well development. This virtually prevents the identification of water-bearing zones. Also, mud commonly infiltrates and affects water quality by sorbing metals and polar organic compounds (Aller et al., 1991). If organic polymer additives are used, bacteria levels in the formation will increase and cause local biodegradation that may affect organic compound analysis (Aller et al., 1991). Only in rare cases should this method be used. Prior consultation with Ohio EPA is recommended before drilling with mud.

## **Dual-Wall Reverse Circulation**

Dual-wall reverse circulation rotary involves the circulation of either mud, water, or air between inner and outer casings of the drill string (Aller et al., 1991) (Figure 6.3). The inner casing rotates, acting as the drill pipe, while the outer pipe acts as casing. The fluid is pumped down the outer casing to cool and lubricate the bit. The fluid then returns to the surface with cuttings through the inner casing. The dual wall maximizes the energy at the bit with minimal loss of fluids. The outer casing allows for stabilization of the borehole, prevents caving around the bit, minimizes cross-contamination from cuttings, and allows minimal vertical contaminant migration.

This method may not be readily available in most areas of Ohio. It is best suited for deep (>150 ft.) drilling through unconsolidated materials, but it is also efficient for penetrating rock. Dual-wall reverse circulation can drill rapidly to depths exceeding 1000 feet. Wells may be completed in the open hole or through the inner casing. Wells completed in the inner casing are limited to a maximum casing diameter of four inches (Strauss et al., 1989); however, with this size, it is often difficult to install the filter pack and annular seal through the drill string.

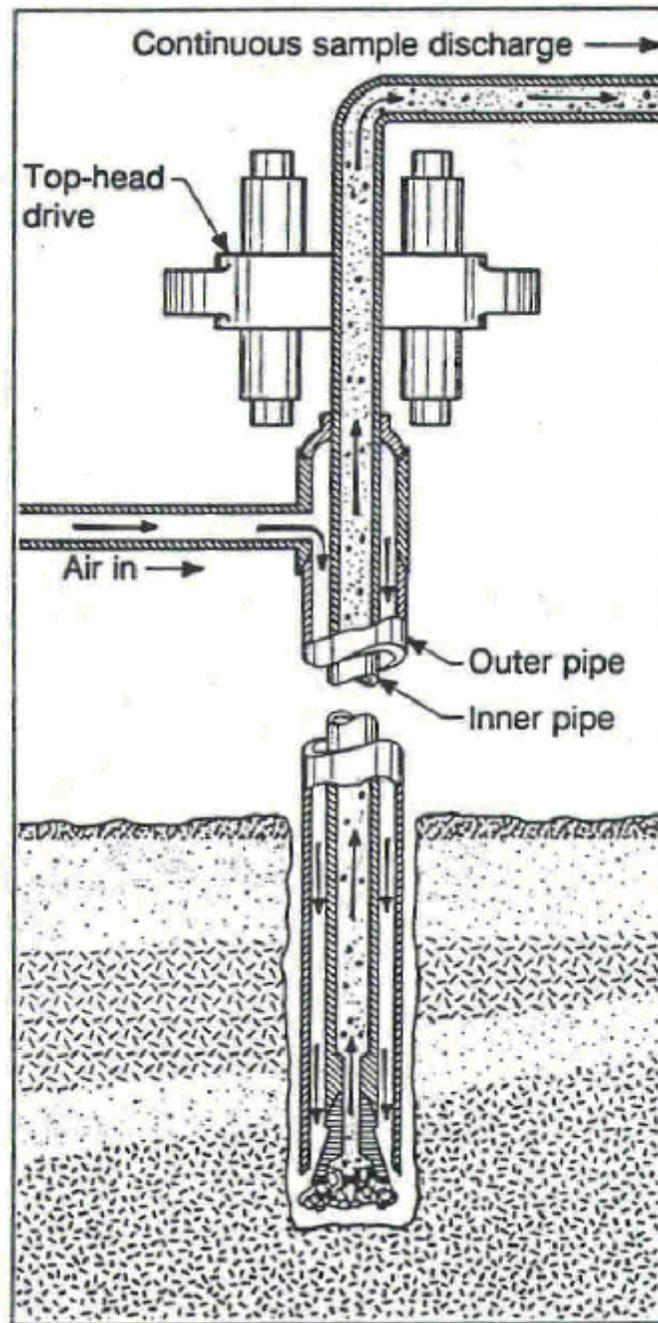
A variety of fluids are utilized with the dual-wall method. The introduction of mud is not recommended. Only clean, potable water (pre-analyzed with rigid QA/QC) should be used. If air is used, in-line filters are necessary to prevent the introduction of lubricants into the hole. Down-hole air hammer bits often are used with the dual-wall method. As with air rotary, the need for lubricants in the hammer bit makes this tool unacceptable.

Strauss et al. (1989) discussed applications of the dual-wall method and a percussion driver system. The driver advances the outer wall pipe by force instead of rotation. An open-faced bit is used that breaks the formation into fragments small enough to pass through the inner casing. These larger samples allow for more accurate determination of formation characteristics than do the pulverized cuttings of the rotary method. Split spoon samplers and Shelby tubes may be inserted through the inner casing and the open-faced bit to sample undisturbed material ahead of the drill string. Penetration rates of 60 ft/hr in unconsolidated sediments to depths of 300 to 450 feet are possible. A third outer casing can be driven while the dual-wall string advances. This is called "triple-wall" drilling. The extra casing is used to prevent cross-contamination by sealing off an upper, shallow, contaminated zone when drilling to a lower zone.

## **RESONANT SONIC**

The resonant sonic drilling method is a relatively new technique that is being used successfully in Ohio. The method performs most efficiently at depths of 30 to 300 feet. It combines rotation with high frequency vibration to advance a core barrel to a desired depth. The vibration is stopped, the core barrel is retrieved, and the sample is vibrated or hydraulically extracted into plastic sleeves or sample trays (Dustman et al., 1992). Monitoring wells can be installed through an outer casing.

Resonant sonic generally requires less time than more traditional methods. Continuous, relatively undisturbed samples can be obtained through virtually any formation. Conventional sampling tools can be employed as attachments (i.e., hydropunch, split spoon, shelby tube, etc.). No mud, air, water, or other circulating medium is required. The sonic method can drill easily at any angle through formations such as rock, sand, clay permafrost, or glacial till.



**Figure 6.3** Diagram of the dual-wall reverse circulation method (Source: *Ground Water and Wells* by E.G. Driscoll, Copyright © 1986; Johnson screens. Printed with permission).

Case histories of projects using the method demonstrate excellent results but indicate several problems (Barrow, 1994). One of the major disadvantages is the limited availability of the rigs and experts to operate them. Current rigs are operated somewhat by feel and by ear. Although numerous gauges monitoring hydraulic pressures are usually present, successful drilling is accomplished because of the skill of the driller. In addition, the equipment is relatively expensive and the cost per foot of penetration is higher than for conventional methods; however, the method has been shown overall to be more cost- and schedule-effective for hazardous waste site characterization (Barrow, 1994). Penetration rates of 15 to 60 feet per hour were cited by Barrow (1994). In addition, the method minimizes the amount of waste by-products generated.

The resonant sonic method can create elevated temperatures in samples from certain formations. This is a potential problem when projects are evaluating the occurrence of volatile organic compounds (VOCs). However, ongoing research is showing that, through proper bit design and operator procedures, the temperatures in most formations can be maintained at in-situ levels or a few degrees above.

Another potential problem is that the speed of sample generation may overwhelm the geologist responsible for logging the borehole. In addition, the amount of samples to be tested may be beyond the capacity of a laboratory to analyze on a timely schedule if it is not prepared to handle large quantities. If the project manager recognizes this, he/she can plan for these problems prior to the start of drilling.

An additional problem is that the method may destroy soft bedrock (i.e., shales); therefore, sample recovery may be low. Also, penetrating sandstone may be difficult because the drill pipe tends to "lock-up."

## **OTHER METHODS**

Several other methods are common in the geotechnical industry, including solid flight augers, jet percussion, reverse circulation, hand augers, and manual driving. While generally not recommended for monitoring well installation, there may be exceptions where these methods may be justified. In these cases (as in all others), the responsible party should document the rationale used for the choice.

**Solid flight augers** function just as hollow-stem augers except that the stem is solid. This prevents the collection of in-situ formation samples. Well installation can be conducted only in stable formations because maintaining an open borehole below the water table after auger removal is often difficult. The hollow-stem auger provides the same function and is more versatile. Therefore, hollow-stem augers are preferred at all times.

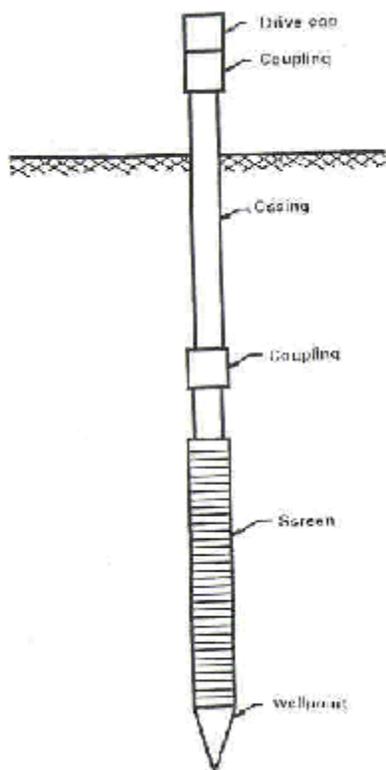
**Reverse circulation** is, in principle, the same as the rotary method but with fluids flowing in the opposite direction. The fluid flows down the borehole annulus to the bit and is returned with the cuttings up the drill string. Reverse circulation differs from the dual-wall method due to the lack of an outer casing wall to manage the fluid and prevent its contact with the borehole wall. This method typically is used to drill large diameter boreholes.

Larger volumes of water/mud are needed for this method than for the direct rotary method. The potential for large losses of fluids often is present when drilling through permeable formations. This can cause extensive ground water quality degradation around the borehole.

Jet percussion is used infrequently and involves injecting water under pressure down the drill pipe against a wedge-shaped bit. Its use is limited to shallow (<150 ft.), unconsolidated deposits with a maximum casing diameter of 4 inches. A hollow-stem auger is the preferred method for these conditions. The injection of fluid, potential for cross-contamination, and limited well diameter restrict the desirability of this method.

Hand augers are most applicable for shallow piezometer and lysimeter installation. They can reach a depth of 15 feet in unconsolidated materials. This method only can be used to penetrate cohesive materials because a stable borehole wall is necessary for well installation. Generally, the borehole cannot be advanced below the water table.

Driven well installation involves the insertion of a well point (or screen) and casing into the subsurface by hand driving or with a large weight (Figure 6.4). Driving the device through fine silts, clays, and boulders is often very difficult. Depths of 50 feet or less are common.



Driven wells should not be used as permanent data collection points. As the tool is driven, it tends to smear clays, preventing ground water from entering the screen and, subsequently, hindering well development. The annular space remains unsealed; therefore, the potential for vertical movement of surface water and/or contaminants increases. Furthermore, formation samples cannot be collected, which hinders proper screening and prevents geologic and contaminant characterization.

This method has greater application for plume delineation and tracking studies, where reconnaissance investigation can help determine the extent of contamination. In these situations, prior knowledge of subsurface geology, water-bearing zones, and sampling depths is necessary. Properly constructed monitoring wells should be installed to verify the data.

**Figure 6.4 Diagram of a well point (Source: Aller et al., 1991).**

## GENERAL RECOMMENDATIONS

General recommendations can be provided regarding selection of drilling methods and practices for sites in Ohio and the factors that dictate the choice. Experience indicates that geology is the primary factor for most sites. Table 6.2 summarizes the methods that generally apply for various geologic environments. Hollow-stem augering is recommended whenever possible. Resonant sonic is also favored; however, because of its limited availability, recommended conventional methods are generally accepted in its place.

Shallow wells in the glaciated portions of northern, western and central Ohio usually can be installed with hollow-stem augers, although penetration of deep, sandy materials may not be possible. Drilling through the consolidated materials at the surface of eastern Ohio may require use of cable tool or air rotary techniques. Air rotary with casing driver may be appropriate to retain the upper unconsolidated and weathered materials as the underlying bedrock is penetrated. Hollow-stem augering may be applicable in eastern Ohio to drill through alluvial deposits and unconsolidated and weathered surface deposits overlying bedrock. Cable tool or air rotary methods may be necessary in western Ohio to penetrate the bedrock underlying the unconsolidated shallow glacial deposits.

Methods requiring use of fluids (air, water, and mud) should be avoided whenever possible. If fluids are necessary, water and air are more acceptable than mud, which can have a long-term effect on ground water quality. Water used should be recovered. All fluids and cuttings should be routed directly to the surface and isolated from contact with the formation. Air rotary with casing driver and the use of air with the dual-wall reverse circulation method provide protection from air infiltration. The use of water for cable tool drilling may be acceptable because it is only necessary while drilling through the unsaturated zone.

**Table 6.2 Summary of drilling methods recommended for different types of geologic materials.**

| GEOLOGIC MATERIALS                       | DRILLING METHODS   |            |                       |                               |                       |
|--|--------------------|------------|-----------------------|-------------------------------|-----------------------|
|  | Hollow-Stem Augers | Cable Tool | Dual-Wall Circulation | Air-Rotary With Casing Driver | Resonant Sonic Method |
| Unconsolidated                           | X                  | X          | X                     | X                             | X                     |
| Consolidated, Fractured and/or Weathered |                    | X          | X                     | X                             |                       |
| Consolidated, Competent                  |                    | X          |                       | X                             | X                     |

## **SAMPLING SUBSURFACE SOLIDS**

During drilling of a monitoring well borehole, samples of formation material should be collected to help in the selection of filter pack and well screen sizes and aid in the placement of the well intake. Field and laboratory analysis of the samples also can provide information that can be used to prepare geologic cross-sections, identify water-producing zones, and determine contaminant concentrations.

Appropriate tools should be used. Cuttings brought to the surface are not suitable as samples because they are pulverized and do not reflect the true nature of the formation. Furthermore, accurate determination of the horizon of the cuttings is often difficult or impossible.

### **SUBSURFACE SAMPLERS**

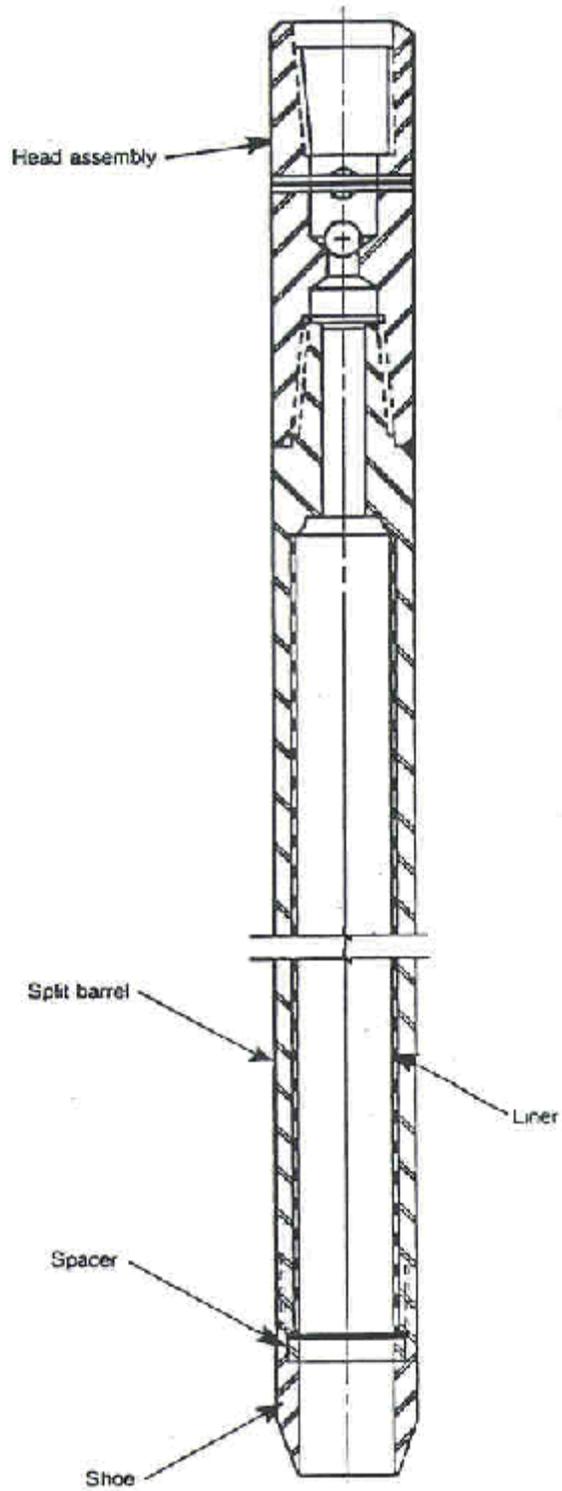
Most samplers have been designed to sample ahead of a bit. Types include thin-wall, split-spoon, core barrel, and continuous tube. The tool chosen should provide samples that represent the subsurface environment to the highest degree possible. Selection should be based on site geology, the drilling method, and investigative goals. All of the samplers discussed here are acceptable.

#### **Split-Spoon Sampler**

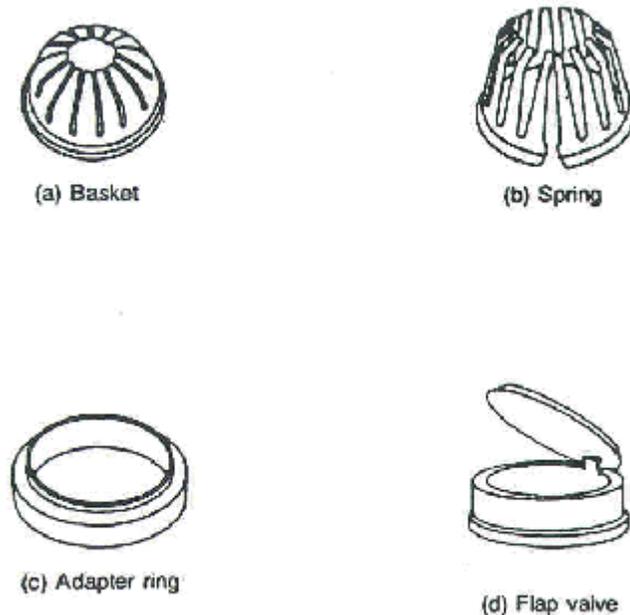
The split-spoon sampler is commonly used for collecting unconsolidated formation samples (Figure 6.5). This tool works efficiently with hollow-stem augers, which allow for sampling directly through the auger and ahead of the bit. It also works efficiently with cable tool but offers limited use with rotary. The sampler is comprised of an 18 to 24 inch long cylinder that splits in half length-wise to yield the cored sample. Samples are collected by lowering the tool to the base of the borehole with drill rods and driving it into the subsurface with a 140 pound weight (or "hammer"). The sampler should be driven about 6 inches less than its length to avoid sample compression. Coarse material sometimes catches in the sampler, preventing complete recovery. To help reduce sample loss, retainers have been designed (Figure 6.6). A complete description of collection of split-spoon samples is contained in ASTM D1586 (1994).

Split-spoon samples are acceptable for formation identification and characterization. However, they are considered to be "disturbed", due to the relatively large wall thickness of the split-spoon, which causes compaction of the sediment as it enters. Because of this compaction, this tool should not be used when samples are to be submitted for laboratory analysis for physical parameters (such as hydraulic conductivity). Split-spoon samples are acceptable for chemical analysis, however.

Standard Penetration Tests (ASTM, Method D1586) typically are conducted with the split-spoon sampler for a relative indication of formation consolidation. Generally, this involves lifting and dropping a weight across a 30 inch span and recording blow counts ("N") for each 6 inches of advancement. "Sample refusal" occurs when blows exceed 50 with little or no downward progress. The sampling effort can be stopped at this point and drilling may continue (if possible).



**Figure 6.5 Diagram of a split spoon sampler (Source: Aller et al., 1991; after Mobile Drilling Company, 1982).**



**Figure 6.6. Types of sample retainers (Source: Aller et al., 1991; from Mobile Drilling Company, 1982).**

### **Thin-wall Sampler**

The thin-wall sampler (or Shelby Tube) is used for collecting undisturbed, in-situ soil samples (Figure 6.7). The wide diameter and thin walls of the tube allow for very minimal disturbance. The tube is attached to the drill rods and slowly pushed ahead of the existing hole. Upon removal, the tube should be sealed on both ends and transported as an entire unit for analysis (e.g., permeability, moisture content, porosity etc.). The "top" or "up" direction should be marked so that the laboratory will orient the sample correctly. The procedures are described in detail in ASTM D1587 (1994).

The thin-wall sampler may not work in sand or non-cohesive sediments (Fetter, 1993). When sampling dense, cohesive materials or coarse gravel, its limited structural strength may prevent penetration. A standard 2-inch inside diameter device often will collapse in soils with "N" values of 30 or greater.

### **Vicksburg, Dennison, and Piston Samplers**

The Vicksburg and Dennison samplers are specialized tools that are used less commonly (Figure 6.8). Both are basically reinforced thin-wall samplers with larger diameters that cause

less sample deformation. The **Vicksburg sampler** has a 5.05-inch inner diameter and is structurally much stronger than the thin-wall sampler.

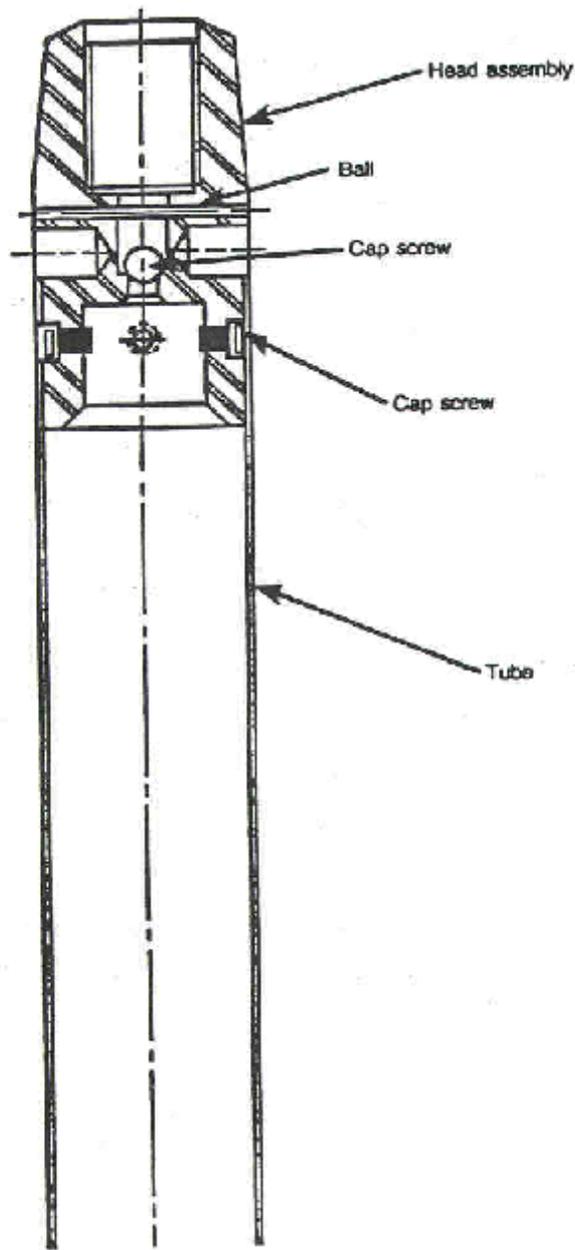
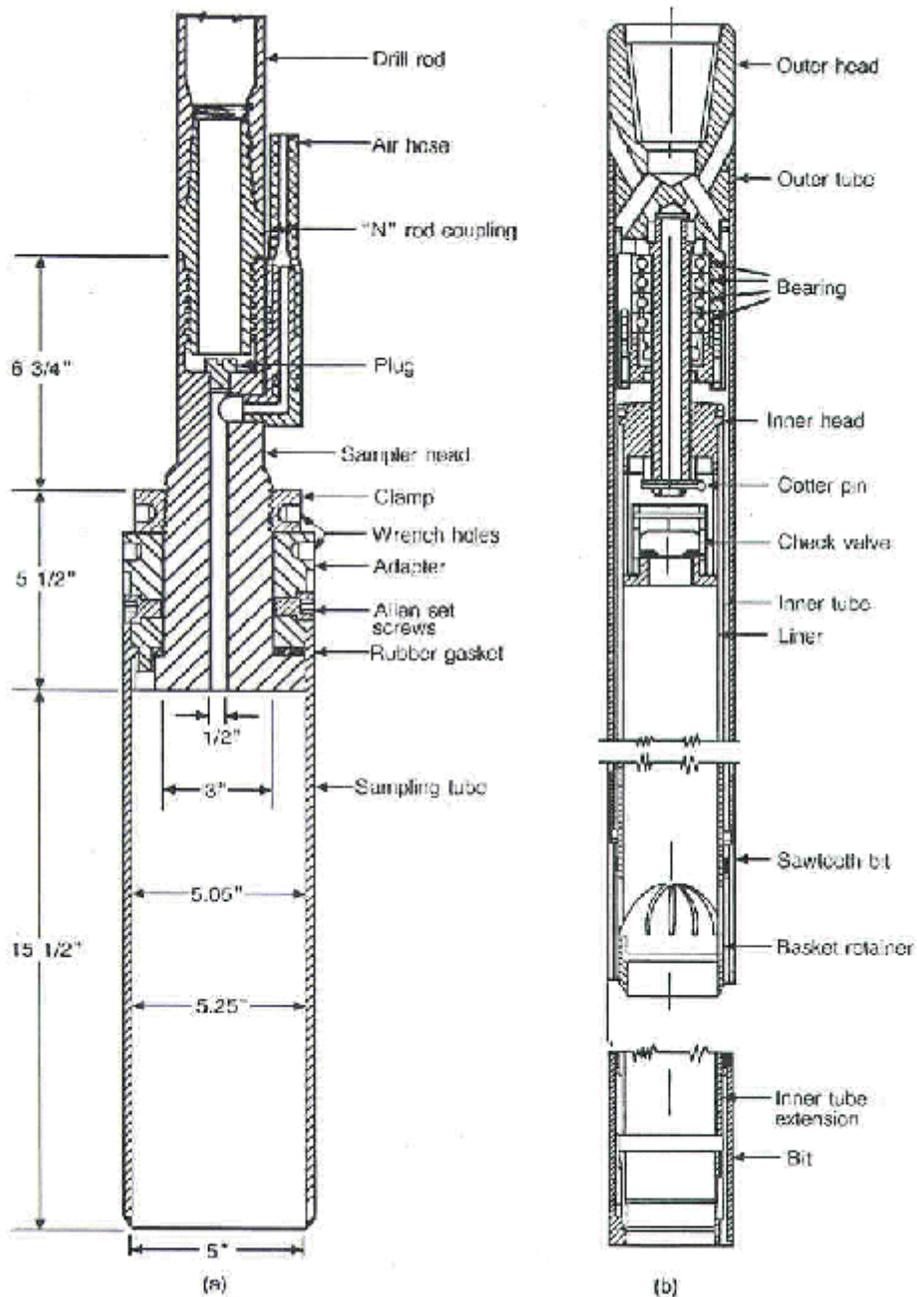


Figure 6.7 Diagram of a thin-wall sampler (Source: Aller et al., 1991, from Acker Drilling Company, 1985).



**Figure 6.8 (A) Vicksburg sampler - Source: from Krynine and Judd (1957). (B) Dennison sampler - Source: from Acker Drilling Company (1985) (Aller et al., 1991).**

The ***Dennison sampler*** is a double-wall device with a thin-wall inner tube. The outer tube is designed to penetrate dense, cohesive formations and highly cemented unconsolidated deposits. The Dennison sampler is available in standard sizes of 3 1/2, 4, 5 1/2, and 7 3/4-inch outer diameter. Measures should be taken to ensure that the auger, borehole, or drill stem can accommodate the device.

***Piston samplers*** include internal sleeve and wireline devices (Figure 6.9 & 6.10). These were designed for use with hollow-stem augers in conjunction with a clam-shell tool at the auger head (Figure 6.11) for heaving sand situations. Piston samplers are limited to collecting one sample per borehole because the clam-shell device does not close following insertion of the sampler unless the entire auger is withdrawn between samples. This is usually impossible when penetrating non-cohesive formations. Further discussion on the use and application of piston samplers can be obtained from papers by Zapico et al. (1987) and Leach et al. (1988).

### **Continuous Sampling Tube**

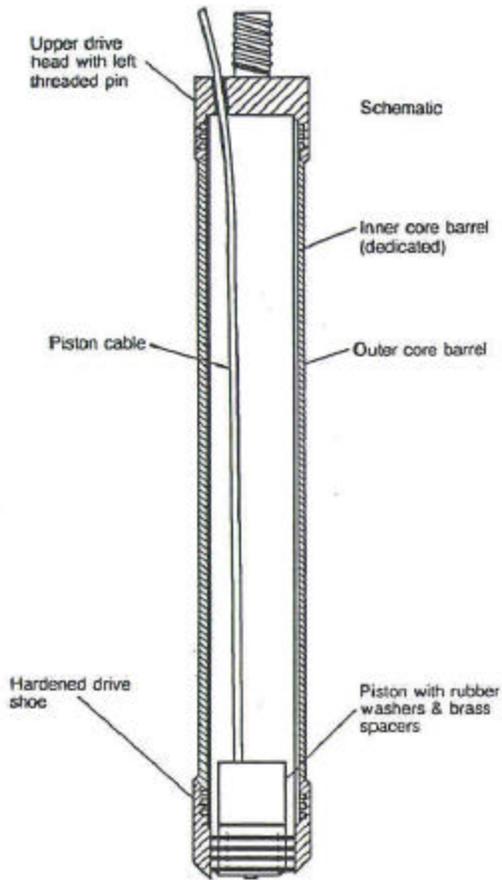
A tube has been developed to allow continuous sampling of unconsolidated material. The device can be used with hollow-stem augers and, when drilling in competent clay and till deposits, rotary methods. A 5 foot long thin-wall tube is attached ahead of the auger. A drilling rod with a special bearing head holds the continuous sampler in place. The nose of the sampler is located directly in front of the bit and advances with the auger. Once full, the column can be retrieved through the hollow-stem and a new tube inserted.

Each tube is similar to a long split-spoon in that it can be split apart to expose the sample for field identification and description. This tool enables faster and more efficient sampling than the split-spoon and thin-wall devices due to the greater length of the sample collected. This method may be most efficient when depth of sampling is great (> 100 feet) and when penetrating relatively fine-grained, cohesive formations where sample recovery is good. Sample recoveries and the use of this device may be limited in coarse-grained sands and gravels.

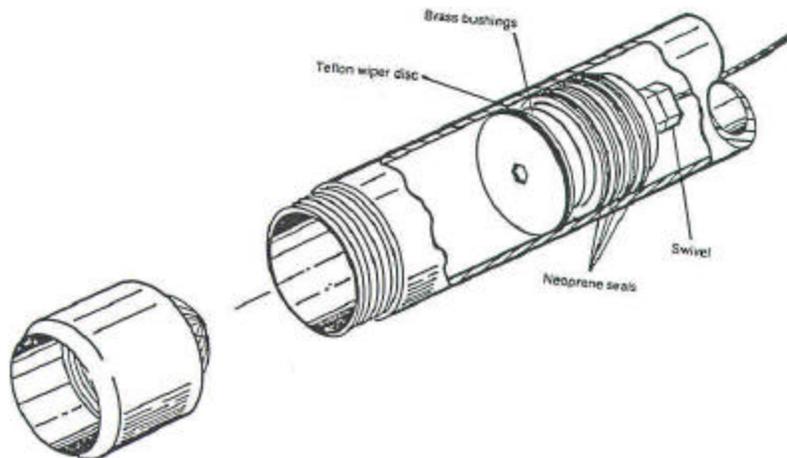
If samples are desired for laboratory analysis of physical parameters (permeability, etc.), a thin-wall sampler should be used at the desired intervals. Because the continuous sampling tube is not driven into the formation, blow counts to determine relative competency are not obtained. Instead, a hand penetrometer can be used to gather data from the samples.

### **Core Barrel**

When reliable samples of rock formations are needed, rotary drilling with coring is recommended. The conventional and wireline methods are commonly used (Aller et al., 1991). Conventional core tubes are attached to the end of the drill rod and the entire rod, core tube, and bit are removed. A wireline core barrel assembly consists of an inner barrel that can be retrieved independently of the outer barrel through a special drill rod (Winterkorn and Fang, 1975). With both methods, the ease of sample removal is enhanced with a split barrel.



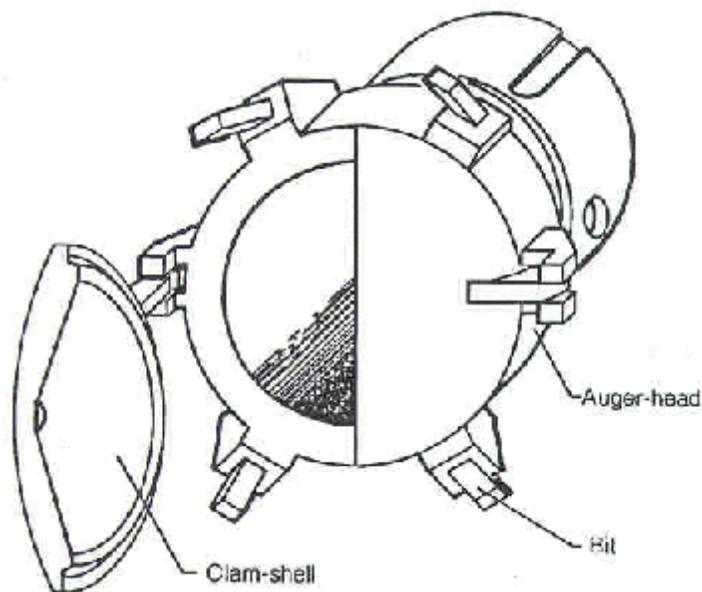
**Figure 6.9. Internal sleeve wireline piston sampler (Source: Aller et al., 1991; from Zapico et al., 1987).**



**Figure 6.10 Modified wire piston sampler (Source: Aller et al., 1991 from Leach et al., 1988).**

With the conventional method, a carbide or diamond-tipped bit is attached to the bottom of a core barrel. The sample moves up inside the tube as the bit cuts deeper. Both single and double-tube barrels can be utilized (Figure 6.12). When using single-wall barrels, the drilling fluid circulates between the core and the barrel. The fluid then flows around the bit, cooling it, and exits up the annulus to the surface. Direct contact of fluid with the collected core can destroy and erode soft and/or poorly cemented material. A double-wall barrel can be used to alleviate this problem. In this case, fluid is circulated between the two walls of the barrel, remaining isolated from the core itself. Good recoveries using the double-wall barrel have been attained in unconsolidated silts and clays (Aller et al., 1991).

The use of the conventional method requires the removal of the drill rods from the borehole to sample. This can be extremely time consuming. The wireline method allows an inner barrel to be brought to the surface without removal of equipment, which offers several advantages: 1) it saves time, 2) it reduces the chance of caving, and 3) it increases bit life by reducing the number of times that it must core through caved material on re-entry into the hole. In addition, an optional feature on the wireline barrel is a water shut-off valve that causes the pump pressure to rise, thereby alerting the driller to a core block and averting unnecessary grinding (Winterkorn and Fang, 1975).



**Figure 6.11 Clam-shell fitted auger (Aller et al., 1991; from Leach et al., 1988).**

## **IMPLEMENTATION**

Once a sampling device has been selected, potential field problems, sampling interval, formation sample storage and preservation, data requirements, sample testing, and quality assurance/quality control need to be considered.

## Common Field Problems

Potential problems that can affect field decisions and interpretation of the sampled materials must be considered. Loss of non-cohesive, fine-grained particles from samples may prevent an accurate description of the subsurface. Therefore, it is important that the reliability and amount of sample collected be observed and recorded continually. Additionally, large particles (greater than 1/3 the inside diameter of the sampler) frequently cannot be collected and often are pushed aside or may prevent penetration completely (Aller et al., 1991). In some cases, use of retainers or specialized devices may be necessary. Also, large gravel or cobbles can lodge and prevent sample collection.

When sampling alternating saturated clay/silt and sand formations, it is possible for clay or silt to plug the sampler without the collection of any sand. It is also common for the sample to be compacted inside the sampler. For example, the tool may be driven 2 feet but only collect 1.5 feet or less of sample. Careful observation of samples and prior knowledge of the subsurface may be necessary to ensure that an accurate cross-section is generated.

## Sampling Interval

Two basic sample collection intervals are used, continuous and discontinuous. Continuous sampling involves collecting a column of samples that completely represents the drilled borehole. This is the most accurate way to characterize the subsurface. The viability and ease of continuous sampling varies among sampling devices and drilling methods. All of the samplers described here can be utilized continuously except the piston sampler.

Discontinuous sampling allows for collection of samples at variable intervals. A common practice is to collect 18 or 24 inch samples at 5 foot intervals in addition to collection at the contact between two different formations. This method may not allow for a complete and accurate description of a geologic column. Discontinuous sampling may be warranted when well clusters are being installed or extensive study has already been completed and site hydrogeology is thoroughly understood. The role of continuous sampling in hydrogeologic investigations is discussed further in Chapter 3.

## Sample Storage and Preservation For Chemical Analysis

If soils are to be sampled and analyzed for contamination, appropriate QA/QC measures should be taken during collection and preservation. Field screening for VOCs using photoionization detectors ("Hnu" meters), flame ionization detectors (OVA meters), or field gas chromatographs is acceptable for choosing samples<sup>1</sup> for laboratory analysis. At no time should these field instruments be used as the sole means to determine concentrations of contamination. An appropriate number of samples should be submitted for laboratory analysis. The use of field screening as a preliminary indicator of site contamination is discussed briefly in Chapter 10.

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<sup>1</sup>The sample used for field screening should not be the sample sent to the laboratory. Two samples should be collected, one for field screening and one for laboratory analysis.

When chemical analyses of formation samples are desired, a portion should be collected and contained in a pre-cleaned glass container with a fluorocarbon (Teflon)-lined cap. Containers should be filled in the order of parameter volatility (i.e., VOCs, semi-volatiles, PCBs/pesticides, metals, etc.). When samples are to be analyzed for the presence of VOCs, the container should be filled gently and tapped slightly until completely full, removing all air space to prevent volatilization (U.S. EPA, 1987).

Pre-cleaned, laboratory-provided containers are recommended. They should be labeled clearly, with information including sample number, project number, sample depth, and borehole location. Proper storage (e.g., ice chests), packaging, and chain-of-custody should be observed. All hazardous and potentially hazardous samples should be shipped in accordance with federal (USC 1801-1812 and 49 CFR 170-179) and state transportation laws (contact the Public Utilities Commission of Ohio).

Generally, samples collected for bulk mineralogy and grain size can be stored directly in a clean container without concern for moisture or oxygen conditions. On the other hand, samples submitted for ion exchange need sealed containers because air drying is known to increase ion exchange capacity (EPRI, 1985). Microbial populations also are known to change after drying and rewetting (EPRI, 1985). If anaerobic conditions exist in the subsurface, the container should have all oxygen removed. This is important if the sample is to be analyzed for ion exchange capacity, soluble metal concentrations, or Eh (EPRI, 1985).

Samples collected in thin-wall tubes generally are stored and transported within the tubes themselves. Upon removal, the tubes should be sealed and cooled to 4° C. They should not be frozen because freezing can change sample pore structure. For samples to be analyzed for VOCs or where an anaerobic environment must be maintained, the tubes should be sealed with tight-fitting Teflon caps. The caps should be taped and covered with a silicone grease or paraffin sealant. The sealant should not interact with the sample (EPRI, 1985). In general, samplers lined with plastics are not recommended if samples are to be transported within the tube. Plasticizers could leach and/or contaminants could be adsorbed by the liner.

Additional guidance on storage, preservation, and transport has been provided for soil samples by the ASTM in Standard Method D4220 and for rock samples by Winterkorn and Fang (1975). It is beyond the scope of this document to provide a complete description of procedures for the collection of formation samples submitted for chemical analysis. For more specific information and procedures, the U.S. EPA (1986b) document, Test Methods for Evaluating Solid Waste, Physical/Chemical Methods (SW-846) should be consulted.

## **Data Requirements**

Logs should be prepared for each boring identifying soil types and features or bedrock lithology. A log should indicate and document the data acquired, as well as any problems that were encountered. For a detailed discussion of data requirements for boring logs, see Chapter 3.

## **QUALITY ASSURANCE/QUALITY CONTROL (QA/QC)**

Proper quality assurance/quality control measures must be implemented during drilling and subsurface sampling. This may include, but may not be limited to, decontamination of equipment, containment and disposal of investigative by-products, control and sampling of added fluids, and personnel safety.

### **DECONTAMINATION**

Decontamination is the process of neutralizing, washing and rinsing equipment that comes in contact with formation material and ground water that is known or suspected to be contaminated (Aller et al., 1991). Without effective procedures, any data generated are subject to critical scrutiny (Nielsen, 1991). The purpose of decontamination is to ensure that representative samples are collected for analysis and to prevent cross-contamination between sites, boreholes, or zones.

The focus of this section is decontamination of field equipment. However, personnel also should implement appropriate levels of decontamination upon exiting the work area. This can range from extensive washes and rinses and appropriate clothing removal in a designated decontaminated zone to a very limited program requiring glove disposal and hand cleaning only. The degree depends mainly on the nature of contamination and the scope of the drilling program. Personnel decontamination should be detailed in a safety plan. Information on personnel decontamination can be found in U.S. EPA (1984).

Planning a program for decontamination requires consideration of:

- The location of a designated area for decontamination.
- The types of equipment that require decontamination.
- The frequency that specific equipment requires decontamination.
- Decontamination procedures and cleaning agents.
- The method for containerizing and disposing of decontamination fluids.
- The use of quality control measures to monitor the effectiveness of decontamination.

### **Decontamination Area**

A decontamination area should be designated. A typical layout is shown in Figure 6.12. At least three zones should be defined, including an exclusion zone, a contamination reduction zone, and a support zone. The intent of this system is to limit the production of contaminated waste and reduce the spread of contamination. It is important that the area be located at a sufficient distance away from the borehole to avoid contamination due to accidental spills.

### **Typical Equipment Requiring Decontamination/Disposal**

Table 6.3 lists typical equipment requiring decontamination. Porous material such as rope, cloth hoses, wooden blocks, and handles cannot be decontaminated completely and should, therefore, be disposed properly. Personal gear such as gloves, boot covers, and clothing that continually

come in contact with equipment, cuttings, and ground water should be cleaned properly or disposed when necessary.

### Frequency

Drilling equipment should be decontaminated before and after arrival and between locations. Further activity is necessary when penetrating an upper contaminated zone followed by a lower uncontaminated zone. All sampling equipment should be cleaned between samples. Disposal of gloves, boot covers, tyvek suits, etc. may be necessary during each boring and/or between borings.

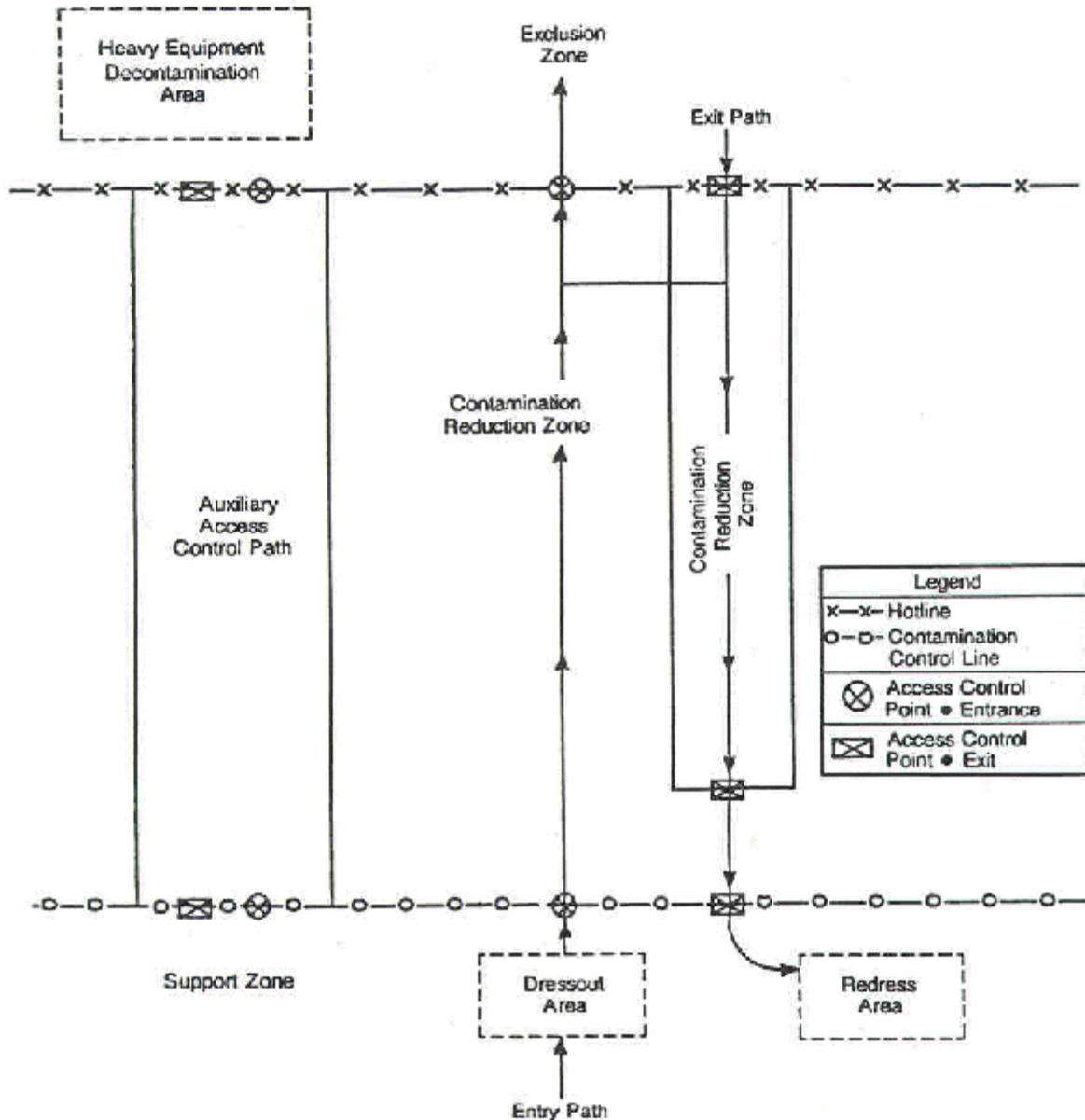


Figure 6.12 Typical layout of a decontamination area (U.S. EPA, 1984).

**Table 6.3 Typical equipment requiring decontamination when drilling and sampling subsurface materials.**

| FIELD ACTIVITY     | EQUIPMENT TO BE DECONTAMINATED                                    |
|--------------------|---|
| Materials sampling | Sampling devices<br>Sample inspection tools<br>Downhole equipment |
| Drilling           | Drill rig, rod, and bits<br>Augers                                |

### **Procedures and Cleaning Solutions**

The decontamination process and fluids depend on the purpose of the investigation and the level of QA/QC required. For example, procedures used when installing a detection monitoring well network at a newly proposed facility may, in general, require less stringent practices than when investigating known or suspected contamination.

Activities must be selected based on their chemical suitability, compatibility with the constituents to be removed during decontamination, and the concentrations of the constituents anticipated. For example, when metals are the contaminant of concern, the process should include an acid rinse. If organics are a contaminant, a solvent rinse should be incorporated. The procedure may be complex when more than one contaminant group is under investigation (Nielsen, 1991). Rinsing agents should not be an analyte of interest.

Procedures may be dependent on whether the equipment comes in contact with the collected sample. Sample-contacting equipment includes devices that contact samples that undergo physical or chemical testing (i.e., split-spoon, shelly tube). Non-contacting equipment includes devices that do not contact samples (i.e., augers, drilling rods, drill rig), but do, however, come into contact with contaminated or potentially contaminated materials. Table 6.4 outlines recommended decontamination sequences and procedures, derived from the current ASTM Standard D5088-90 (1994).

### **Quality Control Measures**

The decontamination procedures should be documented. Additionally, samples should be collected to evaluate the completeness of the process. This generally involves collecting the final rinse and sending it to a laboratory for chemical analysis. The frequency of this evaluation is dependent on project objectives. At a minimum, it is recommended that a QA/QC sample be collected after every tenth wash/rinse.

**Table 6.4 Decontamination procedures for subsurface sampling.**

| EQUIPMENT CONTACTING SAMPLES:   |
|---|
| <ul style="list-style-type: none"><li>C Wash disassembled equipment with non-phosphate detergent and potable water.</li><li>C Rinse with potable water.</li><li>C If more rigorous decontamination is needed (e.g., subsurface is known or suspected to be contaminated, and samples are being collected for chemical analysis) the following sequence should be followed:<ul style="list-style-type: none"><li>- If analyzing the subsurface samples for metals, rinse with 10% hydrochloric or nitric acid (note: dilute HNO<sub>3</sub> may oxidize stainless steel).</li><li>- Rinse liberally with deionized/distilled water (ASTM Type II or equivalent).</li><li>- If analyzing the subsurface samples for organics, rinse with solvent-pesticide grade isopropanol, acetone, methanol, or hexane, alone or, if required, in some combination. Solvent rinse should not be an analyte of interest.</li></ul></li><li>C Rinse liberally with deionized/distilled water (ASTM Type II or equivalent).</li><li>C Air dry thoroughly before using.</li><li>C Wrap with inert material if equipment is not to be used promptly.</li></ul> |
| EQUIPMENT NOT CONTACTING SAMPLES  |
| <ul style="list-style-type: none"><li>C Large equipment should be steam-cleaned or cleaned with a power wash; smaller equipment can be hand-washed with non-phosphate detergent.</li><li>C Rinse with potable water.</li><li>C More rigorous procedures than described above may be employed if more stringent QA/QC is desired (e.g., known or suspected subsurface contamination).</li></ul>  |

## **INVESTIGATION BY-PRODUCTS, CONTAINMENT AND DISPOSAL**

A variety of waste is produced during drilling and sampling that may need to be contained and disposed properly. Typical by-products include: 1) decontamination solutions and rinse water, 2) disposable equipment (gloves, tools, boots, etc.), 3) drilling mud (if used) and borehole cuttings, 4) well development and purging fluids, and 5) soil and rock samples. It is not the intent of this document to define/determine Ohio EPA policy on disposal of these by-products.

All cleansers and rinses should be collected and stored for proper characterization and disposal after use. Collection/storage systems may need to include special concrete or plastic-lined decontamination pads with collection sumps for cleaning large equipment such as rigs. Plastic-lined trenches and/or wash tubs often are used for lighter equipment. Thick plastic sheets typically are placed on the ground around the borehole extending beyond the work area. This prevents contact of the cuttings and drilling fluid with the surface, thereby preventing the spread of contamination.

Investigation by-products typically should be collected in 55 gallon drums and stored away from the drilling area. The contents must be characterized to determine if they are solid or hazardous waste, which will dictate the proper disposal method. Solid waste may be disposed at a solid waste landfill. Hazardous waste must be properly transported for either incineration, landfill disposal, and/or treatment. Hazardous waste may not be stored on-site for more than 90 days without a permit. After 90 days, the site may be considered a hazardous waste storage facility and compliance with applicable rules becomes necessary (see OAC 3745-52-34).

## **CONTROL AND SAMPLING OF ADDED FLUIDS**

The addition of fluids should be prevented or controlled whenever possible. If a fluid must be added, the activity should be documented. The amount added should be recorded and full recovery should be attempted during drilling and development. All water used should be potable and of known chemical quality. Sampling of any water or mud added should be conducted. Samples should be analyzed in a laboratory to verify that contaminants were not added to the borehole.

Appropriate air filtering devices should be used and changed regularly if the air rotary technique is used. This is necessary to prevent contamination from the petroleum lubricants used in the compressor.

## **PERSONNEL SAFETY**

The safety of on-site personnel should be a high priority for any site investigation. Contingency plans should be prepared and personnel should be familiar with the procedures. A plan should include responsibilities of personnel, information and procedures for emergencies, decontamination protocols, operating procedures and training for the use of various drilling and safety equipment, site control (site entry and access areas, etc.), and the assessment of environmental exposures and health hazards. Potential hazards include utilities, noise, site conditions (topography, debris, etc.), temperature, chemical, radiation, biological, toxic, and confined spaces. Many of these potential hazards can be identified before site entry through reconnaissance studies. Assistance in locating utilities can be obtained from Ohio's "Call Before You Dig" service (1-800-362-2764). Continual

monitoring of the air, soil, and ground water for explosive potential, oxygen content, and VOCs, etc. can help identify hazards or allow for appropriate precautions to be implemented.

The degree of effort for safety depends on the nature and scope of the particular investigation. When drilling in highly contaminated areas, extensive efforts and detailed plans may be necessary. In areas with low- to non-detectable contamination, the level of effort may be less extensive. At all times, the unexpected should be expected. For further information on health and safety issues, see Maslansky and Maslansky (1991), Aller et al. (1991), HWOER (1989), NIOSH (1985), NWWA (1980), NDF (1986), U.S. EPA (1984), and 29 CFR 1910.22.

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**TECHNICAL GUIDANCE MANUAL FOR HYDROGEOLOGIC  
INVESTIGATIONS AND GROUND WATER MONITORING**

**CHAPTER 7  
MONITORING WELL DESIGN AND INSTALLATION**

**February 1995**

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## CHAPTER 7

### MONITORING WELL DESIGN AND INSTALLATION

In order to collect representative ground water samples, it is necessary to construct monitoring wells to gain access to the subsurface. This chapter covers installation and construction of single-riser/limited interval wells, which are designed such that only one discrete zone is monitored in a given borehole. It is important that efforts focus on intervals less than 10 feet thick and be specific to a single saturated zone.

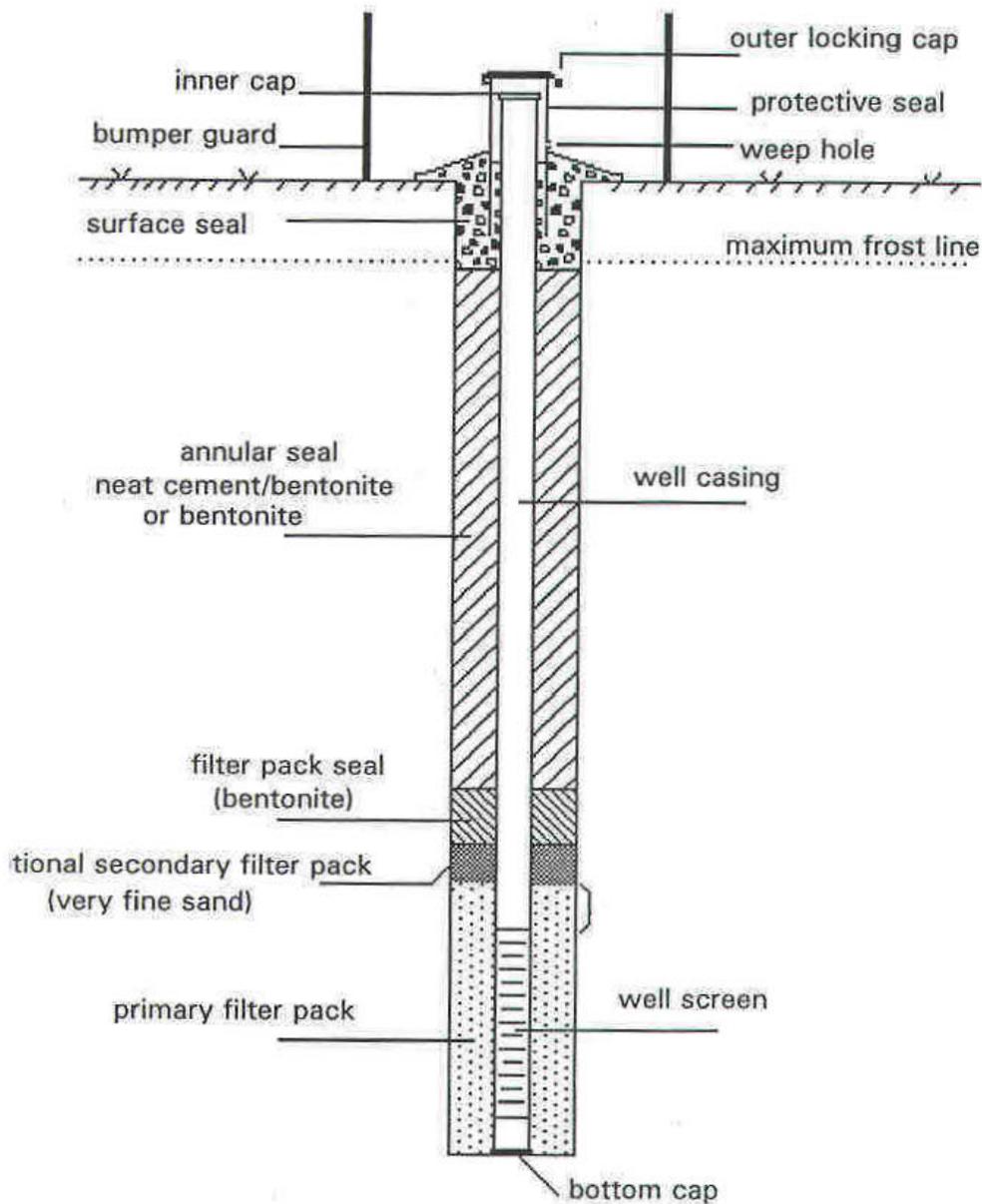
All monitoring wells should be designed and installed in conformance with site hydrogeology, geochemistry, and contaminant(s). While it is not possible to provide specifications for every situation, it is possible to identify certain design components. Figure 7.1 is a schematic drawing of a single-riser/limited interval well. The **casing** provides access to the subsurface. The **intake** consists of a filter pack and screen. The **screen** allows water to enter the well and, at the same time, minimizes the entrance of filter pack materials. The **filter pack** is an envelope of uniform, clean, well-rounded sand or gravel that is placed between the formation and the screen. It helps to prevent sediment from entering the well. Installation of a filter pack and screen may not be necessary for wells completed in competent bedrock. The **annular seal** is emplaced between the borehole wall and the casing and is necessary to prevent vertical movement of ground water and infiltration of surface water and contaminants. **Surface protection**, which includes a surface seal and protective casing, provides an additional safeguard against surface water infiltration and protects the well casing from physical damage.

#### DESIGN OF MULTIPLE-INTERVAL SYSTEMS

It is often necessary to sample from multiple discrete intervals at a given location if more than one potential pathway exists or a saturated zone is greater than 10 feet thick. Chapter 5 discusses the concepts involved in selecting zones to monitor. Multiple-interval monitoring can be accomplished by installing single-riser/limited interval wells in side-by-side boreholes (well clusters) or using systems that allow sampling of more than one interval from the same borehole (multi-level wells, well nests, or single-riser/flow-through wells).

#### WELL CLUSTERS

When monitoring multiple intervals at one location, single-riser/limited interval wells should be installed in adjacent, separate boreholes. These well clusters can be used to determine vertical gradients when distinct differences in head exist. They may be used to monitor discrete zones or evaluate chemical stratification within a thick zone. If flow direction has been determined prior to installation, the shallow well should be placed hydraulically upgradient of the deeper well to avoid the potential influence on its samples caused by the presence of grout in the annular space of the deeper well.



**Figure 7.1 Cross-section of a typical single-riser/limited interval monitoring well.**

## **MULTI-LEVEL WELLS**

Multi-level wells allow sampling of more than one interval in a single borehole. Individual tubes run from sampling levels to the surface. These levels are isolated within the well either by packers or grout. Probes, lowered into the casing, can locate, isolate and open a valve into a port coupling to measure the fluid pressure outside the coupling or obtain a sample.

The use of multiple-level monitoring wells in Ohio has been limited due to: 1) cost of installation, 2) difficulty in repairing clogs, and 3) difficulty in preventing and/or evaluating sealant and packer leakage. Detailed workplans (including construction and installation, methods to measure water levels and obtain samples, references to situations where these types of wells have been used successfully, and advantages and disadvantages) should be submitted prior to installing multi-level systems. Until more site-specific data is available concerning their performance, multi-level wells should only be considered when a single zone having no to little vertical flow is being monitored at different depths.

## **NESTED WELLS**

Nested wells involve the completion of a series of single-riser wells in a borehole. Each well is screened to monitor a specific zone, with filter packs and seals employed to isolate the zones. Nested wells are not recommended because they are difficult to install in a manner that ensures that all screens, filter packs, and seals are properly placed and functioning. It is more efficient to install single-riser wells for each interval to ensure that representative samples can be collected. Aller et al. (1991) indicated that individual completions generally are more economical at depths less than 80 feet. According to Dalton et al. (1991), the cost of installing well clusters is usually only marginally higher than the cost for nested wells. Well clusters can enable savings on sampling and future legal costs that may be necessary to prove the accuracy of nested wells.

## **SINGLE RISER/FLOW-THROUGH WELLS**

Single riser/flow-through wells are monitoring wells that, in general, are screened across the entire thickness of a water-bearing zone. These wells are typically small in diameter and provide a "transparent" cross-section of the flow field (Aller et al., 1991). If purging is performed immediately before sampling, only composite water samples are yielded, which are not adequate for most monitoring studies. If natural, flow-through conditions can be maintained, and if a sampling device can be lowered with minimal disturbance of the water column, vertical water quality profiles potentially can be identified. To achieve and document the collection of such samples is very difficult, however, and the resulting data may be questioned. Furthermore, these wells are conducive to allowing cross-contamination between different zones and, therefore, should not be used in contaminated areas. Flow-through wells are not recommended.

## **CASING**

The purpose of casing is to provide access to the subsurface for sampling of ground water and measurement of water levels. A variety of casing has been developed. Items that must be considered during well design include casing type, coupling mechanism, diameter, and installation.

## **CASING TYPES**

There are three categories of casing commonly used for ground water monitoring, including fluoropolymers, metallics, and thermoplastics (Aller et al., 1991). All have distinctive characteristics that determine their appropriateness.

## Fluoropolymers

Fluoropolymers are synthetic "plastics" composed of organic material. They are resistant to chemical and biological attack, oxidation, weathering, and ultraviolet (UV) radiation. They have a broad useful temperature range, a high dielectric constant, a low coefficient of friction, display anti-stick properties, and have a greater coefficient of thermal expansion than most other plastics and materials (Aller et al., 1991). A variety of fluoropolymers are marketed under various trademarks. Some manufacturers use one trade name to refer to several of their own materials, which may not always be interchangeable in service or performance (U.S. EPA, 1992). Standard properties of the various materials have been provided by Nielsen and Schalla (1991) and Aller et al. (1991).

The most common fluoropolymer used for monitoring wells is polytetrafluoroethylene (PTFE). It can withstand strong acids and organic solvents and, therefore, it is useful for environments characterized by the presence of these chemicals. It maintains a low tensile strength, which theoretically limits installation of Schedule 40 PTFE to an approximate depth of 250<sup>1</sup>. It is also very flexible, which makes it difficult to install with the retention of straightness that is needed to ensure successful insertion of sampling or measurement devices. Dablow et al. (1988) found that the ductile nature of PTFE can result in the partial closing of screen slots due to the compressive forces of the casing weight. This makes slot size selection very difficult. The inert nature of PTFE often prevents the annular seal from bonding with the casing completely, which can allow infiltration of surface water. PTFE is costly, generally ten times more expensive than thermoplastics.

## Metallics

Metallic materials include low carbon, carbon, galvanized, and stainless steel. Metallics are very strong and rigid and can be used to virtually unlimited depths. Corrosion problems are the major disadvantage for low carbon, carbon, and galvanized casings. Electrochemical and chemical attack alters water sample quality. U.S.EPA (1992) has listed the following as indicators of corrosive conditions (modified from Driscoll, 1986):

- C Low pH (< 7.0).
- C Dissolved oxygen exceeds 2 ppm.
- C Hydrogen sulfide in quantities as low as 1 ppm.
- C Total dissolved solids (TDS) greater than 1000 ppm.
- C Carbon dioxide exceeds 50 ppm.
- C Chloride (Cl<sup>-</sup>), bromide (Br<sup>-</sup>), and fluoride (F<sup>-</sup>) content together exceeds 500 ppm.

According to Barcelona et al. (1983), flushing before sampling does not minimize the bias of low carbon steel due to the inability to predict the effects of disturbed surface coatings and corrosion products accumulated at the bottom of the well. Due to their high corrosion potential, all metallics except stainless steel are unacceptable for monitoring wells.

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<sup>1</sup> The maximum depth for PTFE casing is dependent on site hydrogeology. If the casing largely penetrates unsaturated soils, the depth may be limited to approximately 100 feet. However, if the casing is placed mostly in water-bearing zones, then depth may be as great as 375 feet.

Stainless steel is manufactured in two common types, 304 and 316. Type 304 is composed of iron with chromium and nickel. Type 316's composition is the same as Type 304's, but includes molybdenum, which provides further resistance to sulfuric acid solutions. Stainless steel is readily available in a wide variety of diameters.

Stainless steel can perform quite well in most corrosive environments. In fact, oxygen contact develops an external layer that enhances corrosion resistance (Driscoll, 1986). Yet, under very corrosive conditions, even stainless steel can corrode and release nickel and chromium into ground water samples (Barcelona et al., 1983). Combinations and/or extremes of the factors indicating corrosive conditions generally are an indication of highly corrosive environments. For example, Parker et al. (1990) found that both 304 and 316 showed rapid rusting (<24 hrs.) when exposed to water containing chloride above 1000 mg/l. Like PTFE, stainless steel is relatively expensive in comparison with thermoplastics. Nielsen and Schalla (1991) and Aller et al. (1991) provided additional information on the properties of stainless steel.

## **Thermoplastics**

Thermoplastics are composed of large, synthetic organic molecules. The most common type used for monitoring wells is polyvinyl chloride (PVC), while a material used less often is acrylonitrile butadiene styrene (ABS). These materials are weaker, less rigid, and more temperature-sensitive than metallics. Thermoplastics are very popular due to their light weight, high strength to weight ratio, low maintenance, ease of joining, and low cost.

Common, acceptable PVC types are Schedule 40 and Schedule 80. The greater wall thickness of Schedule 80 piping enhances durability and strength, provides greater resistance to heat attack from cement, and allows construction of deeper wells. Only rigid PVC should be used for monitoring wells. Flexible PVC is composed of a high percentage of plasticizers (30 - 50%), which tend to degrade and contaminate samples (Jones and Miller, 1988). All PVC casing should meet Standard 14 of NSF International. This standard sets control levels for the amount of chemical additives to minimize leaching of contaminants (NSF International, 1988). Additional specifications have been provided by Nielsen and Schalla (1991) and Aller et al. (1991).

Drawbacks of PVC include brittleness caused by ultraviolet (UV) radiation, low tensile strength, relative buoyancy in water, and susceptibility to chemical attack. It is immune to corrosion and is resistant to most acids, oxidizing agents, salts, alkalies, oils, and fuels (NWWA/PPI, 1981). Additionally, Schmidt (1987) showed that no degradation of PVC occurred after six months immersion in common gasolines. However, studies have shown that high concentrations (parts-per-thousand or percentage concentrations) of tetrahydrofuran, methyl ethyl ketone, methyl isobutyl ketone, and cyclohexane degrade PVC (Nielsen and Schalla, 1991). Barcelona et al. (1983) reported that low molecular weight ketones, aldehydes, amines, and chlorinated alkenes and alkanes may cause degradation. There is a lack of published information regarding the concentrations of these compounds at which deterioration is significant enough to affect either the structural integrity of casing or ground water sample quality.

## TYPE SELECTION

Many regulated parties choose PVC casing because of its lower cost; however, well integrity and sample representativeness are more important criteria. The high cost of analysis and the extreme precision of laboratory instruments necessitate the installation of wells that produce representative samples. Above all, the burden of proof is on the regulated party to demonstrate that casing is appropriate. The proper selection can be made by considering casing characteristics in conjunction with site conditions.

Casing characteristics include strength, chemical resistance and chemical interference potential. The **strength** must withstand the extensive tensile, compressive, and collapsing forces involved in maintaining an open borehole. Since the forces exerted are, in large part, related to well depth, strength often is important when planned depth exceeds the maximum range of the weakest acceptable material (100 to 375 ft. - PTFE). In these instances, either stainless steel or PVC should be chosen. Strength can be the overriding factor because the concern for chemical resistance and interference become insignificant if an open borehole cannot be maintained. Nielsen and Schalla (1991) provided specific strength data for commonly used materials.

The casing also must withstand **electrochemical corrosion and chemical attack** from natural ground water and any contaminant(s). Chemical resistance is most important in highly corrosive environments, when contaminants are present at extremely high levels, and when wells are intended to be part of a long-term monitoring program. For extended monitoring in corrosive environments, PTFE and PVC are preferred over stainless steel because of the potential for the metallic material to degrade. If high concentration of organics (parts per thousand) are present, either PTFE or stainless steel should be selected. U.S. EPA (1992) recommended that PVC not be used if a PVC solvent/softening agent<sup>2</sup> is present or the aqueous concentration of a solvent/softening agent exceeds 0.25 times its solubility in water. It is suitable in most situations where low (parts per billion to low parts per million) levels of most organic constituents are present (Nielsen and Schalla, 1991).

The casing also should not interfere with sample quality by **adding (leaching) or removing contaminants**. In most cases, the magnitude of this interference is a function of the ground water's contact time with the casing. The longer the contact, the greater the potential for leaching and sorption. Various studies have been conducted [Barcelona and Helfrich (1988), Curran and Tomson (1983), Gillham and O'Hannesin (1989), Jones and Miller (1988), Miller (1982), Parker and Jenkins (1986), Parker et al. (1990), Reynolds and Gillham (1985), Schmidt (1987), Sykes et al. (1986), Tomson et al. (1979), Hewitt (1992, 1994), Parker and Ranney (1994)] to compare the sorbing and leaching characteristics of the three favored materials. No conclusive results have been obtained to indicate that any one is best. Most of these studies involved contact lasting days, weeks, and even months and, therefore, the results cannot be correlated to field conditions where contact is often minimal because sampling is generally conducted soon after purging.

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<sup>2</sup>Known PVC solvent/softening agents include: tetrahydrofuran, cyclohexane, methyl ethylketone, methyl isobutyl ketone, methylene chloride, trichloromethane, 1-1-dichloroethane, trichloroethene, benzene, acetone, and tetrachloroethene.

In many cases, concern about sorption or leaching may be exaggerated. Barcelona et al. (1983) and Reynolds and Gillham (1985) both concluded that the potential sorption biases for casing may be discounted due to the short contact after purging. Also, Parker et al. (1990) indicated that sorption of various constituents never exceeded 10 percent in the first 8 hours of their tests. They concluded that, on the basis of overall sorption potential for organic and inorganic compounds, PVC is the best compromise.

In summary, the appropriate casing should be determined on a case-by-case basis. PVC is acceptable when free product is not present and the solubility limits of organic contaminants are not approached (e.g., levels that exceed 0.25 times the solubility). Ohio EPA recognizes the difficulty inherent in establishing a "cut-off" level for when aqueous concentrations of organics cause failure of PVC. To be certain that casing will retain integrity, particularly when monitoring is planned for long periods of time (e.g., 30 years), Ohio EPA may require a more resistant casing when aqueous concentrations are relatively high but still below the criteria mentioned above.

## **HYBRID WELLS**

Casing not in contact with the saturated zone generally is not subject to attack. Therefore, it may be possible to install less chemically resistant material above the highest seasonal water level and more inert material where ground water continually contacts the casing. Such a "hybrid well" commonly is installed for cost reduction reasons only. For example, when monitoring a zone with high concentrations of organic compounds, stainless steel or PTFE could be installed opposite the saturated materials, while PVC could be used opposite the unsaturated materials. Thus, resistant, more expensive casing would be present where contact with highly contaminated ground water may occur, while less resistant, inexpensive casing would be present where contact does not occur.

Different varieties of steel never should be installed in the same well. Each type is characterized by its own electro-chemical properties. Installation of different types in contact can increase the potential for corrosion.

## **COUPLING MECHANISMS**

Casing sections should be connected using threaded joints that provide for uniform inner and outer diameters along the entire length of the well. Such "flush" coupling is necessary to accommodate the insertion of tools and sampling devices without obstruction and to help prevent bridging during the installation of the filter pack and annular seal. It should be noted that thread types vary between manufacturers and matching can be difficult. A union among non-matching joints should never be forced, otherwise structural integrity of the joint and the entire well could be compromised. To alleviate these problems, the American Society of Testing and Materials has developed Standard F 480-90 (1992) to create a uniformly manufactured flush-threaded joint. Most manufacturers now produce the F 480 joint, which is available in both PVC and stainless steel.

It is recommended that either nitrile, ethylene propylene, or Viton O-rings be used between sections to prevent the seal and/or affected water from entering (Nielsen and Schalla, 1991). Nielsen and Schalla (1991) indicated that Teflon tape can be used in place of O-rings, although it does not ensure as good a seal. Solvent cements should never be used because they are known to leach organics. Although welding stainless steel can produce a flush joint that is of equal or greater

strength than the casing itself, this method is not recommended due to the extra assembly time, welding difficulty, corrosion enhancement, ignition danger, and the potential to lose materials into the well (Nielsen and Schalla, 1991).

Threaded steel casing provides inexpensive, convenient connections. It should be noted that threaded joints reduce the tensile strength of the casing; however, this does not cause a problem for most shallow wells. Also, threaded joints may limit or hinder the use of various sampling devices when thin-walled stainless steel (Schedules 5 and 10) is employed. Thin-walled casing is too thin for threads to be machined, so the factory welds a short, threaded section of Schedule 40 stainless steel pipe to the end of the thin-walled pipe. These joints are made to be flush on the outside, but not the inside.

If hybrid wells are installed, it is essential that the joint threads be matched properly. This can be accomplished by purchasing casing screen that is manufactured to ASTM F480-90 (1992) standard coupling.

## **DIAMETER**

Choice of casing diameter is also site-specific. Small wells are considered to be from 2 to 4 inches in diameter. The minimum diameter for use in monitoring wells is 2 inches. Advantages of small diameter wells are as follows:

- ⊘ Water levels require less time to recover after purging.
- ⊘ They produce a smaller volume of purged water that must be disposed.
- ⊘ Construction costs are lower.

Some disadvantages of small diameter wells include:

- ⊘ Access may be limited for sampling devices.
- ⊘ Filter packs and seals are more difficult to install.
- ⊘ They offer a lower depth capability due to lesser wall thickness.
- ⊘ Development can be more difficult.
- ⊘ Less ground water is pumped during a hydraulic test or a remediation extraction.
- ⊘ The amount of available water may be too small for chemical analyses.

Further discussion of well diameter can be found in articles by Schalla and Oberlander (1983), Schmidt (1982), and Rinaldo-Lee (1983).

## **INSTALLATION**

Casing should be cleaned thoroughly before installation. Strong detergents and even steam cleaning may be necessary to remove oils, cleansing solvents, lubricants, waxes, and other substances. (Curran and Tomson, 1983; Barcelona et al., 1983). It is strongly recommended that only factory-cleaned materials be used for monitoring wells. Casing can be certified by the supplier and individually wrapped in sections to retain cleanliness. If it has not been factory-cleaned and sealed, it should be washed thoroughly with a non-phosphate, laboratory grade detergent (e.g., Liquinox) and rinsed with clean water or distilled/deionized water as suggested by Curran and

Tomson (1983) and Barcelona et al. (1983). The materials should be stored in a clean, protected place to prevent contamination by drilling and site activities.

When installing casing, it is important that it remain centered in the borehole to ensure proper placement and even distribution of the filter pack and annular seal. In addition, centering helps ensure straightness for sampling device access. If a hollow-stem auger is used, no additional measures are necessary because the auger acts as a centralizing device. If casing is installed in an open borehole, centralizers made of stainless steel or PVC can be used. They are adjustable and generally attached just above the screen and at 10 to 20 foot intervals along the riser. If centralizers are used, measures should be taken to prevent them from bridging the filter pack and seal material during their installation.

## INTAKES

Although every well is unique, most have a screen and filter pack. Together, these comprise an "intake". Monitoring wells in cohesive bedrock may incorporate open borehole intakes.

## FILTER PACK

Wells monitoring unconsolidated and some poorly consolidated materials typically need to have a screen (discussed later) surrounded by more hydraulically conductive material (filter pack). In essence, the filter pack increases the effective well diameter and prevents fine-grained material from entering.

### Types of Filter Packs

Filter packs can be classified by two major categories, natural and artificial. **Natural packs** are created by allowing the formation to collapse around the screen. In general, natural packs are recommended for formations that are coarse-grained, permeable, and uniform in grain size. According to Nielsen and Schalla (1991), they may be suitable when the effective grain size (sieve size that retains 90%, or passes 10%) is greater than 0.010 inch and the uniformity coefficient (the ratio of the sieve size that retains 40% and the size that retains 90%) is greater than 3. Ideally, all fine-grained particles are removed when the well is developed, leaving the natural pack as a filter to the surrounding formation.

Installation of **artificial packs** involves the direct placement of coarser-grained material around the screen. The presence of this filter allows the use of a larger slot size than if the screen were placed in direct contact with the formation. Artificial packs generally are necessary where: 1) the formation is poorly sorted; 2) the intake spans several formations and/or thin, highly stratified materials with diverse grain sizes; 3) the formation is a uniform fine sand, silt or clay; 4) the formation consists of thinly-bedded materials, poorly cemented sandstones, and highly weathered, fractured, and solution-channeled bedrock; 5) shales and coals that provide a constant source of turbidity are monitored; and 6) the borehole diameter is significantly greater than the diameter of the screen (Aller et al., 1991). Artificial packs generally are used opposite unconsolidated materials when the effective grain size is less than 0.010 inches and when the uniformity coefficient is less than 3.0 (Nielsen and Schalla, 1991).

An artificial pack may include two components. The **primary pack** extends from the bottom of the borehole to above the top of the screen. In some cases, it may be desirable to place a **secondary pack** directly on top of the primary pack. Its purpose is to prevent the infiltration of the annular seal into the primary pack, which can partially or totally seal the screen.

### **Nature of Artificial Filter Pack Material**

The artificial pack material should be well-sorted, well-rounded, clean, chemically inert, of known origin, and free of all fine-grained clays, particles and organic material. Barcelona et al. (1983) recommended clean quartz sand or glass beads. Quartz is the best natural material due to its non-reactive properties and availability. Crushed limestone should never be used because of the irregular particle size and potential chemical effects. Materials should be washed, dried, and packaged at the factory, and typically are available in 100 lb. bags (approximately one cubic foot of material) (Nielsen and Schalla, 1991).

Selection of material should be based on the formation particle size. If chosen grains are too small, it is possible that loss of the pack to the formation can occur (Nielsen and Schalla, 1991), which could lead to the settling of the annular seal into the screened interval. On the other hand, if the grains are too large, the pack will not effectively filter fine-grained material, leading to excessively turbid samples.

The primary pack generally should range in grain size from a medium sand to a cobbled gravel. Most materials are available in ranges, such as 20- to 40-mesh (0.033 to 0.016 inches, Table 7.1). The grain size of the primary filter pack should be determined by multiplying the 70% retention size of the formation by a factor of 3 to 6 (U.S. EPA, 1975). A factor of 3 is used for fine, uniform formations; a factor of 6 is used for coarse, non-uniform formations (Figure 7.2). In situations where the material is less uniform and the uniformity coefficient ranges from 6 to 10, it may be necessary to use the 90% retention (10% passing) size multiplied by 6 (Nielsen and Schalla, 1991). This is to ensure that the bulk of the formation will be retained. The ratio of the particle size to the formation grain size should not exceed 6, otherwise, the pack will become clogged with fine-grained material from the formation (Lehr et al., 1988). If the ratio is less than 4, a smaller screen slot size will be necessary, full development of the well may not be possible, and well yield may be inhibited. When monitoring in very heterogeneous, layered stratigraphy, a type of pack should be chosen that suits the layer with the smallest grain size.

It is preferred that the filter pack be of uniform grain size. Ideally, the uniformity coefficient should be as close to 1.0 as possible and should not exceed 2.5 (Nielsen and Schalla, 1991, ASTM D5092-90, 1994). Uniform material is much easier to install. If non-uniform material is used, differing fall velocities cause the materials to grade from coarse to fine upwards along the screen. This can result in the loss of the upper fine-grained portion to the well during development.

The secondary filter pack material should consist of a 90% retention sieve size (10% passing) that is larger than the voids of the primary pack to prevent the secondary pack from entering the primary pack (Nielsen and Schalla, 1991). In general, the secondary 90% retention size should be one-third to one-fifth of the primary 90% retention size (Nielsen and Schalla, 1991).

**Table 7.1 Common filter pack characteristics for typical screen slot sizes (From Nielsen and Schalla, 1991).**

| Size of Screen Opening [mm (in.)] | Slot No. | Sand Pack Mesh Size | 1% Passing Size (D <sub>1</sub> ) (mm) | Effective Size (D <sub>10</sub> ) (mm) | 30% Passing Size (D <sub>30</sub> ) (mm) | Range of Uniformity Coefficient | Roundness (Powers Scale) | Fall Velocities <sup>a</sup> (cm/s) |
|-----------------------------------|----------|---------------------|--|--|--|---------------------------------|--------------------------|-------------------------------------|
| 0.125(0.005)                      | 5        | 40-140              | 0.09-0.12                              | 0.14-0.17                              | 0.17-0.21                                | 1.3-2.0                         | 2-5                      | 6-3                                 |
| 0.25 (0/010)                      | 10       | 20-40               | 0.25-0.35                              | 0.4-0.5                                | 0.5-0.6                                  | 1.1-1.6                         | 3-5                      | 6-6                                 |
| 0.50 (0.020)                      | 20       | 10-20               | 0.7-0.9                                | 1.0-1.2                                | 1.2-1.5                                  | 1.1-1.6                         | 3-6                      | 14-9                                |
| 0.75 (0.030)                      | 30       | 10-20               | 0.7-0.9                                | 1.0-1.2                                | 1.2-1.5                                  | 1.1-1.6                         | 3-6                      | 14-9                                |
| 1.0 (0.040)                       | 40       | 8-12                | 1.2-1.4                                | 1.6-1.8                                | 1.7-2.0                                  | 1.1-1.6                         | 4-6                      | 16-13                               |
| 1.5 (0.060)                       | 60       | 6-9                 | 1.5-1.8                                | 2.3-2.8                                | 2.5-3.0                                  | 1.1-1.7                         | 4-6                      | 18-15                               |
| 2.0 (0.080)                       | 80       | 4-8                 | 2.0-2.4                                | 2.4-3.0                                | 2.6-3.1                                  | 1.1-1.7                         | 4-6                      | 22-16                               |

<sup>a</sup> Fall velocities in centimeters per second are approximate for the range of sand pack mesh sizes named in this table . If water in the annular space is very turbid, fall velocities may be less than half the values shown here. If a viscous drilling mud remains in the annulus, fine particles may require hours to settle.

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**Figure 7.2 Artificial filter pack design criteria** (Source: Design and Installation of Ground Water Monitoring Wells by D.M. Nielsen and R. Schalla, *Practical Handbook of Ground Water Monitoring*, edited by David M. Nielsen, Copyright © 1991 by Lewis Publishers, an imprint of CRC Press, Boca Raton, Florida. With permission.)

### **Dimension of Artificial Filter Pack**

The distance between the casing and the borehole wall should be at least 2 to 4 inches to allow for proper placement of the filter pack and annular seal. Therefore, the filter pack thickness should be 2 to 4 inches. It is important that the thickness not be excessive, otherwise the potential for effective development is reduced.

The primary pack should extend from the bottom of the screen to at least 2 feet above its top. In deeper wells (i.e., >200 feet), the pack may not compress initially. Compression may occur after installation of the annular seal, which may allow the seal to be in close contact with the screen. Therefore, additional pack material may be needed to account for settling and, at the same time, provide adequate separation of the seal and the screen. However, extension of the pack should not be excessive because it enlarges the zone that contributes ground water to the well, which may cause excess dilution. The length of the secondary pack should be one-foot or less.

## Artificial Filter Pack Installation

Methods that have been used for artificial pack installation include tremie pipe, gravity emplacement, reverse circulation, and backwashing (Nielsen and Schalla, 1991). The material must be placed in a manner that prevents bridging and particle segregation. Bridging can cause the presence of large voids and may prevent material from reaching the intended depth. Segregation can cause a well to produce turbid samples. During installation, regular measurements with a weighted tape should be conducted to determine when the desired height has been reached, and also act as a tamping device to reduce bridging. The anticipated volume of filter pack should be calculated.<sup>3</sup> Any discrepancy between the actual and calculated volumes should be explained.

The preferred method for artificial pack installation is to use a **tremie pipe** to emplace material directly around the screen. The pipe is raised periodically to help minimize the risk of bridging. The pipe generally should be at least 1.5 inches ID, but larger diameters may be necessary where coarser-grained packs are being installed. When driven casing or hollow-stem augering is used to penetrate non-cohesive formations, the material should be tremied as the casing and auger is pulled back in one to two foot increments to reduce caving effects and ensure proper placement (Nielsen and Schalla, 1991). When installing wells through cohesive formations, the tremie pipe can be used after removal of the drilling device.

**Gravity emplacement** is accomplished by allowing material to free-fall to the desired position around the screen. Placement by gravity should be restricted to shallow wells with an annular space greater than 2 inches, where the potential for bridging or segregation is minimized (Nielsen and Schalla, 1991). For low-yielding formations, it may be possible to bail the borehole dry to facilitate placement; however, segregation is generally only a problem for deep wells with shallow water levels. Also, segregation is generally not a problem if the pack has a uniformity coefficient of 2.5 or less. Gravity placement also can cause grading if the material is not uniform. In addition, formation materials are often incorporated during placement, which can contaminate the pack and reduce its effectiveness. For most cases, gravity placement is not recommended.

**Reverse circulation** involves the insertion of a sand and water mixture through the annulus. Sand is deposited around the screen as the water returns to the surface through the casing. Due to the potential water quality alteration, this method generally is not recommended.

**Backwashing** is accomplished by allowing material to free-fall through the annulus while clean water is pumped down the casing. The water returns up the annulus carrying fine-grained material with it. This creates a more uniform pack; however, the method is not commonly used for monitoring well installation and generally is not recommended due to the potential for alteration of ground water quality. Nonetheless, it is sometimes used for placing packs opposite non-cohesive heaving sands and silts.

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<sup>3</sup> Anticipated filter pack volume can be calculated by determining the difference in volume between the borehole and casing (using outside diameter of the well) from the bottom of the borehole to the appropriate height above the well screen.

## **SCREEN**

The screen is the final link to retaining the borehole and keeping unwanted formation particles out of ground water samples.

### **Screen Types**

Recommended screen compositions are stainless steel, PTFE, and PVC. The same discussion and concerns for casing material apply to screens. Only manufactured screens should be used, since these are available with slots sized precisely for specific grain sizes. Field-cut or punctured screen should never be used, due to the inability to produce the necessary slot size and the potential for the fresh surface to leach or sorb contaminants. A bottom cap or plug should be placed at the base of the screen to prevent sediments from entering and to ensure that all water enters the well through the screen openings.

Slotted and continuous slot, wire-wound screen are the common types used for monitoring wells. In deep wells, slotted screen generally retains structural integrity better than wire-wound; however, continuous slot, wire-wound screens provide almost twice the open area of slotted casing. More open area per unit length enhances well recovery and development. A slot type should be chosen that provides the maximum amount of open area in relation to the effective porosity of the formation. Driscoll (1986) recommended that the percentage of open area should be at least equal to the effective porosity of the formation and filter pack. In common situations with 10 to 30 percent effective porosities, continuous slot screens are preferred, although not required (Nielsen and Schalla, 1991).

### **Slot Size**

When selecting a screen slot size for an artificially filter-packed well, a sieve analysis should be conducted on the pack material. The selected size should retain at least 90% of the pack. In many situations it is preferable to retain 99% (Nielsen and Schalla, 1991 and ASTM D 5092-90, 1994) (Figure 7.3). See Table 7.1 for a guide to the selection of slot sizes for various packs.

For naturally-packed wells, the screen should retain from 30 to 60% (Aller et al., 1991). As a rule of thumb, a 50% retention may be adequate (based on Wisconsin Administrative Code, 1990). With small diameter (4-inch or less), low yield wells, development may not be effective to remove a sufficient amount of fines and a 60 to 70% retention size may be more desirable. For additional information on pack and screen selection, see Aller et al. (1991), Nielsen and Schalla, (1991), and ASTM D 5092-90 (1994).

It should be noted that if a PTFE screen is used in a deep well, a slightly larger slot size than predicted should be selected due to the material's lower compressive strength, which allows the openings to compress (Dablow et al., 1988).

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**Figure 7.3 Selection of screen slot size based on the filter pack grain size.** (Source: Design and Installation of Ground Water Monitoring Wells by D.M. Nielsen and R. Schalla, *Practical Handbook of Ground Water Monitoring*, edited by David M. Nielsen, Copyright © 1991 by Lewis Publishers, an imprint of CRC Press, Boca Raton, Florida. With permission.)

### Length

Screen length should be tailored to the desired zone and generally should not exceed 10 ft. A 2 to 5 ft. screen is desirable for more accurate sampling and discrete head measurements. Longer screens produce composite samples that may be diluted by uncontaminated water. As a result, concentrations of contaminants may be underestimated. Furthermore, the screen should not extend through more than one water-bearing zone to avoid cross-contamination. When a thick formation must be monitored, a cluster of individual, closely spaced wells, screened at various depths, can be installed to monitor the entire formation thickness. The length of screens that monitor the water table surface should account for seasonal fluctuation of the water table. For related information on screen length, refer to Chapter 5.

### OPEN BOREHOLE INTAKES

When constructing monitoring wells in competent bedrock, an artificial intake is often unnecessary because an open hole can be maintained and sediment movement is limited. Installing a filter pack in these situations may be difficult due to loss of material into the surrounding formation. In some cases, however, intakes are a necessary component of bedrock wells. A screen and filter pack should be installed in highly weathered, poorly cemented, and fractured bedrock (Nielsen and Schalla, 1991). They are usually necessary when monitoring the unconsolidated/consolidated interface in Ohio.

Open hole wells often are completed by casing and grouting the annulus prior to drilling into the monitoring zone. In cases where the zone has been drilled prior to sealing the annulus, a bridge (cement basket or formation packer shoe) must be set in the hole to retain the grout/slurry to the desired depth (Driscoll, 1986).

If an open hole well is installed, the length of open hole generally should not exceed 10 feet to prevent sample dilution. To maintain a discrete monitoring zone in consolidated formations, the casing should be extended and grouted to the appropriate depth to maintain the 10 foot limit. Driven casing may be necessary to avoid loss of the annular seal into the surrounding formation.

## **ANNULAR SEALS**

The open, annular space between the borehole wall and the casing must be sealed properly to: 1) isolate a discrete zone, 2) prevent migration of surface water, 3) prevent vertical migration of ground water between strata, and 4) preserve confining conditions by preventing the upward migration of water along the casing. An effective seal requires that the annulus be filled completely with sealant and the physical integrity of the seal be maintained throughout the lifetime of the well (Aller et al., 1991).

## **MATERIALS**

The sealant must be of very low permeability (generally  $10^{-7}$  to  $10^{-9}$  cm/sec), capable of bonding with casing, and chemically inert with the highest anticipated concentration of chemicals expected. Cuttings from the existing borehole, no matter what the type of materials, should never be used. They generally exhibit higher permeability and cannot form an adequate seal.

The most common materials used are bentonite and neat cement grout. Each has specific, unique, and desirable properties. These materials are discussed briefly here. Additional information can be found in Gaber and Fisher (1988), ASTM Method C-150 (1992), and Nielsen and Schalla (1991).

### **Neat Cement Grout**

Neat cement grout is comprised of portland cement and water, with no aggregates added. It is a hydraulic cement produced by pulverizing cement clinker consisting essentially of hydrated calcium silicates, and usually containing one or more forms of calcium sulfate as an interground addition. Several types of portland cements are manufactured to accommodate various conditions that may be encountered. Table 7.2 lists the types as classified by ASTM C150-92 (1992). Type I is most commonly used for monitoring wells.

Air-entraining portland cements have been specially processed to form minute air bubbles within the hardened structure. The air-entraining materials are added during the grinding of the clinker. The finished product is more resistant to freeze-thaw action. Air-entraining cements are designated with an "A" after the ASTM cement type. They have been used to construct water supply wells; however, they are less desirable than standard cements because of their greater permeability. Therefore, air-entraining varieties are not recommended for subsurface sealing of monitoring wells.

Water added to the neat cement should be potable and contain less than 500 ppm total dissolved solids (Gaber and Fisher, 1988). Low chloride and sulfate concentrations also are desirable (Campbell and Lehr, 1973). As the water to cement ratio increases, the compressive strength of the cement decreases and shrinkage increases. The American Petroleum Institute recommends a ratio of 5.2 gallons of water per 94 pound sack of cement. Additional water makes it easier to pump, but adversely affects the grout's sealing properties. Excess water can cause shrinkage and separation of the cement particles, which compromises seal integrity (Nielsen and Schalla, 1991).

**Table 7.2 ASTM cement designation (modified from Gaber and Fisher 1988).**

| <b>CEMENT TYPE</b>     | <b>DESCRIPTION</b>   |
|------------------------|--|
| Type I                 | General purpose cement suitable where special properties are not required.   |
| Type II                | Moderate sulfate resistance. Lower heat of hydration than Type I. Recommended for use where sulfate levels in ground water are between 150 to 1500 ppm.  |
| Type III               | High early strength. Ground to finer particle size, which increases surface area and reduces curing time period before drilling may resume from 48 hours to 12 hours. When Type III cement is used, the water-to-cement ratio must be increased to 6.3 to 7 gallons of water per sack. |
| Type IV                | Low heat of hydration cement designated for applications where the rate and amount of heat generated by the cement must be kept to a minimum. Develops strength at a lower rate than Type I.   |
| Type V                 | Sulfate-resistant cement for use where ground water has a high sulfate content. Recommended for use when levels in ground water exceed 1500 ppm.   |
| Type IA, IIA, and IIIA | Air entraining cements for the same use as Types I, II, and III. Not recommended for monitoring well construction.   |

The major disadvantages of neat cement are its heat of hydration, shrinkage upon curing, and its effect on water quality. During curing, heat is released, which is generally of little concern; however, generally if large volumes of cement are used or the heat is not rapidly dissipated, the resulting high temperatures can compromise the integrity of PVC casing. However, the borehole for most monitoring wells is small, and heat significant enough to cause damage generally is not created.

Shrinkage is undesirable because it causes cracks and voids. To reduce shrinkage, up to 5 percent bentonite by weight can be added (Gaber and Fisher, 1988), with an additional 1.3 gallons of water for each 2 percent of bentonite per 94 pound sack of cement. Such bentonite/neat cement grout mixtures are highly recommended. Bentonite should not be pre-mixed with water, but should be added dry to the cement/water slurry (ASTM 5092-90, 1994). The addition of bentonite also retards settling time and reduces peak temperatures. Other additives, such as accelerators (e.g., calcium chloride) and retarders, are commercially available but are not recommended due to their potential to leach (ASTM Method 5092-90, 1994).

Upon settling, neat cement grouts often lose water into the formation and affect water quality. Neat cement typically ranges in pH from 10 to 12; therefore, it is important to isolate the annular seal from the screen and filter pack.

## **Bentonite**

Bentonite is composed of clay particles that expand many times their original volume when hydrated. The most acceptable form is a sodium (Na) rich montmorillonite clay that exhibits a 10 to 12-fold expansion when hydrated. Other types, such as calcium (Ca) bentonite, are less desirable because they offer lower swelling ability and surface area to mass ratios. However, other types should be considered if Na bentonite is incompatible with the formation or analyses of concern. For example, the capability of bentonite may be adversely affected by chloride salts, acids, alcohols, ketones, and other polar compounds. Ca bentonite may be more appropriate for calcareous sediments.

Bentonite is available in a variety of forms, including pelletized, coarse grade, granular and powder. **Pellets** are uniform in size and consist of compressed, powdered Na montmorillonite. They typically range from 1/4 to 1/2 inch in size. Pellets expand at a relatively slower rate when compared to other forms. **Coarse grade**, also referred to as crushed or chipped, consists of irregularly shaped, angular particles of montmorillonite that range from 1/4 to 3/4 inches in size. **Granular** particles range from 0.025 to 0.10 inches in size. **Powdered** bentonite is pulverized montmorillonite, factory-processed after mining. Powdered and granular forms are generally mixed with water to form a slurry. Risk of losing a slurry to the underlying filter pack and surrounding formation should be considered. High-solids, bentonite (>30% clay solids) has been developed specifically for monitoring well construction and provides an effective seal.

## **SEAL DESIGN**

It is important that the design of annular seals incorporate measures to prevent infiltration into the filter pack. Contact with the seal can cause sampled ground water to be artificially high in pH. Additionally, bentonite has a high cation exchange capacity, which may affect the chemistry of samples (Aller et al., 1991). In the saturated zone, a 2-foot pure bentonite seal can minimize the threat of infiltration. Above the bentonite seal, neat cement, bentonite, or neat cement/bentonite grouts should be placed in the remainder of the annulus to within a few feet of the surface. Because bentonite requires a sufficient quantity and quality of water in order to achieve and retain hydration, bentonite generally, should only be used in the saturated zone. Where saturated conditions do not exist, neat cement-bentonite should be used.

## SEAL INSTALLATION

It is important that annular seals are installed using techniques that prevent bridging, which may cause gaps, cracking or shrinking. Surface water and/or contaminants potentially can migrate through any voids created. The 2 foot bentonite seal above the filter pack is commonly installed by placing granular bentonite, bentonite pellets, or bentonite chips around the casing by dropping them directly down the annulus. If feasible, this practice is acceptable for wells less than 30 feet deep if a tamping device is used. However, for wells deeper than 30 feet, coarse-grained bentonite should be placed by means of a tremie pipe.

The bentonite should be allowed to hydrate or cure prior to sealing the remainder of the annular space. This will help prevent invasion of grout into the screened interval. If a two foot bentonite seal is desired in the unsaturated zone, granular material should be used. It should be added and hydrated in stages using water that is potable and free of analytes of concern.

For the remainder of the annulus, sealants should be in slurry form (e.g., cement grout, bentonite slurry) and should be placed with a tremie pipe (Figure 7.4). The bottom of the pipe should be equipped with a side discharge deflector to prevent the slurry from jetting a hole through the filter pack.<sup>4</sup> The seal should be allowed to completely hydrate, set, or cure in conformance with the manufacturer's specifications prior to completing the surface seal and developing the well.

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**Figure 7.4 Tremie pipe emplacement of annular seal material** (Source: Design and Installation of Ground Water Monitoring Wells by D.M. Nielsen and R. Schalla, *Practical Handbook of Ground Water Monitoring*, edited by David M. Nielsen, Copyright © 1991 by Lewis Publishers Division, an imprint of CRC Press, Boca Raton, Florida. With permission.)

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<sup>4</sup>Side discharge deflectors may not be necessary when a bentonite seal has been placed properly.

## **SURFACE SEAL/PROTECTIVE CASING COMPLETIONS**

### **SURFACE SEAL**

A neat cement or concrete surface seal should be placed around a protective casing to a depth just below the frost line (3-5 ft.). If the same material was used in the annular seal, the surface seal can be a continuation; otherwise, the surface seal is installed directly over the annular seal after settling and curing. The surface seal should slope away from the well and extend beyond the edge of the borehole to divert surface water. Air-entraining cements may be desirable in cold climates to alleviate cracking caused by freezing and thawing.

### **ABOVE-GROUND COMPLETIONS**

Whenever possible, monitoring wells should extend above the ground surface to prevent surface water from entering and to enhance visibility. From the frost line upward, a steel protective casing should encompass the well. The protective casing should be at least two inches larger in diameter than the inner casing, extend above it, and have a locking cap. The lock should be protected by plastic or rubber covers so the use of lubricants to free and maintain locking mechanisms can be avoided. A small drain or "weep hole" should be located just above the surface seal to prevent the accumulation of water between the casings (See Figure 7.1). This is especially useful in cold climates, where the freezing of trapped water can damage the inner casing. A permanent reference point on the well inner casing must be surveyed to the nearest 0.01 ft. This permanent marker should be used for all water level measurements. Additionally, the well identification number or code should be marked permanently and clearly.

Bumper or barrier guards should be placed beyond the edge of the surface seal or within 3 to 4 feet of the well (See Figure 7.1). These guards are necessary to reduce and prevent accidental damage from vehicles. Painting the guard posts yellow or orange and installing reflectors can increase visibility and help prevent mishaps.

### **FLUSH-TO-GROUND COMPLETIONS**

Flush-to-ground completions are discouraged because the design increases the potential for surface water infiltration; however, they are occasionally unavoidable. This type of completion should be used only when the location of a well would disrupt traffic areas such as streets, parking lots, and gas stations, or where easements require them (Nielsen and Schalla, 1991).

If flush-to-ground completion is installed, very careful procedures must be followed. A highly secure subsurface vault generally is completed in the surface seal, allowing the well casing to be cut below grade (Figure 7.5). An expandable locking cap on the casing and a water-proof gasket should be installed around the vault lid to prevent surface water infiltration. The completion should be raised slightly above grade and sloped away to help divert surface water. It should be marked clearly and locked to restrict access. This is especially important at gas stations to prevent the misidentification of wells as underground tank filling points.

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**Figure 7.5 Typical flush-to-ground monitoring well completion** (Source: Design and Installation of Ground Water Monitoring Wells by D.M. Nielsen and R. Schalla, *Practical Handbook of Ground Water Monitoring*, edited by David M. Nielsen, Copyright © 1991 by Lewis Publishers Division, an imprint of CRC Press, Boca Raton, Florida. With permission.)

## DOCUMENTATION

During monitoring well installation, pertinent information should be documented, including design and construction, the drilling procedure, and the materials encountered (see Chapter 3 for a listing of the particular geologic information needs). Accurate "as-built" diagrams should be prepared that, in general, include the following:

- C Date/time of start and completion of construction.
- C Boring/well number.
- C Drilling method and drilling fluid used.
- C Borehole diameter and well casing diameter.
- C Latitude and longitude.
- C Well location ( $\pm 0.5$  ft.) with sketch of location.
- C Borehole depth ( $\pm 0.1$  ft.).
- C Well depth ( $\pm 0.1$  ft.).
- C Casing length and materials.
- C Screened interval(s).
- C Screen materials, length, design, and slot size.
- C Casing and screen joint type.

- C Depth/elevation of top and bottom of screen.
- C Filter pack material/size, volume calculations, and placement method.
- C Depth/elevation to top and bottom of filter pack.
- C Annular seal composition, volume (calculated and actual), and placement method.
- C Surface seal composition, placement method, and volume (calculated and actual).
- C Surface seal and well apron design/construction.
- C Depth/elevation of water.
- C Well development procedure and ground water turbidity.
- C Type/design of protective casing.
- C Well cap and lock.
- C Ground surface elevation ( $\pm 0.01$  ft.).
- C Surveyed reference point ( $\pm 0.01$  ft.) on well casing.
- C Detailed drawing of well (include dimensions).
- C Point where water encountered.
- C Water level after completion of well development.

In addition, the following should be documented in work plans (when appropriate) and reports:

- C Selection and rationale materials for selection of casing and screen.
- C Selection and rationale for well diameter, screen length, and screen slot size.
- C Filter pack selection and emplacement.
- C Annular sealant selection and emplacement.
- C Security measures.
- C Locations and elevations of wells.
- C Well development.

A complete, ongoing history of each well should be maintained. This can include sample collection dates, dates and procedures for development, water level elevation data, problems, repairs, personnel, and methods of decommissioning. This information should be kept as a permanent on-site file, available for agency review upon request.

On July 18, 1990, Ohio House Bill 476 went into effect. This bill requires that all logs for monitoring wells drilled in Ohio be submitted to the Ohio Department of Natural Resources, Division of Water (ODNR). The ODNR can be contacted for further information.

## **MAINTENANCE**

The condition of wells must be maintained to keep them operational and insure that representative samples can be obtained. Maintenance consists of conducting inspections and periodic checks on performance. Proper documentation (see previous section) is needed to serve as a benchmark for evaluation. Maintenance includes, but is not limited to, the following:

- C Ensuring visibility and accessibility
- C Inspecting locks for rusting
- C Inspecting surface seals for cracking.
- C Checking survey marks to insure visibility.

- C Determining depth (see Chapter 10 for recommended procedures).
- C Removing sediments (if needed).
- C Evaluating performance by doing hydraulic conductivity tests.
- C Evaluating turbidity and re-developing or replacing well if turbidity increases.

Routine inspections generally can be conducted during sampling. Additional evaluation can be conducted by comparing new ground water quality data with previous data. If the maintenance check indicates a problem, rehabilitation should be conducted.

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**TECHNICAL GUIDANCE MANUAL FOR HYDROGEOLOGIC  
INVESTIGATIONS AND GROUND WATER MONITORING**

**CHAPTER 8  
MONITORING WELL DEVELOPMENT**

**February 1995**

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## **CHAPTER 8**

### **MONITORING WELL DEVELOPMENT**

The purpose of a monitoring well is to provide a sample that is representative of ground water quality. Due to the effects of installation, the ground water entering a new well may not be representative of natural conditions with respect to yield, chemical characteristics, and amount of suspended particulate matter. To allow for the collection of representative samples, monitoring wells must be developed properly. Panko and Barth (1988) defined development as the process by which a monitoring well is stimulated to: 1) enhance hydraulic communication with the geologic strata of concern, 2) remove particulate matter and fluids (when used) remaining from well drilling and construction, and 3) stabilize chemical changes that may have occurred during drilling and construction. According to Aller et al. (1991), development is defined as "techniques used to repair damage to the borehole from the drilling process so that natural hydraulic conditions are restored, yields are enhanced, and fine materials are removed."

A key aspect of development is that it can reduce sample turbidity by removing fine particulate matter (clay and silt) from the filter pack and the geologic formation near the well intake, enhancing inflow to the well. Additionally, it can increase the life of wells by reducing or eliminating the potential for filling with fine particles or organic matter. Such "silting up" reduces yield and can result in anaerobic activity (NCASI, 1981). When sampling for metals, improper development can lead to clogged filters and excessive filtration times. It is essential that filtration not be viewed as a substitute for proper development.

### **FACTORS AFFECTING DEVELOPMENT**

Several factors may affect the performance and selection of a method or combination of methods for monitoring well development. These include, but may not be limited to, site hydrogeologic environment, well design and drilling method employed (Aller et al., 1991).

#### **HYDROGEOLOGIC ENVIRONMENT**

Ground water moves more easily through permeable, consolidated formations and "clean", coarse-grained sand and gravel; therefore, development may be accomplished quickly and easily. In contrast, flow through relatively impermeable silty or clayey material is slow or limited; consequently, the process can be difficult.

The ease of development is usually less predictable for unconsolidated formations than for rock. In general, more difficulty may be encountered when materials are unconsolidated. If a borehole is not stable, even distribution of the filter pack around the screen may not be achieved, hindering development. (Aller et al., 1991). If materials are silt and clay, drilling may cause smearing along the borehole wall, which also causes problems. On the other hand, drilling causes minimal damage to homogeneous sand and gravel, and development is not affected (Hackett, 1987).

Different types of formations may be developed more effectively by using certain techniques. For example, a highly stratified, coarse-grained deposit is handled best by methods that concentrate

energy on small parts of the formation. If the deposit is rather uniform, techniques that apply the same force over the entire length of the well screen can produce satisfactory results. Techniques that withdraw water quickly can reduce the hydraulic conductivity of formations containing a significant amount of silt and clay (Driscoll, 1986). Development of fine-grained materials generally should be accomplished by gentle action (Gass, 1989).

## **WELL DESIGN**

Typical monitoring well design (e.g., small diameter, artificial filter pack, and limited screen open area) makes development difficult. Generally, wells should be designed to keep entrance velocities low enough to avoid degassing and/or alteration of water quality (Gass, 1986). The thickness of the pack has considerable effect on the procedure because it reduces the amount of energy imparted to the borehole wall. The pack should be as thin as possible if development is to be effective at removing fine particulates. Conversely, it must be thick enough to ensure adequate borehole support and good distribution of material around the screen. Generally, a minimum of two inches is sufficient.

Selection of the proper screen slot size and configuration is also essential for successful development. Slots are chosen to permit removal of fine material from the formation (see Chapter 7). Large slots may filter too much material and cause settlement and damage. Alternatively, it may not be possible to develop or sample properly if the slots are too small. According to Driscoll (1986), development works best when screens have both maximum open area and a slot configuration that permits the forces to be directed efficiently into the formation. In general, screens that are continuous slot, wire-wound facilitate easier development because they have the greatest open area (Gass, 1986). However, a study conducted by Paul et al. (1988) indicated that there is no difference in water turbidity obtained from wells finished with factory slot, factory slot with a filter wrap, or continuous, slotted screens.

Large diameter wells (i.e., four inches or larger) are much easier to develop due to equipment availability. However, the high cost of construction materials has resulted in the installation of smaller wells with machine-slotted screens (Gass, 1986).

## **DRILLING METHODS**

The drilling process influences not only choice of development procedures, but also the intensity with which the procedures must be applied (Aller et al., 1991). All methods impair the ability of a formation to transmit water to a borehole or well. Problems that can occur include: 1) the use of air rotary drilling to penetrate consolidated rock can cause fine particles to build up on the borehole walls and may plug fractures and pore spaces, 2) driving casing or using augers can cause smearing of fine-grained particulates between the casing/screen and the natural formation, 3) mud rotary can cause mudcakes to build up on the borehole wall, and 4) all drilling methods potentially can compact sediments. Development must rectify these problems in order to enhance yield and allow collection of representative samples.

If a drilling fluid of any type is utilized, ground water quality can be affected; consequently, use is discouraged. If a fluid must be used, development should remove any that has infiltrated into the formation in order to allow in-situ ground water quality to return to pre-installation conditions.

## **OTHER FACTORS**

**Site accessibility** and **type and availability of equipment** should be considered during the selection of an appropriate method or combination of methods. The need for **proper disposal of contaminated discharge water** also can drive selection. **Time and cost** may dictate selection; however, methods that minimize time and cost often prove to be inadequate. Cost/benefit analysis generally favors proper and complete development. If it is inadequate, time and cost for drilling, well installation, ground water sampling, and sample analysis may be wasted on data that is not representative.

## **DEVELOPMENT METHODS**

Methods most commonly used to develop monitoring wells include pumping and overpumping, surging, bailing, air lifting and air surging. A combination of two or more often is implemented. In general, procedures involve movement of water at alternating high and low velocities through the well screen and filter pack to break down the mud cake on the borehole wall. This is followed by pumping or bailing to remove fine sediments that are in and immediately around the screen (ASTM Method D5092-90, 1994).

Other methods exist, such as backwashing, jetting with water or air, or adding chemicals. Although various chemicals, including acids, surfactants, chelating agents, wetting agents, disinfectants, and dry ice have been employed for water supply wells, their use for monitoring wells must be avoided. The addition of air, water, or chemicals may affect sample analysis in unpredictable ways. Air forced into a formation can reduce its permeability (Kraemer et al., 1991) and can cause volatilization of organics, if present. Water should be added only on rare occasions (i.e., when an insufficient amount exists to provide enough energy to develop the wells adequately). If water is added, it should be chemically analyzed for potential impact on in-situ ground water quality.

The following provides a general description of methods commonly used. The advantages and disadvantages of each are summarized.

### **PUMPING AND OVERPUMPING**

Probably the most widely accepted technique is to pump a well using an intake that is raised and lowered (without excessive surging) throughout the length of the screened interval (Puls and Powell, 1992). Alternate pumping and equilibration cycles should continue until the water is clean and no additional sediment accumulates in the bottom of the well. According to Keely and Boateng (1987), however, some settlement and further loosening of fines can occur after the first attempt. Accordingly, a second series of cycles may need to be conducted 24 hours later.

Overpumping at a rate that substantially exceeds water removal during purging and sampling or that causes dewatering increases influx of fine particles, thereby opening screen slots, pore spaces,

and fractures. However, high rates may not be advisable when wells are in a pristine area and adjacent to a contaminant plume because of the potential to draw in contaminants. Other disadvantages of pumping and overpumping include bridging of particles against the screen and the need for proper disposal of contaminated water.

Development by pumping is most effective in coarse-grained, unconsolidated deposits and rock formations. However, it generally has limited application in highly conductive formations because it is difficult to pump monitoring wells at sufficient rates to create the high entrance velocities necessary for removal of fine particulates (Barcelona et al., 1985). The pumps utilized must be capable of pumping at very low to very high rates and be controlled by valving. Small diameter pumps that offer a wide range have recently been developed.

Monitoring wells can be developed by using either a centrifugal or submersible pump. A centrifugal pump may be effective for low-yielding wells; however, it can be utilized only if the depth to water is less than approximately 25 feet. The use of a submersible pump is not limited by water level, but is affected by well diameter, construction material of the impeller, and type and concentration of contaminants. According to Kraemer et al. (1991), the presence of fine-grained materials can clog or damage pumps with plastic impellers. The bladder of squeeze-type pumps also may be damaged by fines. It is recommended that a bailer be initially used to remove accumulated sediments. Prior to well development, the pumps should be decontaminated in a manner consistent with the procedures described in Chapter 6 for drilling and subsurface sampling equipment.

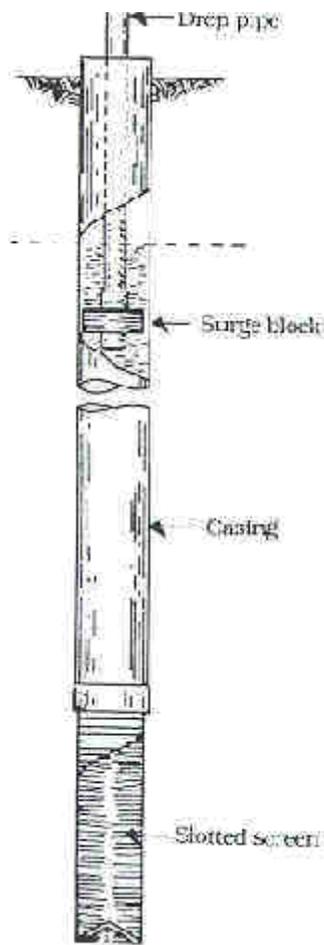
## **SURGING**

Surging involves pulling and pushing water into and out of a well intake by using a plunger or block. This process destroys bridging and can be effective for small diameter monitoring wells. A surge block is a device with a flexible gasket that is close in size to the well diameter (Figure 8.1). It is attached to a rod that is raised and lowered. Water is forced out of the intake on the downstroke, breaking up the bridged sediments and enabling water and sediments to flow back into the well on the upstroke. The surge block should fit with a minimum clearance of one-fourth inch (Barcelona et al., 1985). It should be of sufficient weight to overcome the inertia and drag of the cable reel and friction of the discs against the casing on the downstroke. Also, it should be of sufficient density to overcome the effects of buoyancy (Schalla and Landick, 1986).

Prior to surging, wells should be bailed. In order to minimize damage, surging should start slowly and increase in force during the process. High differential pressures may cause collapse of the well screen or casing. Also, surging may damage the filter pack (e.g., channels or voids may form near the screen if the pack sloughs away) (Keely and Boateng, 1987) or cause a significant amount of fines to accumulate, which can make it impossible to remove the surge block. Therefore, it is necessary to withdraw the block at intervals and remove the sediment with a sand pump or bailer. According to a study by Paul et al. (1988), surging of wells screened in fine-grained sediments should be avoided because it increases turbidity, does not improve hydraulic response significantly, and is unnecessarily costly. Bailing may be a better option for these wells.

For screen lengths of five feet or less, surging above the screen is effective for the entire screen length (Gass, 1986). For lengths greater than five feet, surging should be initiated at the top of the screen and worked gradually downward at 2-3 ft. intervals (Aller et al., 1991). Though surging within

the screened interval may be performed, precautions must be taken to prevent particulates from locking up the surge block or causing damage to the well.



**Figure 8.1 Development with a surge block** (Source: "Monitoring Well Development" by T.E. Gass. *Water Well Journal*, Vol. 40, No. 1, p. 53 (Figure 1). 1986. Reprinted from *Water Well Journal* with permission from National Ground Water Association. Copyright 1986).

## BAILING

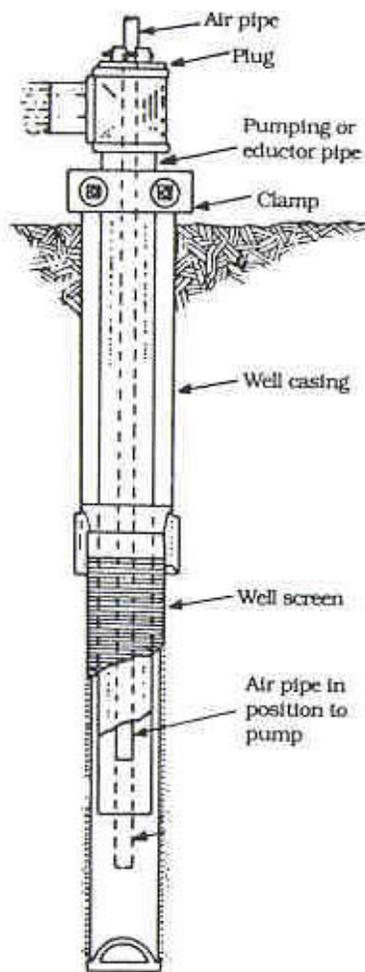
A bailer may be used to obtain effects similar to those offered by a surge block. Rapid removal creates an inward and outward thrust of water that breaks up bridges that may have formed adjacent to the well intake. To enhance the removal of particulates, rapid short strokes near the bottom of the well can be used to agitate and suspend sediments. Development by bailing should be limited to gentle action in low-yielding wells (Gass, 1989). If a well is de-watered, it should be allowed to recover and bailing should be resumed.

Development by bailing is very labor-intensive. Depending on the volume of water that must be removed, it may be useful to rig a tripod and pulley to aid in the lifting of the bailer from the well (Kraemer et al., 1991).

## AIR-LIFT PUMPING AND AIR SURGING

Other techniques commonly utilized are air lift pumping and air surging. These methods may induce and trap air in the formation outside the well intake and alter ground water quality. Furthermore, if ground water is highly contaminated, the methods can expose field personnel to hazardous materials. Use is not recommended unless the technique does not introduce air into the well screen and it can be demonstrated that the quality of water to be sampled will not be affected. Air from the compressor must be filtered to insure that oil is not introduced into the well (Barcelona et al., 1985). Generally, air techniques may be effective at removing debris, but cause very little positive effect beyond the well screen (Gass, 1986).

One method that does not introduce air is **two pipe air-lift pumping** (Figure 8.2). Air is injected through the inner pipe at high pressure to bubble out into the surrounding outer pipe. The bubbles reduce the unit weight of the water, causing the column of water and sediments to be lifted upward, allowing ground water from the formation to flow into the well (Gass, 1986).



**Figure 8.2 Two pipe air-lift system** (Source: "Monitoring Well Development" by T.E. Gass. *Water Well Journal*, Vol. 40, No. 1, p. 54 (Figure 4). 1986. Reprinted from *Water Well Journal* with Permission from National Ground Water Association. Copyright 1986).

To avoid injecting air into the screened interval, Aller et al., (1991) recommended that the bottom of the pipe be no more than ten feet from the top of the screen. Scalf et al. (1981) indicated that the use of air is restricted by the submergence factor, which equals the height of water in feet above the bottom of the pipe while pumping (blowing water out) divided by the total length of the pipe. The submergence factor should be on the order of at least twenty percent. This may be difficult to achieve with many shallow wells.

Development by ***air surging*** involves applying air intermittently to allow water to fall back down the casing and create a backwashing or surging action to break up any bridging (Keely and Boateng, 1987). This method is not recommended because it causes mixing of aerated water with the water in the well (Aller et al., 1991). Schalla and Landick (1986) have developed an air-vented surge plunger for developing small-diameter wells that does not introduce air into the formation unless the unit is lowered into the screened interval.

## **BACKWASHING**

Backwashing or rawhiding (Gass, 1986) involves allowing water that is pumped to the top of a well to flow back through the pump and out through the well intake. Backwashing breaks up the bridged particles, allowing them to be pumped and removed; however, it may not be forceful enough to obtain favorable results. The method may only develop materials opposite the upper part of the intake or preferentially develop the most permeable zones in stratified deposits. Also, it may allow potentially contaminated water to enter uncontaminated zones. Thus, the technique may not be appropriate for areas of known or suspected contamination.

## **TIMING AND DURATION OF DEVELOPMENT**

Development should not be implemented until the seal has cured and settled. Ideally, a time of 48 hours is required for neat cement and bentonite grout mixtures (Gaber and Fisher, 1988). However, the time required varies with site conditions and grout type.

The well should be developed to a point that water can enter as readily as hydraulic conditions allow and is representative of formation water. In general, a representative condition is assumed when the water is visually clear of sediments (e.g., turbidity # 5 NTU) and pH, temperature, and specific conductance have stabilized to  $\pm 10\%$  over at least 3 successive well volumes. The duration of development varies with the type of formation and method used. For example, surging and/or pumping may provide a sediment-free sample within minutes, whereas, bailing may take hours. The duration, along with pH, temperature, and conductivity measurements, should be recorded on the well completion diagram.

In some instances, collection of non-turbid samples is difficult or unattainable. If a well does not provide a sediment-free sample, development can stop if:

- A minimum of 10 well volumes have been removed, plus any volume of water or fluid that may have entered the well and formation during construction and development.

- Several procedures have been tried.
- Proper well construction has been verified.
- Temperature, conductivity, and pH have stabilized to  $\pm 10\%$  over at least three successive well volumes. (It should be noted that pH, temperature, and conductivity may not stabilize if water quality has been degraded)

During the course of their active lives, monitoring wells may need to be redeveloped. Unlike water supply wells, monitoring wells remain predominantly unpumped. There is no continuous removal of fines over an extended period. According to Kraemer et al. (1991), no matter how complete development appears to be, there is a high probability (especially for wells completed in fine-grained formations) that introduction of pumps or bailers will create a surge rendering the water produced somewhat turbid. Therefore, it is recommended that performance be evaluated during the life of a well. This may include, but not be limited to, noting a significant drop in yield during purging, noting increased turbidity, measuring total well depth to determine if sediments have been deposited, and using a camera to determine if incrustation of the screen has occurred.

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**TECHNICAL GUIDANCE MANUAL FOR HYDROGEOLOGIC  
INVESTIGATIONS AND GROUND WATER MONITORING**

**CHAPTER 9  
MONITORING WELL AND BOREHOLE ABANDONMENT**

**February 1995**

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## CHAPTER 9

### MONITORING WELL AND BOREHOLE ABANDONMENT

Boreholes that are not completed as monitoring wells and monitoring wells that no longer are being sampled or used for ground water level measurements must be abandoned properly to: 1) prevent poor quality water from one saturated zone entering another, 2) prevent contamination of the ground water by surface contaminants, 3) restore an aquifer to as close to its original condition as possible, 4) eliminate physical hazards, and 5) reduce potential for future liability. A suitable program should be designed and implemented to meet these objectives.

The sealing material and the method of abandonment depend on: 1) the design and construction of the well/borehole, 2) hydrogeologic conditions, 3) the chemical environment, 4) safety hazards and 5) disposal of contaminated materials removed. In general, well abandonment should consist either of a method for well removal and simultaneous grouting of the borehole with bentonite, neat cement, or a bentonite/cement mixture, or a method for grouting in-place that ensures complete sealing.

### SEALING MATERIALS

The chosen sealing material should:

- Not react with contaminants, ground water or geologic materials.
- Have a hydraulic conductivity comparable or lower than that of the in-situ material.
- Form a tight bond with the borehole wall and well casing.
- Be resistant to cracking and/or shrinking.
- Be of sufficient structural strength to withstand subsurface pressures.
- Be capable of being placed at the appropriate depth.

Chapter 7 should be consulted for details on different types of sealants and their application. Although each has advantages and disadvantages, no single material exhibits all of the desirable characteristics. Therefore, every situation must be evaluated carefully to determine the appropriate choice. Generally, materials used are comprised of concrete, neat cement, or sodium bentonite.

In general, wells completed in unconsolidated formations or non-creviced rock may be satisfactorily sealed with neat cement, bentonite or a combination of the two. Wells that penetrate limestone or other creviced or channeled rock formations should be filled with concrete grout or neat cement to ensure seal permanence. The use of fine-grained materials to seal creviced rock may not be desirable because the materials might be displaced by flow of water through crevices (American Water Works Association, 1984). Neat cement and sodium bentonite, or a combination, should be used for sealing an abandoned well/borehole below the water table (Gordon and Koch, 1988). Above the water table, a cement/bentonite mixture should be utilized. In general, placement of pure sodium bentonite above the water table is not appropriate due to the lack of water for hydration and possible shrinking of the material if it becomes dry. Neat cement may shrink if placed above the water table; therefore, it is recommended that two to six weight percent of bentonite mixed with neat cement be utilized. At no time should a borehole or well be backfilled with cuttings or with any materials of unknown integrity. However, in some geologic environments, such as coarse gravel,

where excessive loss of sealing materials may occur, or when grout may affect the water quality of nearby monitoring wells, clean sand or gravel in conjunction with regular materials can be used (Gordon and Koch, 1988; Kraemer et al., 1991).

## PROCEDURES

### PLANNING

Careful review should be conducted prior to abandoning monitoring wells. This may include:

- Review of records pertaining to well construction and repair or modifications.
- Review of all analytical chemical data for soil and ground water.
- Review of the hydrogeologic/geologic characteristics in the vicinity of the well.
- Current conditions of the well such as depth to bottom, amount of siltation, etc.

If a well is to be left in place, borehole geophysical logging techniques may be helpful in determining its integrity. This may include caliper logs to measure inside diameter; television logs to identify casing breaks, screen size, etc; gamma logs to verify geologic information; cement bond logs to determine if the casing is firmly attached to the grout; flow logs to determine if vertical flow occurs within the casing; and hydraulic integrity tests to determine if the casing is intact (ASTM, D5299-92). For additional information on downhole logs, see Chapter 11.

Prior to abandonment of monitoring wells, it is recommended that a work plan detailing the procedures/methods be submitted to the appropriate regulatory authority.<sup>1</sup> The information should include:

- Reasons for abandonment.
- Identification and location coordinates.
- Casing diameter and material.
- Screen material, length and depth.
- Total depth.
- Geologic materials opposite well screen.
- Drilling log and construction diagrams.
- Type and concentrations of contaminants present<sup>2</sup>, if any.
- Procedure for disposal of any contaminated soil, well construction materials and water.
- Method for abandonment.
- Type of sealing material.
- An estimation of the volume of sealing material needed.
- Measures to protect the health and safety of individuals.

---

<sup>1</sup>If a regulated entity is conducting a hydrogeologic investigation or a ground water monitoring program, an abandonment workplan should be submitted prior to initiating the program. In this situation, a separate workplan is not necessary.

<sup>2</sup>If contamination was detected or suspected in the original well or boring, appropriate health and safety requirements should be followed.

## FIELD PROCEDURE

Monitoring wells have often been abandoned by pulling the surface casing where possible, followed by pouring cement or bentonite into the hole. This procedure is inappropriate, especially if the construction of the well is unknown or the well intake spans more than one saturated zone. Incomplete seals may form due to bridging. Additionally, the procedure has little effect on the filter pack, which may allow communication between saturated zones.

In general, the following basic procedure is recommended for abandoning monitoring wells and boreholes. Steps 1 and 2 are not necessary for abandonment of exploratory boreholes. It should be understood that no single method and material are suitable for all situations. Site-specific characteristics may merit modifications or procedures not discussed below. Additional information can be found in the references listed.

1. Inspect the well and remove any obstacles (i.e., pumps, pressure lines, other debris, etc.) that may interfere with the placement and performance of the sealing material. If necessary, a camera survey can help to identify the depth and construction of the well if this information is not known. The outer protective casing should be removed.
2. Since the primary purpose of abandonment is to eliminate vertical fluid movement, it is strongly recommended that the casing and screen be removed and the boring be overdrilled to remove the annular seal and filter pack. When the well is removed, there is less concern about channeling in the annular space or an inadequate casing/grout seal (Aller et al., 1991). The casing and well screen can be removed by pulling or bumping the casing, overdrilling around the casing using a hollow stem auger, or overdrilling through the well using a solid stem auger or rotary bit (see Table 9.1). The method used should depend on the type, length, and diameter of the casing, conditions of the annular seal, and site geology. Aller et al. (1991) and ASTM 5299-92 provided a discussion on various removal techniques. The borehole should be overdrilled using a bit with a diameter at least 1.5 times greater than the original diameter of the borehole. Drilling should be slightly deeper than the original depth to assure complete removal. To achieve an effective seal, the borehole should be cleared of any excess mud filtercake.

In some instances, such as when safety problems occur, or when dealing with large diameter wells, casing removal can be difficult. If the well construction is known, the screen and filter pack do not span more than one saturated zone, and circumstances prevent complete removal of the casing and screen, then the following procedure can be used (based on Renz, 1989):

- a. The well can be filled with clean silica sand to one foot above the screen in the event that the screened area is adjacent to a highly permeable formation.
- b. One foot of bentonite pellets can be placed above the screen in a manner that prevents bridging (i.e., through a tremie pipe or by tamping after installation).
- c. The pellets should be hydrated.
- d. To allow the sealant to permeate and be effective, the casing should be perforated to one foot above the bentonite seal either by splitting it vertically (synthetic casing) or by making horizontal cuts every two feet with a retractable blade (steel casing).

3. The borehole should be pressure grouted using a tremie pipe as the drilling stem is removed. The sealant should be applied in one continuous procedure to prevent segregation, dilution, and bridging (Aller et al., 1991). The pipe should be in constant contact with the sealant to prevent air pockets from forming. The borehole should be sealed from the bottom up to the frost line (approximately two to three feet from the surface). The overflowing grout should be regularly evaluated as it reaches the surface. When the observed material is similar to that being pumped in, this stage of the plugging is considered complete. Wells abandoned in-situ should be sealed from the bottom up to approximately five feet from the surface.

**Table 9.1 Techniques for casing removal.**

| <i><b>TECHNIQUE</b></i> | <i><b>METHOD</b></i>   |
|-------------------------|--|
| Pulling or bumping      | ☐ Use a rig to pull out the well casing; this may be appropriate only for steel casing since plastic/teflon casing may break.  |
| Overdrilling            | ☐ Drill around the well using the well casing as a guide, then pull out the casing. This method is limited by well diameter due to the high torque required to turn large diameter augers. |
| Drilling through well   | ☐ Use a solid stem or rotary bit to drill the casing out. This can be done only with plastic/teflon well material. It can be difficult to retrieve the cutting.                            |

4. The grout plug should be inspected 24 hours after installation to check for settling and grout should be added if needed. If the well is abandoned in-place, the casing should be cut off approximately five feet below ground level and a PVC or stainless steel cap should be emplaced. The boring should be grouted to within two to three feet from the surface with an appropriate material. Monitoring wells abandoned in place should be marked with a piece of metal to allow for location by a metal detector or magnetometer (Aller et al., 1991).
5. The remaining area above the plug should be completed in a manner that is compatible with the site. For example, its top can be covered with one to two feet of soil if vegetative growth is desired. If the area is to be surfaced, then the final seal can be completed with cement or concrete.
6. Proper abandonment of monitoring wells should be documented and reported to the Ohio EPA division regulating the site. The information should include, at a minimum:
  - ☐ Identification (e.g., registration number, location, owner, and any distinct features).
  - ☐ Well construction details.

- C Date, time and person responsible and contractor/consultant performing the work.
- C Authority under which the abandonment was performed.
- C Procedures and materials (including predicted volume of grout, volume of grout used, and an explanation if any discrepancy exists between these values) .
- C Method/procedures for disposal of any contaminated materials.

Additionally, Ohio Revised Code 1521.05(B) requires that an abandonment report be filed with the Ohio Department of Natural Resources (ODNR), (Figure 9.1). The form can be obtained from ODNR, Division of Water (614-265-6717).

**WATER WELL SEALING REPORT**  
 (For Abandoned or Unused Wells)  
**OHIO DEPARTMENT OF NATURAL RESOURCES**  
 Division of Water, Ground Water Resources Section  
 1939 Fountain Square Drive  
 Columbus, Ohio 43224-1360

**LOCATION**

County \_\_\_\_\_ Township \_\_\_\_\_ Section \_\_\_\_\_  
 Property Owner \_\_\_\_\_  
 Address of Property \_\_\_\_\_  
 Location: \_\_\_\_\_ miles \_\_\_\_\_ n, e, s, w \_\_\_\_\_ of \_\_\_\_\_ nearest intersection \_\_\_\_\_  
 on the \_\_\_\_\_ n, e, s, w \_\_\_\_\_ side of \_\_\_\_\_ road name \_\_\_\_\_

**ORIGINAL WELL**

ODNR Well Log Number \_\_\_\_\_ Copy attached? Yes or No \_\_\_\_\_  
 (circle one)

**MEASURED CONSTRUCTION DETAILS**

Depth of Well \_\_\_\_\_ Date of measurements \_\_\_\_\_  
 Size of Casing \_\_\_\_\_ Static Water Level \_\_\_\_\_  
 Well Condition \_\_\_\_\_ Length of casing \_\_\_\_\_

**SEALING PROCEDURE**

Method of Placement \_\_\_\_\_

| Placement: | From  | To    | Sealing Material | Volume |
|------------|-------|-------|------------------|--------|
| From       | _____ | _____ | _____            | _____  |
| From       | _____ | _____ | _____            | _____  |
| From       | _____ | _____ | _____            | _____  |

Was Casing Removed? Yes \_\_\_\_\_ No \_\_\_\_\_  
 (circle one)

Condition of Casing \_\_\_\_\_

Perforations: From \_\_\_\_\_ To \_\_\_\_\_  
 Taken \_\_\_\_\_ To \_\_\_\_\_

Date Sealing Performed \_\_\_\_\_

Reason(s) for Sealing \_\_\_\_\_

**CONTRACTOR**

Name \_\_\_\_\_ OOH Registration # \_\_\_\_\_  
 Address \_\_\_\_\_  
 City/State/Zip \_\_\_\_\_ Signature \_\_\_\_\_

**Figure 9.1 ODNR form for reporting well abandonment procedures.**

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**TECHNICAL GUIDANCE MANUAL FOR HYDROGEOLOGIC  
INVESTIGATIONS AND GROUND WATER MONITORING**

**CHAPTER 10  
GROUND WATER SAMPLING AND ANALYSIS**

**February 1995**

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## CHAPTER 10

### GROUND WATER SAMPLING AND ANALYSIS

The intent of this chapter is to summarize procedures for collecting representative ground water samples. Although the chapter is intended specifically for the sampling of monitoring wells, the procedures may be useful for other types of ground water sampling. Hydropunch™ (Chapter 11) and well point sampling for reconnaissance studies require slightly modified protocols.

#### OBJECTIVES

The objectives of ground water sampling are diverse and often specific to a site or problem. In general, regulatory requirements and sample representativeness must always be considered.

#### REGULATORY

Regulations may specify frequencies for sample collection and parameters for analysis. Requirements for documentation of procedures may also be specified. It is recommended that appropriate divisions within Ohio EPA be consulted when planning sampling programs (see Chapter 2 for appropriate regulatory authority). To satisfy regulatory requirements when determining ground water quality, it is important that representative samples are obtained.

#### SAMPLE REPRESENTATIVENESS

A representative sample reflects ground water quality as it occurs in the subsurface. The first step toward obtaining representative samples is proper monitoring well installation and development. Prior to sampling, steps must be taken (i.e., purging) to ensure that stagnant water in either the well or a dedicated pump is not included in samples. This water may be altered from formation water due to contact with the atmosphere and/or interaction with the well screen and casing. Representative samples can be collected by utilizing appropriate techniques and equipment for sampling, decontamination, and preservation/handling. Proper laboratory Quality Assurance/Quality Control (QA/QC) procedures must be followed to ensure that chemical analysis reflects sample quality. Alteration due to change in sample environment, faulty sampling equipment, and procedures should be minimized.

#### Alteration Due to Change in Sample Environment

Transfer of ground water from in-situ to atmospheric conditions can alter it significantly unless proper techniques are used. Aeration/oxidation, pressure, and temperature are three major environmental factors.

#### *Aeration/Oxidation*

The addition of oxygen upon exposure to the atmosphere increases the redox state of ground water samples. Species such as iron (Fe), manganese (Mn), arsenic (As), and cadmium (Cd) may be

oxidized from a reduced state (Gillham et al., 1983), which can cause them to precipitate from solution. The oxidation of Fe is particularly important for sample stability. Ground water may contain high concentrations of dissolved Fe due to anoxic (low oxygen) subsurface conditions. Upon exposure, it can oxidize rapidly and precipitate ferric hydroxide, which causes an increase in pH that may alter sample integrity further. Ferric hydroxide is known to remove contaminants from solution including, but not limited to, copper (Cu), zinc (Zn), cobalt (Co), cadmium (Cd), arsenic (As) and lead (Pb).

### ***Pressure Differences***

Pressure changes caused by the release of ground water into a well and the atmosphere may cause shifts in chemical equilibrium. Ground water may have high partial pressures of CO<sub>2</sub> gas, and upon exposure, samples supersaturate and degas CO<sub>2</sub>. This is known to cause increases in pH by up to 0.5 to 1 standard units and may cause various metals to dissolve or precipitate. If volatile organic compounds (VOCs) are present, sudden pressure changes cause their volatilization. This will result in a negative bias with respect to true VOC concentration.

### ***Temperature Differences***

Temperature changes can affect the solubility and volatility of constituents (Parker, 1994). The temperature of a sample may change because of differences between ambient air and subsurface conditions.

### **Alteration Due to Sampling Technique**

The method and design of the sampling device potentially can alter samples. Tools that require air to contact ground water (not recommended) can potentially aerate samples. Devices can leach contaminants into samples or sorb contaminants from them. Also, improper decontamination of equipment can alter samples.

## **PLANNING AND PREPARATION**

The success of any ground water sampling event in collecting representative samples hinges on the planning and preparation conducted prior to entering the field. Procedures, plans, sampling frequency, and event planning and preparation should be evaluated appropriately.

### **WRITTEN PLAN**

Written, detailed, site-specific protocol should be developed to document sampling and analysis procedures. The protocol can be incorporated into a single, stand-alone document (sometimes called a sampling and analysis plan) or can comprise a section of a more comprehensive document. The submittal, format, and/or disposition may be dictated by regulatory requirements. In general, a plan must include (at a minimum) the components listed in Table 10.1

**Table 10.1 General components of a ground water sampling and analysis plan.**

| <b>GENERAL COMPONENTS OF A GROUND WATER SAMPLING AND ANALYSIS PLAN</b>  |
|---|
| <ul style="list-style-type: none"> <li>• Parameter selection</li> </ul>   |
| <ul style="list-style-type: none"> <li>• Sampling frequency</li> </ul>  |
| <ul style="list-style-type: none"> <li>• Field procedures prior to sampling ground water, including:               <ul style="list-style-type: none"> <li>- well inspection</li> <li>- water level measurements</li> <li>- total depth of well</li> <li>- detection and sampling of immiscible liquids</li> </ul> </li> </ul> |
| <ul style="list-style-type: none"> <li>• Well purging</li> </ul>  |
| <ul style="list-style-type: none"> <li>• Field measurements of ground water               <ul style="list-style-type: none"> <li>- parameters (e.g., pH, temperature, and conductivity)</li> <li>- calibration of field equipment</li> </ul> </li> </ul>  |
| <ul style="list-style-type: none"> <li>• Sample withdrawal</li> </ul>   |
| <ul style="list-style-type: none"> <li>• Sample handling, including:               <ul style="list-style-type: none"> <li>- order of collection</li> <li>- filtration</li> <li>- preservation</li> <li>- containers</li> <li>- holding times</li> <li>- shipping</li> </ul> </li> </ul>                                       |
| <ul style="list-style-type: none"> <li>• Decontamination procedures</li> </ul>  |
| <ul style="list-style-type: none"> <li>• Documentation, including:               <ul style="list-style-type: none"> <li>- field logbook</li> <li>- chain-of-custody</li> <li>- sample analysis request sheet</li> <li>- field and laboratory QA/QC samples</li> <li>- detection limits</li> </ul> </li> </ul>                 |
| <ul style="list-style-type: none"> <li>• Laboratory analysis</li> </ul>   |

## **PARAMETER SELECTION**

The analysis of samples should quantify the general quality of the ground water and/or any contamination that may be present. These goals can be achieved through proper parameter selection.

### **Parameters to Characterize General Quality**

Regulated entities are encouraged to include analysis for pH, alkalinity, TDS, fluoride ( $F^-$ ), hydrogen sulfide ( $H_2S$ ), total hardness and non-carbonate hardness, specific conductance, chloride ( $Cl^-$ ), nitrate ( $NO_3^-$ ), sulfate ( $SO_4^{2-}$ ), phosphate ( $PO_4^{3-}$ ), silicate ( $SiO_2$ ), sodium ( $Na^+$ ), potassium ( $K^+$ ), calcium ( $Ca^{+2}$ ), magnesium ( $Mg^{+2}$ ), ammonia ( $NH_4^{+1}$ ), total iron (Fe), and manganese (Mn). The results can provide an overall picture of ground water geochemistry that is useful to site characterization. For example, an understanding of site geochemistry can help in determining chemical species and mobility in the subsurface. Several analytes (e.g., cations, anions, pH, temperature, TDS, specific conductance, etc.) may help indicate releases of inorganic contaminants.

### **Parameters to Characterize Contamination**

Additional parameters are necessary to characterize the presence or absence of ground water contamination. Regulation or policy can dictate selection by specifying parameters, defining project goals, and/or by mandating a certain kind of investigation. Detection monitoring may include analysis for a mandated set of indicator parameters (e.g., total organic carbon, total organic halogen, pH, specific conductance) to determine if contamination has occurred. In many situations, entities may be required to augment the set and monitor site-specific waste constituents to allow for "clean" closure demonstrations. When indicator parameter results/suggest contamination, assessment monitoring is implemented to verify the release and determine contaminant concentration and the rate and extent of contaminant migration. Under assessment, a more detailed set of parameters, specific to the waste constituents and their breakdown products, is typically monitored.

In instances where a set of parameters is not mandated, past waste constituents and handling practices should be considered. Because waste may change through time upon release transport, it is important that potential breakdown products also are considered. If accurate disposal records are available and waste constituents are well-documented, the list of parameters can be relatively limited. The list should be more extensive if practices are poorly understood. It may be necessary to monitor suites of parameters (e.g., volatiles, semi-volatiles, metals, etc.) when specific waste constituents are not known. Where regulation/policy allows, lists may be narrowed as the waste information becomes better understood. Additionally, the parameter list often can be narrowed to those constituents found at the site when parameters of concern have been identified sufficiently.

## **SAMPLING FREQUENCY**

Ground water monitoring regulations often specify sampling frequencies (i.e., semi-annually or quarterly). At a minimum, these should be adhered to. Greater frequencies may be dictated by site

hydrogeology. U.S. EPA (1989) suggested using the Darcy equation to determine average linear velocity of ground water (see Chapter 3). If velocity is low, less frequent sampling is required. High velocity indicates the need for more frequent sampling. Linear flow velocity can be used to determine an interval that yields an independent sample. Sample independence is an important concept for statistical data analysis (see Chapter 13). Barcelona et al. (1985) provided a nomograph based on hydraulic parameters that can be useful. Barcelona et al. (1989) indicated that data collected over a period of two years or more is often needed to establish seasonal trends before an adequate frequency can be selected.

The type of contaminant source (i.e., spill, intermittent source, or continuous source) should also be considered for sites with releases and known contamination (Barcelona et al., 1985). Spills tend to move as a slug through the subsurface, potentially limiting the sampling time frame at a particular well as the slug passes. Intermittent sources may cause high and low concentration trends to develop as individual slugs move. Continuous sources may develop a large plume requiring a sampling frequency based on ground water flow velocity.

## **EVENT PLANNING AND PREPARATION**

Before any sampling begins, planning and preparation should be a high priority. All personnel should be familiar with site-specific written protocol and trained in the proper use of the equipment. All equipment and paperwork should be organized. Instruments should be in working order and properly decontaminated. Field logs for recording notes should be organized. Arrangements with the laboratory should be made to ensure that samples can be handled and analyzed within the required holding times and to obtain labels, appropriate containers, and preservatives. The following are general checklists for preparation procedures and equipment:

### ***Preparation Procedures:***

- Determine sampling date and time.
- Determine all sampling locations.
- Estimate total sampling and travel time to insure appropriate lab arrangements.
- Determine the number and type of analyses needed from each location.
- Determine purge water management practices.
- Determine decontamination procedures.
- Determine safety procedures.
- Determine the number of field, equipment, and trip blanks and duplicate samples needed.
- Determine sample volumes needed, total number of samples, and container type.
- Determine the construction, sampling history and recharge rate of each well.
- Be aware of any nearby production wells that may be affecting measured water levels.
- Determine those samples that need to be filtered and secure appropriate equipment.
- Check to see that the equipment is working properly.
- Calibrate all instruments and calculate bailer volume (if necessary).
- Collect all preservatives and pre-order if lab-supplied preservatives are used.
- Understand all transportation and chain-of-custody procedures.

### ***General Supply and Equipment Checklist:***

- Keys to locks on wells.
- Map of site and well locations.
- Field notebook or logbook.
- Indelible marking pens.
- Appropriate lab analysis and chain-of-custody forms.
- Preservatives.
- Filtration equipment.
- Ice and cold packs.
- Coolers for ice and samples.
- Purging and sampling devices.
- Appropriate tubing.
- Appropriate sample containers and labels.
- Thermometer.
- pH meter.
- Specific conductance meter.
- Water level meter.
- Calibrated bucket (to determine volume of purged water).
- Tool box.
- Extra batteries.
- Safety equipment.
- Plastic sheeting for ground cover.
- Decontamination solutions and equipment.
- Flashlight.
- Photoionization detector (PID) or organic vapor analyzer (OVA).
- Equipment for detecting immiscibles (e.g., interface probe).

### **PRELIMINARY FIELD PROCEDURES**

Prior to removing samples from a well, several tasks should be completed to document conditions, ensure the well is ready for sampling, and gather field data. These tasks include inspection and preparation, well measurements, and immiscible layer detection and sampling.

#### **WELL INSPECTION AND PREPARATION**

Upon arrival, a thorough inspection of the well and protective quard should be conducted and observations recorded to document whether damage or tampering has occurred. The cap and lock also should be checked. Cracks in the casing and/or surface cement seal should be noted, as well as soil washouts and depressions around the casing.

Before taking any measurements, all weeds and debris should be cleaned from the well area. A clean plastic sheet should be placed on the ground to prevent contamination of equipment. The plastic should be disposed properly following completion of sampling at each well. It is important that all equipment be wrapped and stored off the ground to avoid contamination.

## **WELL MEASUREMENTS**

Appropriate measurements should be made inside wells before any water is purged and sampled. These include the detection of gases and immiscible liquids and the measurement of static water levels and total well depth.

### **Detection of Gases**

Immediately, upon removal of the well cap, a photoionization detector (PID) or an organic vapor analyzer (OVA) should be utilized to detect volatile gases. For further information on types and uses of these instruments, see Anastas and Belknap (1980), Brown et al. (1980) and DuBose et al. (1981). This measurement can give useful information about potential ground water quality and allow for sampling personnel to take appropriate safety precautions. It also may be useful to determine the potential for the presence of immiscible layers, which necessitate additional sampling procedures and concerns.

### **Water Level**

In addition to providing hydrogeologic information on a continuing basis, measurement of the water level in a well enables determination of the volume of water contained, which may be useful for purging determinations. Measurements should be taken from the entire well network before any water removal to obtain a single "snapshot" of current hydraulic head conditions and to avoid potential effects on the water levels in nearby wells.

Measurements can be taken manually or automatically. Table 10.2 summarizes the manual methods. In general, the electrical probe method is recommended. The wetted tape method is not recommended because the chalk on the tape has the potential to contaminate well water. Automatic, continuous recording devices may be useful for collection of long-term data and in pumping tests. Water level measurements are described in more detail by Dalton et al. (1991), Aller et al. (1991), and ASTM Method D4750-87 (1992).

Generally, measurements should be accurate to within  $\pm 0.1$  to  $\pm 0.01$  ft. The precision should depend on the slope of the potentiometric surface or water table and the distance between wells. Greater precision is necessary where the slope is gradual or wells are close together (Dalton et al., 1991). It is advisable to take at least two readings at each well, with the second used to verify accuracy of the first. All wells should have professionally surveyed reference points for accurate water level determination. Typically, one point on the top of the inner riser pipe is used. Equipment should be properly decontaminated before use in each well to ensure sample integrity and prevent cross-contamination. Techniques are discussed later in this chapter.

**Table 10.2 Summary of methods for manual measurement of water levels (based on Dalton et al., 1991).**

| MEASUREMENT METHOD | MEASUREMENT ACCURACY (in feet) | DESCRIPTION   | MAJOR INTERFERENCES OR DISADVANTAGES   |
|--------------------|--------------------------------|---|--|
| NON-FLOWING WELLS  |                                |   |  |
| Wetted-tape        | 0.01                           | The water level is determined by lowering a weighted steel tape with bottom 2-3 feet coated with carpenters chalk into the well. The water level is calculated by subtracting the submerged distance, as indicated by the lack of chalk color, from the reference point at the top of the well. | <ul style="list-style-type: none"> <li>• Water on the side of the casing or cascading water may wet the tape above the actual water level and result in measurement error.</li> <li>• Addition of foreign material to well.</li> <li>• Approximate depth to water may be unknown, thus too short or too long a length of chalked tape may be lowered into the well.</li> </ul> |
| Air-line           | 0.25                           | A small straight tube (usually #0.375 inches in diameter), of accurately known length is installed in the well along with a pressure gauge and a fitting for an air source. A water level measurement is made when air is pumped into the tube and the pressure monitored.                      | <ul style="list-style-type: none"> <li>• Less precise</li> <li>• Air-line or fittings can leak</li> </ul>  |
| Electrical Probe   | 0.02 to 0.1                    | An electric probe is lowered into the well. When the probe comes into contact with water, a potential between the two dissimilar metals in the probe is measured at the surface on a millivolt meter.   | <ul style="list-style-type: none"> <li>• Errors result from changes in cable length.</li> <li>• Contact cannot be made reliably when LNAPLs are on the water surface.</li> </ul>   |
| Transducer         | 0.01 to 0.1                    | A transducer is lowered a known distance into the well and allowed to equilibrate with fluid temperature. Distance of submergence of the transducer is read on the signal conditioning unit and is subtracted from the cable length referenced at the top of the well.                          | <ul style="list-style-type: none"> <li>• Accuracy is dependent upon range and sensitivity of the device.</li> </ul>  |
| Float              | 0.02 to 0.5                    | A float is attached to the end of a steel tape and suspended over a pulley and lowered into the well. A counter weight is attached to the opposite end. Depth to water is read directly from the steel tape at a known reference point from top of casing.                                      | <ul style="list-style-type: none"> <li>• Error can be caused by float or cable drag, line shift, submergence of counter-weight, and temperature and humidity.</li> </ul>   |

**Table 10.2 (continued) Summary of methods for manual measurement of water levels (based on Dalton et al., 1991).**

| MEASUREMENT METHOD        | MEASUREMENT ACCURACY (in feet) | DESCRIPTION   | MAJOR INTERFERENCES OR DISADVANTAGES   |
|---------------------------|--------------------------------|---|--|
| Popper                    | 0.1                            | A metal cylinder with a concave bottom is attached to steel tape and lowered into the well. A distinct "pop" can be heard when the cylinder is dropped onto the water surface | <ul style="list-style-type: none"> <li>• Accuracy is dependent upon skill of measurer and depth to water.</li> <li>• Potential to agitate water.</li> <li>• Contact cannot be made reliably when LNAPLS are on the water surface.</li> </ul> |
| Acoustic Probe            | 0.02                           | Adaptation of the popper and electrical method [Schrale and Brandywyk (1979)]. Electric device is lowered into the well until an audible sound is emitted.                    | <ul style="list-style-type: none"> <li>• Cascading water can cause false measurements.</li> <li>• Contact cannot be made reliably when LNAPLS are on the water surface.</li> </ul>   |
| Ultrasonic                | 0.02 to 0.1                    | Water level measurements are determined by an instrument that measures the arrival time of a reflected transmitted sonic or ultrasonic wave pulse.                            | <ul style="list-style-type: none"> <li>• Accuracy can be limited by the change of temperature in the path of the sound wave and other reflective surfaces in the well (i.e., casing, pumps, etc.)</li> </ul>                                 |
| <b>FLOWING WELLS</b>      |                                |   |  |
| Casing Extension          | 0.1                            | A simple extension is attached to the well casing to allow water level to be measured directly.   | <ul style="list-style-type: none"> <li>• The device is only practical when additional height requirement is only several feet.</li> </ul>  |
| Manometer/ Pressure Gauge | 0.1 to 0.5                     | The pressure of water within a sealed or "shut-in" well is measured.  | <ul style="list-style-type: none"> <li>• Gauge inaccuracies.</li> <li>• Calibration is required.</li> </ul>  |
| Pressure Transducers      | 0.02                           | Procedures are the same as described above for transducers. The range of a pressure transducer must be carefully matched with shut-in well pressure.                          | <ul style="list-style-type: none"> <li>• Changes in temperature in the transducers cause errors.</li> </ul>  |

## **Well Depth**

Measuring depth of a well can indicate whether siltation has occurred. In addition to decreasing depth, natural siltation can block water from entering and bias analytical results by increasing sample turbidity.

Depth can be determined with a weighted tape measure or marked cable, each of which should be composed of inert materials. Often, the same device that is used to measure water levels can be used. Heavier weights are necessary as depth increases to effectively "feel" the well bottom. The measurement should be recorded on the field log.

It generally is not necessary to measure well depth every time water levels or samples are obtained. It may not be possible to obtain depth from a well with a dedicated pump unless the pump is removed. In addition, the logistics of decontaminating the entire length of the measuring tape in contact with contaminated ground water may cause depth measurements to be impractical. It is recommended that depth measurements be taken once a year in wells that do not have dedicated pumps. Measurements in wells with pumps should be taken whenever the pump is removed for maintenance. If silting is suspected to be a problem (e.g., noted increase in sample turbidity, or decrease in pump efficiency), the pump should be removed and the well depth measured.

## **DETECTION OF IMMISCIBLE LIQUIDS**

If the presence of dense or light, low solubility organic liquids is suspected, the sampling program should include devices and protocols to detect them. Dense non-aqueous phase liquids (DNAPL) are often called "sinkers" because their density (greater than water) causes them to sink. Light non-aqueous phase liquids (LNAPL) are often called "floaters" because their density (less than water) causes them to float on the water table surface. If floaters are of concern, it is important that, upon opening the well cap, the air in the casing is monitored with a photoionization detector or an organic vapor analyzer. In addition to providing information on worker health risks, air monitoring can serve as a first indication of the presence of volatile floaters.

Various probes and methods have been developed to detect these immiscible layers. Probes and reactive pastes have been developed to determine air/immiscible and water/immiscible interfaces. Indicator pastes are used to coat an interface probe or a weighted tape. An observed reaction indicates the presence of an immiscible. Probes and pastes can be utilized for detecting both floaters and sinkers (U.S. EPA, 1992). Transparent bailers also can be used.

## **SAMPLING IMMISCIBLE LIQUIDS**

If a floater is found to be present, a bailer or submersible pump should be used to remove it (U.S. EPA, 1992) to prevent mixing of the liquid with ground water and alteration of samples from their true state. Any floaters greater than 2 feet in thickness can be evacuated using a bottom valved bailer. The bailer should be lowered slowly to a depth less than the product/water interface. A modified, top-filling bailer (bottom valve sealed off with a fluorocarbon resin sheet between the ball and ball seat) can be used to remove immiscible layers less than 2 feet in thickness. A stainless steel weight is added to the retrieval line above the bailer to counter its buoyancy. In either case,

a peristaltic pump also can be utilized if depth to product is less than 25 feet. Any floaters less than 2 inches thick should be collected from the top of the water column using a bailer (U.S. EPA, 1992). Samples collected in this manner consist of both an aqueous and non-aqueous phase.

Sinkers also should be removed before a well is purged. Dual-check valve bailers, Kemmerer devices and syringe samplers often are used. Submersible pumps can be used if the dense phase is sufficiently thick (U.S. EPA, 1992). It is important that appropriate QA/QC procedures be followed when collecting samples of any immiscible liquids. If any immiscible layer is removed, it should be properly collected, containerized, characterized, and disposed. The Division of Hazardous Waste Management, Ohio EPA, should be contacted for guidance on these issues.

## SAMPLING EQUIPMENT

A variety of sampling equipment has been developed, all of which display advantages and disadvantages. It is important to remember that there is no tool that can be used in every situation. Site-specific hydrogeology, geochemistry, types of contaminants, and well design all can limit adequacy. Ultimately, the ideal scheme should employ a completely inert material, should not subject samples to negative pressures and only to moderate positive pressures, and should not expose samples to the atmosphere (ASTM, Method D4448-85, 1992) .

## CRITERIA FOR SELECTION

In general, the choice of device should be based on the **characteristics of the device** in combination with the **characteristics of the site/project**. The following paragraphs discuss these characteristics and the criteria that should be considered.

### Device Characteristics

Characteristics of devices are as follows:

- **Device composition** - The chosen tool should have sample-contacting parts made of "inert" materials that limit the potential for bias through sorption or leaching of contaminants, degradation, or corrosion. Barcelona et al. (1985) summarized and ranked materials according to their effects on ground water samples. For rigid material (casing, screen, bailers etc.), they recommended, in order of preference, Teflon, stainless steel (316 and 304), PVC and steel. For flexible material (tubing, bladders, gaskets, etc.), they recommended, in order, Teflon, Polypropylene/Polyethylene, PVC, Viton, Silicone, and Neoprene. The Agency recommends that flexible tubing be composed of Teflon or be Teflon-lined. According to Barcelona et al. (1988), polyethylene tubing may cause gross errors when determining concentrations of trace organics. PVC tubing should **not** be used because it is known to leach plasticizers into samples (Barcelona et al., 1985).
- **Device design and technique of use** - The device must deliver samples to the surface with minimal atmospheric exposure, should not apply negative pressures or a vacuum on the sample, and should limit agitation, both in the well and in the transfer process. Furthermore, the tool should not introduce air or non-inert gas into samples as part of its lift mechanism.

- **Flow rate control and capacity** - When pumps are used, low flow rates are desirable to limit agitation and turbulent flow, especially for VOCs (Barcelona et al., 1985, U.S. EPA, 1986a). The ability to maintain a steady low flow varies significantly. Flow control that involves "valving" should be avoided, since it can cause pressure changes and subsequent sample alteration. Instead, a mechanism that directly controls the rate (i.e., a rheostat to vary the power supplied to an electric submersible pump) should be utilized (Herzog et al., 1991).
- **Operation and Maintenance** - The device should be easy to operate, clean, and maintain. If personnel are not properly trained, the margin of potential error is greater. The device should allow for in-field maintenance. Mechanically simple equipment usually can be easily repaired and has inexpensive, replaceable parts. The device should be easy to decontaminate. Cleaning can be best achieved if it is necessary for only a minimal surface area and assembly and disassembly is easy. Cleaning can be avoided altogether if equipment dedication, where each well is assigned specific equipment or has a device permanently installed, is practiced.
- **Device reliability, durability, and portability** - The device should be reliable for extended periods and be able to withstand a variety of chemical environments. Dedicated equipment may need to withstand extended contact with ground water and any existing contamination. Equipment that is transported into locations where access is limited should be sufficiently portable. Excess weight and volume of battery packs, generators, air compressors, tubing, etc. can limit portability.
- **Capital, operation, and maintenance costs** - These should be considered, however, they should not be overriding factors. Obtaining a sample that is representative of site conditions should be of more importance than cost, particularly when the costs of well installation, chemical analysis, and possible litigation in the event of discrepant analytical results are considered. These costs often far outweigh equipment purchase costs (Nielsen and Yeates, 1985).

## Site/Project Characteristics

Characteristics of sites/projects that should be considered are as follows:

- **Monitoring Well Diameter** - Not all sampling equipment can be emplaced adequately into all well diameters. The device must be compatible.
- **Well Obstructions or Constrictions** - These could hinder the installation of sampling equipment. For example, casing joints may not be flush and could prevent insertion. Also, a well that is not plumb can restrict access.
- **Depth to the Sampling Interval** - Deeper zones require greater lift capacity and generally increase sampling times, which may limit the desirability of labor-intensive devices. Options generally become limited as depth increases.
- **Parameters of Interest** - The suitability of various devices may depend on the parameters of greatest concern. Some devices perform better for inorganics, while some are more suitable for VOCs.

## TYPES OF EQUIPMENT

The following is a discussion of sampling equipment currently available. Table 10.3 summarizes the recommended devices. Devices not mentioned may be acceptable if they meet the appropriate criteria and agency review. Site-specific conditions and objectives can allow for variations from the recommendations. For additional information, see ASTM D4448-85 (1992), Barcelona et al. (1985), Nielsen and Yeates (1985), Electric Power Research Institute (EPRI, 1985, 1987), Gillham et al. (1983), Herzog et al. (1991), Parker (1994), Pohlman and Hess (1988), and U.S. EPA (1992).

### Bailers

Bailers are the simplest and most portable of all sampling devices. A bailer is a rigid tube that fills with water when lowered into a well. When it is retracted, it is sealed on one or both ends by check valves. A single check valve bailer (open bailer) has a valve at its bottom that seals the sample chamber when the bailer is withdrawn. A dual check valve bailer (point source bailer) also has been designed to sample discrete zones in a water column. Water flows through valves at both ends as the bailer is lowered. When the desired level is reached, the bailer is pulled back, both valves close and water from the interval is retained. Without careful procedures, however, sampling discrete depths may be difficult.

A bottom-draining bailer is preferred. This allows for lessened sample disturbance during transfer to the container. Transfer by pouring from the top of a bailer is discouraged due to the potential for the agitation and aeration.

Bailers are readily available in a variety of diameters and the desirable compositions of Teflon, stainless steel, and PVC. The diameter should be 75% (or less) of the inside diameter of the well casing to allow for adequate clearance. Bailers composed of flexible materials allow for easy insertion into non-plumb wells. The cable used to raise and lower the bailer should be a non-reactive substance (e.g., stainless steel, teflon-coated wire/rope, polypropylene).

If dedication is not practiced, the simple design of bailers allows for relative ease of decontamination; however, it is recommended that new cable be employed for each well to reduce the potential for cross-contamination.

While bailers can recover samples from virtually unlimited depths, they are very time- and labor-intensive and the practicality of bailers decreases as well depth and diameter increase. Another potential disadvantage is that check valves are known to malfunction when water is high in suspended solids. Furthermore, both laboratory and field studies have demonstrated that levels of VOCs in samples obtained with bailers are statistically lower than in samples obtained with other devices (Imbrigiotta et al. 1988; Tai et al. 1991). In addition, it has been demonstrated that bailing can cause increased turbidity (Puls and Powell, 1992; Puls et al., 1992; Backhus et al., 1993). However, a literature survey by Parker (1994) found that bailers can recover representative samples under some circumstances and that loss of volatile and oxidizable analytes can be reduced by careful bottom-emptying. Finally, the continual entrance and exit to and from the water column can prolong well development or cause overdevelopment.

## **Bladder Pumps**

Bladder pumps are technically simple devices. Water enters a flexible bladder from the bottom and is squeezed up to the surface through a discharge line by gas pressure applied to the outside of the bladder. An air compressor and regulator turn the pressure on and off, which allows new water to enter the bladder and the cycle is repeated. The separate bladder chamber does not allow the sample to come in contact with the compressed air. Check valves at the top and bottom prevent backwash from the sample tube and bladder. Flow can be readily controlled and low rates of 100 ml/min are easily obtainable. Teflon bladders and Teflon/stainless steel outer shells are recommended and readily available.

Bladder pumps have been used to depths greater than 200 feet and are available in sizes that fit into 2 inch wells (Herzog et al., 1991). The need for a power source and compressed air limits mobility, especially for use in more remote areas. Potential problems are that sediment can damage the inner bladder and that high suspended solids can cause failure in check valves for some models (Herzog et al., 1991). Strainers or screens are available that attach below the bladder to filter material.

Bladder pumps are generally recognized as the best overall sampling device for both inorganic and organic constituents (U.S. EPA, 1992). Muska et al. (1986) found that reproduce ability of analytical data for the bladder pump was very good. Kasper and Serkowski (1988) found that the composition, sampling rate, and reliability of the bladder pump outperformed both the gas and mechanically driven piston pumps. Tai et al. (1991) found that a bladder pump yielded good recoveries of VOCs compared to a control sample. Pohlmann and Hess (1988) determined that bladder pumps are suitable for collecting samples for almost any constituent.

## **Electrical Submersible Pumps**

A variety of electrical submersible pumps are currently available, but many were not designed for collection of samples to be analyzed for trace levels of contaminants. A submerged, motorized pump drives impellers that deliver water to the ground surface by centrifugal force. Turbulent flow and agitation of the water within the pump potentially can enhance degassing and volatilization of the sample in proportion with pumping rate, although impeller design and modifications are being made to reduce this. Tai et al. (1991) indicated that the submersible pump they tested (helical rotor) may be acceptable for sampling for VOCs.

Submersible pumps offer several distinctive characteristics that make them useful. Pumping depths of 150 feet or greater can be maintained by many submersible pumps (Herzog et al., 1991).

Submersible pumps are composed of a number of intricate parts that make cleaning and maintenance difficult. Other disadvantages include difficulty in maintaining low flow (for many models), the relatively high cost, and the need for outside repair.

Recent advances have miniaturized submersible pumps to fit into 2-inch wells. The adaptation of Teflon/stainless steel components has also made them more compatible for ground water sampling. In addition, low flow, 2-inch pumps composed of inert materials have recently been developed. If

used for ground water sampling, models with inert components and low flow capabilities should be employed.

### **Gas-Driven Piston Pumps**

Although not commonly used, the gas-driven piston pump is an acceptable device as long as parts contacting samples are inert in composition. This device utilizes gas pressure to drive a piston between two chambers, one for gas and one for water. Gas is injected through one of two tubes to lower the piston in the gas chamber, allowing water to fill the upper water chamber. Pressure is then applied to a separate tube that pushes the piston upward and drives the sample to the ground surface. Water and gas remain totally separated from each other. These pumps can operate at great depths and collect large samples. Disadvantages are that valves and pistons are known to be damaged by fine-grained sediments and mobility is limited by the need for a gas supply. Additionally, the valving mechanism may cause a series of pressure drops that could cause sample degassing and pH changes (U.S. EPA, 1992).

### **Syringe Samplers**

Syringe samplers may be used for low volume sampling for inorganics and non-volatile organics. These samplers can operate at great depths to provide discrete samples from specific zones. A sample container is pressured or evacuated and lowered into a well. A sample is collected by opening the container or releasing the pressure, which draws the water in. The sample does not come into contact with any atmospheric gases and is subject to very slight negative pressure, thus neither aeration nor degassing should occur (Herzog et al., 1991). The syringe sampler is withdrawn and transferred to a collection bottle, or it can be utilized as the sample container.

Syringe devices cannot be used for purging large volumes and are ineffective for collecting large samples. These devices are relatively new and may not be readily available. In addition, ground water containing high concentrations of suspended solids may leak around the syringe device (U.S. EPA, 1992). Researchers have concluded that these samplers are inferior in comparison to other devices when sampling for VOCs (Imbrigiotta et al., 1988).

### **Suction Lift Pumps (Peristaltic/Centrifugal)**

Suction lift pumps deliver samples by applying a vacuum at the surface. The negative pressure is applied by a portable pump attached to a tube lowered into the well. Suction pumps are limited by practical suction limits, which restricts their use to wells with water levels less than 25 feet below ground. Centrifugal and peristaltic are the two major types. A vacuum flask is often employed to avoid contact of the sample with the moving parts if the centrifugal pump is used. The centrifugal also requires priming before sampling can begin. The peristaltic pump is self-priming and utilizes a squeeze action on the tubing to create a vacuum. The sample does not come in contact with the moving parts; therefore, only the tubing needs to be decontaminated between wells. Of the two, the peristaltic offers many advantages over the centrifugal. Centrifugal pumps typically cause greater agitation.

Suction lift pumps are very portable, widely available, and relatively inexpensive. Delivery rates are controlled easily, providing adequate rates for sampling. The device can be used in wells of any diameter and plumbness. The major drawback is that the application of strong negative pressure promotes degassing and loss of VOCs; therefore, these devices are not recommended for collecting samples to be analyzed for volatile or semi-volatile compounds and dissolved gases. The National Council of Industry for Air and Stream Improvement (NCASI, 1984) found a 10 to 30 percent loss in VOC concentrations from peristaltic/vacuum flask systems compared to results for bailers, bladder pumps, or submersible pumps. Imbrigiotta et al. (1988) also attributed losses of VOCs due to the vacuum created by peristaltic pumps. Use of suction lift pumps for sampling ground water to be analyzed for inorganics is recommended (Pohlmann and Hess, 1988).

### **Other Devices**

The **gas drive sampler** involves application of positive gas pressure into a sample chamber to force the water up to the ground surface. Water enters through a valve from the bottom of the sampler into the sample chamber. When pressure is applied, the valve closes and water is forced through a line to the surface. When the pressure is reduced, the valve reopens, allowing water to enter the chamber, and the cycle is repeated.

Gas drive samplers are available with inert components and in a variety of diameters. They can provide continuous flow at acceptable rates for sampling. The major drawback against their use is that they allow for gas contact with the sample, which can enhance the loss of dissolved gases, VOCs, and the potential for chemical alteration. Gas can also mix with the sample, causing further alteration. For these reasons, use is generally not recommended. Additionally, mobility of gas drive samplers is limited by the need to provide compressed gas. When sampling very deep wells, excessive gas pressures are needed, and the device must be designed to handle this added stress.

**Gas lift samplers** inject air or gas into the water column to "blow" water to the surface. The gas acts as a carrier fluid; however, the inserted gas (even if inert) causes degassing and volatilization. Additionally, aeration and turbulence can further alter the original water chemistry (Lee and Jones, 1983). Gas lift systems are unacceptable due to this alteration.

### **Use of Packers**

For sampling wells completed in deep, high yield formations, it may be desirable to use packers. Packers are inflatable rubber devices that can be inserted into the well casing and, upon inflation, isolate a particular interval. They cannot be used with bailers.

A packer is generally placed just above the well screen to isolate the screen from the overlying water. Directly below the packer, a pump is placed (preferably a bladder pump) with the discharge tubing running up through the center of the packer. The packer material should not cause significant sorbing or leaching. Pumping should not cause drawdown beneath the packer. This can cause the weight of the overlying stagnant water to collapse the packer onto the sampling pump.

One disadvantage of packers is that vertical movement of water outside the well is possible, depending on the pumping rate and formation properties. Also, the packer material may contribute organic contaminants to samples. It is important that all site-specific limitations be assessed before use, with proper justification provided by the regulated entity. For further discussion on the use of packers, see Oliveros et al. (1988).

**Table 10.3 Recommendations for sampling mechanisms<sup>1</sup>.**

| <b>MECHANISM</b>                             | <b>RECOMMENDATIONS</b>  | <b>POTENTIAL FOR CHEMICAL ALTERNATION</b> | <b>COMMENTS</b>   |
|--|---|---|---|
| Bailer                                       | Dual check valve bailers with bottom emptying device are recommended.<br><br>Can be used for sampling organics and inorganics.  | slight to moderate                        | Samples may show statistically lower analytical results. Other techniques <i>may</i> be more appropriate when low levels of organics exist. |
| Bladder pump                                 | Highly recommended.<br><br>Can be used for sampling organics and inorganics   | minimum to slight                         | Provides efficient well purging and representative samples over a range of conditions.  |
| Electric Submersible Pumps                   | Pumps must be constructed of inert components and capable of sampling at low flow rates.<br><br>Can be used to sample organics and inorganics.                            | slight to moderate                        | Good for purging and sampling deep, high yielding wells.  |
| Gas Driven Piston Pumps                      | Acceptable if sample compositions are met.<br><br>Can be used to sample organics and inorganics.  | slight to moderate                        | Difficult to decontaminate.   |
| Syringe Sampler                              | Recommended for low volume sampling of discrete zones.<br><br>Can be used for sampling inorganics and non-volatile organics, not recommended when sampling for volatiles. | minimum to slight                         | Cannot be used for purging.   |
| Suction Lift Pumps (Peristaltic/Centrifugal) | Not recommended for sampling for volatiles and semi-volatiles.  | moderate to high                          | Can cause significantly lower recoveries of purgeable organic compounds and gases.  |

<sup>1</sup>This table does not address gas drive and gas lift samplers because these devices are generally not recommended.

## SAMPLING PROCEDURES

Upon completion of the preliminary procedures, ground water samples can be collected by either traditional methods or low flow rate purging and sampling (“micropurging”). These approaches are discussed below, followed by a summary of general considerations that apply to both.

### TRADITIONAL METHODS

#### Equipment

Under the traditional approach, ground water samples are collected using pumps or bailers. Because of the potential loss of VOCs and increased agitation, it is recommended that use of bailers be avoided; however, eliminating bailer use entirely is not practical. Limitations imparted by site-specific technical and logistical factors can outweigh the quantitative differences in analytical results. For example, it may be impractical to install a pump in a low-yielding well. Freezing temperatures may also limit the use of pumps.

If bailers are used, it is important that procedures used be documented and applied consistently. Muska et al. (1986) and Tai et al. (1991) found that bailers provided lower precision in analytical data and attributed it mainly to sampling technique. A bailer should never be dropped into a well. It should be lowered slowly to prevent potential redevelopment and to minimize disturbance and aeration of the water column. It should be submerged only to a depth necessary for filling and should be removed in a manner that causes as little agitation as possible. A bailer and cable should never come in contact with the ground.

It is recommended that sampling equipment be dedicated to specific wells to eliminate the need for decontamination. This is most important when pumps are used. Their often intricate design can make them difficult to clean adequately. Bailers can be effectively decontaminated; however, they are inexpensive and dedication is usually cost-effective. Dedication of pumps also avoids the disturbance of the water column associated with device insertion. Kearl et al. (1992) found that equipment placement mobilizes colloids sorbed or trapped in low flow formations and that 3 to 6 hours is insufficient to allow colloidal density velocity and direction to stabilize. The authors felt that at least 24 hours should be allowed for normal conditions to return.

#### Purging

Under the traditional approach, sample collection is preceded by purging of a specified amount of water, usually three to five well volumes. As a check on efficiency in wells where three or more volumes can be removed, field parameters such as temperature, specific conductance, pH, and dissolved oxygen should be monitored for stability to determine if additional purging may be necessary. More may be necessary if variation (±10%) is documented. Wells with yields too low to produce three to five volumes should be purged to dryness. One well volume can be calculated as follows:  $V = H \times F$

Where:  $V$  = one well volume.  
 $H$  = difference between depth of well and depth to water (ft).  
 $F$  = factor for volume of 1-foot section of casing (gallons).

Table 10.4 provides F for various casing diameters. Multiplying the computed volume (V) times the number of desired volumes to be purged will give the volume of water in gallons to be evacuated. Wells with yields too low to produce three to five volumes before going dry should be purged to dryness.

**Table 10.4 Volume of water in one-foot section of well casing.**

| Diameter<br>(Inches) | F <sup>1</sup><br>(Gallons) |
|----------------------|-----------------------------|
| 1.5                  | 0.09                        |
| 2                    | 0.16                        |
| 3                    | 0.37                        |
| 4                    | 0.65                        |
| 6                    | 1.47                        |

<sup>1</sup> F is the volume (in gallons) in a 1-foot section of the well and is computed using:

$$F = 3.14 \left(\frac{D}{2}\right)^2 \times 7.48 \frac{\text{gal}}{\text{ft}^3}$$

Where: D=the inside diameter of the well casing (ft).

Purging rates should be at or below rates used for development and those observed for well recovery. Excessive rates may result in the introduction of ground water from zones above or below the well screen, which could dilute or increase contaminant concentration of samples. Overpurging also may cause formation water to cascade down the screen, enhance the loss of volatile constituents, and introduce oxygen into the subsurface, which may alter water geochemistry and affect chemical analysis. As indicated by Puls and Powell (1992), excessive rates may also lead to increased sample turbidity and the exposure of fresh surfaces capable of adsorbing dissolved metals. If bailers are used for purging, entrance and exit to and from the water column should be as slow as possible. Water entrance velocities into bailers can correspond to unacceptably high purging rates (Puls and Powell, 1992).

## Sampling

Higher yield wells that produce water at a rate sufficient to allow for purging of the minimum three to five well volumes should be sampled immediately following purging and field parameter measurement. This minimizes the time for physical and chemical alteration of the water in the well casing.

Ideally, samples should be collected from wells that are purged to dryness as soon as sufficient water is available. Extended recovery times after purging (hours) allow the ground water to equilibrate with atmospheric conditions. It is recommended that samples be collected as soon as

sufficient water is available, but flexible alternatives may be acceptable. Herzog et al. (1988) concluded that the common practice of next day sampling for low yield, slow recovery wells is adequate. The intervening time should be consistent from event to event. In addition, it is important to evaluate all data from slowly recovering wells based on the possibility that it may be unrepresentative of actual conditions.

Where dedicated equipment is not used, sampling should progress from wells least likely to be contaminated to those most likely to be contaminated to minimize the potential for cross-contamination.

## **MICROPURGE SAMPLING**

Recent studies (Kearl et al., 1994; FERMCO, 1993) have indicated that low rate/low volume purging and low rate sampling at the screened interval using dedicated bladder or submersible pumps is a viable alternative to traditional methods. If this approach is used, it is recommended that the purge rate not exceed 100 ml/min unless it is adequately demonstrated that higher rates will not disturb the stagnant water above the well screen (i.e., will not result in water level drawdown). The amount of water purged can be either two pump and tubing volumes as recommended by Kearl et al. (1994) or a volume established through in-line monitoring and stabilization of water quality indicators as recommended by Barcelona et al. (1994). Barcelona et al. (1994) found that dissolved oxygen and specific conductance were among the most useful indicators, and that values stabilized consistently after pumping less than one half a bore volume at a low, fixed rate. Sample collection should occur immediately following purging and field parameter measurement.

Micropurge sampling offers several advantages. It lessens the volume of water to be purged and disposed, increases the life and integrity of the filter pack, and minimizes disturbance to the well (i.e., water turbidity). Samples may not need to be filtered, which may allow for the quantification of the total mobile dissolved phase and the contaminants sorbed to mobile particles.

## **GENERAL CONSIDERATIONS**

### **Disposal of Purged Water**

Though it is not the intent of this document to define/determine Ohio EPA's policy on disposal of purged water, the following guidance is provided. In general, purged water should be containerized until the ground water samples are analyzed. If the samples are free from contaminants (i.e., constituent concentrations are not above ambient/natural levels), then it may be acceptable to discharge the purged water onto the ground within the limits of the site/facility.<sup>2</sup> Purged ground water that exhibits constituent concentrations above ambient/natural quality needs to be managed as a wastewater or hazardous waste. If the water has been contaminated by a listed hazardous waste constituent or exhibits a characteristic of hazardous waste as specified in 3745-51 of the Ohio Administrative Code, it will need to be managed as a hazardous waste.

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<sup>2</sup>Under detection monitoring, it may be possible to discharge the purged water without containerizing if historical ground water records indicate that ground water quality beneath the site is similar to the ambient quality. The Division with authority over the site/facility should be contacted for approval of this disposal method.

## Field Measurements of Ground Water

In addition to supplying information on general ground water quality and the adequacy of purging, field measurements can be valuable as an indicator of contamination. Changes in **pH** from background may indicate that contamination has occurred. Slight changes also may influence the mobility of many inorganic contaminants. **Specific conductance** measures the ability of water to conduct an electric current. Since current depends on the amount of "charged" ionic species, specific conductance can approximate of the amount of ions present. High ionic concentrations can be an indicator of contamination when compared to background. Additionally, it may be useful to measure the susceptibility of metal species to be oxidized from their natural state. The ability of an environment to cause oxidation/reduction is measured by its redox potential, designated as **Eh**. Due to the unstable nature of these parameters, laboratory determinations are of limited value.

Field measurements performed to fulfill regulatory requirements should be obtained after purging and before samples are collected for laboratory analysis. Portable field instruments should be used. Down-hole probes have been developed that can measure in a well to increase data representativeness. All probes should be appropriately decontaminated before insertion to prevent contamination of the well water. Flow-through cells can be used when sampling with pumps.

Calibration of instruments should occur in the field, as close to the time of use as possible and, at least, be at the frequency suggested by the manufacturer. All calibration and recalibration checks should be recorded.

## Sample Acquisition and Transfer

Transfer to a container or filtration device should be conducted to minimize agitation and aeration. Samples should be transferred directly to the final container for laboratory submittal and not collected in a larger container with subsequent transfer to smaller containers. (Exceptions for filtration are allowable.) When sampling for VOCs, collection, handling, and containerization **should not** take place near a running motor or any type of exhaust system.

Samples to be analyzed for VOCs should be placed in 40 ml glass vials until a meniscus is formed. The vials should then be topped with a fluorocarbon-lined cap. It is very important that no air bubbles or headspace remain in order to prevent the loss of volatiles. Air bubbles can be checked for by inverting the vial and tapping. If any bubbles are present, the sample should be discarded and retaken. The container should not be "topped-off" to fill the additional head space (U.S. EPA, 1992).

If a pump is used to collect samples, the flow rate should not exceed 100 ml/min to avoid agitation and reduce the loss of volatiles (Barcelona et al. 1985, U.S. EPA, 1992). Such a low rate helps ensure that immobile particulates are kept out of samples.

Samples should be collected and containerized in the following order of volatilization sensitivity (U.S. EPA, 1986a):

- Volatile organic compounds (VOCs).
- Purgeable organic carbon.
- Purgeable organic halogens.
- Total organic halogens (TOX).
- Total organic carbon (TOC).
- Extractable organics.
- Total metals.
- Dissolved metals.
- Phenols.
- Cyanide.
- Sulfate and chloride.
- Nitrate and ammonia.
- Radionuclides.

### **Sample Splitting**

Samples are often split into two separate portions and submitted to different laboratories to determine the accuracy of lab results. The proper procedure is to fill the two containers alternately until both are filled. However, if VOCs are to be determined, the first container should be completely filled, followed by filling of the split container.

## **SAMPLE PRESERVATION AND HANDLING**

Once a sample has been removed from a well, appropriate procedures must be utilized to store and preserve it. This is necessary to ensure that the sample maintains its in-situ state as much as possible in transit to the laboratory. Issues that must be considered include filtration, preservation, containers, labels, holding times, and shipping.

### **FILTRATION**

#### **Background**

Ground water samples collected from monitoring wells may contain noticeable amounts of sediment or particulate matter, often referred to as turbidity. This condition may be unavoidable when monitoring some geologic environments. The sediment may include particles that are too large to be mobile in the subsurface. The presence of these larger particles is due to the effects of well installation and the sampling.

Turbidity is an important field concern for samples to be analyzed for metals (e.g., cadmium, nickel, zinc) or metalloids (e.g., arsenic, selenium). As stated previously, a goal of monitoring is to collect representative samples. Laboratory analyses of samples should quantify species that are dissolved, occur as mobile precipitates, or are adsorbed onto mobile particles (colloids). If immobile particles to which metals are bound are allowed to remain in field-acidified samples, laboratory "total" analyses will overestimate the true concentration of mobile species because acidification dissolves precipitates or causes adsorbed metals to desorb. Other potential problems involved with collecting "total" data are as follows:

- Well performance and amount of sample turbidity may vary temporally. Additionally, turbidity may vary with the type of sampling device used and the person conducting the sampling. Consequently, comparisons of ground water quality data over time may not reflect actual trends.
- The amount of sediment entering a well may be variable across a site due to natural hydrogeologic conditions. As a result, comparisons of ground water quality data may not be representative of actual spatial variations. Subsequently, it may be difficult to perform upgradient vs. downgradient comparisons to distinguish contamination.

Because of these problems, particulate matter is often removed by filtration prior to containerization and acidification; however, the question of whether to field filter remains controversial. Filtration has the potential to remove particles that may be mobile in certain hydrogeologic environments. As described by McCarthy and Zachara (1989) and Puls et al. (1990), colloidal material (particles less than 10 micron) may be transported large distances. Furthermore, the potential for filtration problems, including filter clogging, variable particles size retention, filter media leaching, and aeration, is well documented (Puls and Powell, 1992). Because of these difficulties, some investigators (Puls and Barcelona, 1989a & b; Kearl et al., 1992; Puls and Powell, 1992) have recommended against field-filtering. Their approach is buttressed by stringent adherence to well installation, construction, and development and sampling procedures that minimize turbidity. An important component of this approach is that samples must be collected at a very low rate using deciated pumps.

### **Ohio EPA Position**

Filtration decisions for samples being analyzed for metals or metalloids may be guided by applicable regulatory requirements. New federal regulations [40 CFR 258.53(b)] for ground water monitoring at municipal solid waste landfills specify that analyses for metals be performed on unfiltered samples. Accordingly, Ohio EPA was required by U.S. EPA to propose a policy (DDAGW 04-03-220) banning field filtration for municipal solid waste landfills. As of June 1, 1994, no samples should be filtered for this type of facility.

Project requirements also can dictate the approach to filtration. For example, unfiltered samples may be appropriate to estimate exposure in a risk assessment when the unfiltered water is of potable quality (U.S. EPA, 1989). Samples filtered with a medium with a small pore size (e.g., 0.1 micron for dissolved concentrations) may be appropriate for geochemical modeling (Puls and Powell, 1992).

For sites and facilities that are not municipal solid waste landfills and when project requirements do not pre-dispose an approach, filtration decisions should be made on a case-by-case basis. Filtration should be avoided if possible. It should not be necessary when monitoring formations that are likely to exhibit a high degree of particle mobility. For other types of formations, the best way to avoid filtration is to use well installation and sampling procedures that minimize turbidity. However, significant turbidity is unavoidable in some situations, and filtration is necessary to remove immobile particulates. For example, reducing turbidity may be difficult when a clay-rich glacial deposit is monitored. The particulates included in samples may be presumed to be immobile in

the subsurface, as clay and natural organic matter can attract contaminants and physically retard particle movement.

## **Recommended Procedures**

### ***Deciding When to Filter***

It is recommended that entities work closely with the Agency to define project and regulatory requirements. For instances where these requirements do not mandate any particular approach to filtration, Ohio EPA has developed a general framework (Figure 10.1) for making decisions. Once it is documented that monitoring well installation, design, and development practices were adequate, ground water samples should be collected with the chosen device in a manner that minimizes agitation. Water turbidity should then be determined using a nephelometer. The Agency believes that it is practical to establish a value (5 nephelometric turbidity units (NTUs)) to serve as a "cut-off" for determining when filtration is necessary. Water below 5 NTU should not be filtered. This is based on the assumption that any immobile component of turbidity present will impart an insignificant amount of species to a sample analysis. This approach is supported by the work of Puls and Powell (1992), who found that turbidity levels less than 5 NTUs generally can be achieved, even for fine-grained glacial tills, if low flow purging and sampling techniques are used. These methods consistently produced filtered and unfiltered samples that showed no significant differences in concentrations.

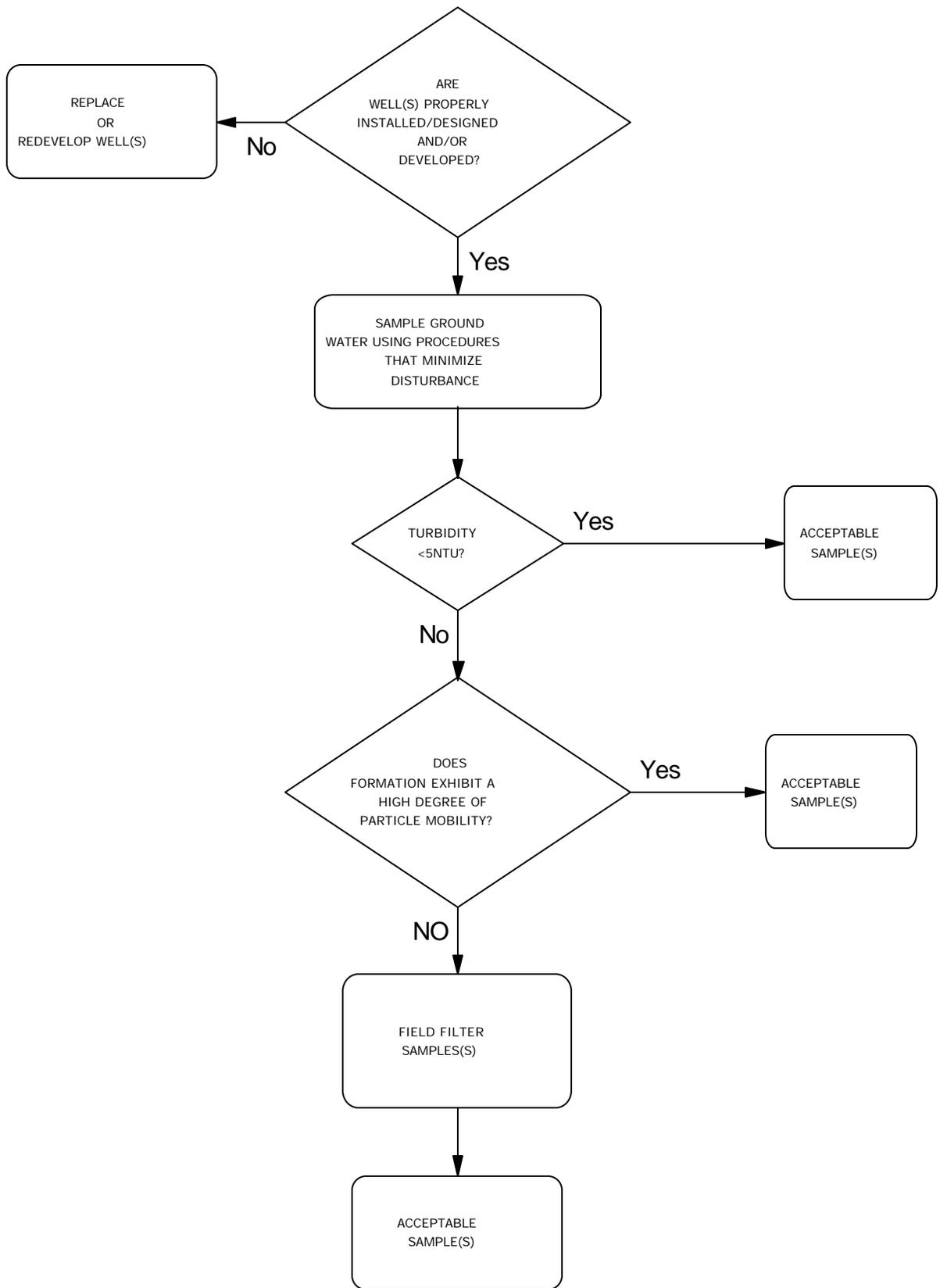
If the water exceeds 5 NTUs in turbidity, subsurface geology should be considered. Field filtration should not be necessary when sampling from karst; bedrock with open, interconnected fractures; clean, highly porous gravel-to-boulder sized deposits; and any other formation characterized by a high degree of particle mobility. If the water is not drawn from such an environment, then it is reasonable to assume that a portion of the turbidity may be attributable to immobile sediment. Field filtration can be used to remove the immobile fraction.

Regulated entities should exercise professional judgement when applying the approach described in Figure 10.1. Decisions may need to ensure data consistency and comparability over time and space. Deviations may be necessary if the practices would cause undesirable problems in data interpretation. For example, if a site is underlain by karst bedrock and the historical data base for metals has been based on analyses of filtered samples, filtration could be continued to ensure data consistency and comparability. If a single zone is monitored both by wells that are capable of providing samples that meet the turbidity criterion and wells that are not capable of meeting it, it may be prudent to filter all of the samples to ensure spatial consistency and valid statistical comparisons.

Some entities may wish to collect both filtered and unfiltered samples. The advantage of having both types of data is that a comparison can help determine the form in which a chemical exists (e.g., primarily adsorbed to particulate matter or primarily dissolved) (U.S.EPA, 1989)<sup>3</sup>. The comparative data may help justify which data set is more appropriate.

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<sup>3</sup>For example, if the concentration of a chemical is much greater in unfiltered samples compared to filtered samples, it is likely that the majority of the chemical is sorbed onto particulate matter and not dissolved in the ground water.



**Figure 10.1 Ground water field filtration decision tree.**

## ***Filter Media***

Filtration media should be inert and selected to minimize bias. Polycarbonate membrane filters are recommended. Puls and Barcelona (1989b) have stated that this material should be used due to its more uniform pore size, ease of cleaning, and minimization of adsorptive losses. The NCASI (1982) also found polycarbonate to be most appropriate. Cellulose membranes and glass microfiber filters have been used commonly.

Theoretically, the filter pore size should equal the size of the largest mobile particles in the formation, although differences in particles passing different sizes may be lessened significantly by clogging. Traditionally, 0.45 micron filters have been used; however, different pore sizes can be used in specific instances if justified. Puls and Powell (1992) suggested use of a coarse filter size such as 5 micron. If estimates of dissolved metal concentrations are desired, use of 0.1 micron filters is recommended (Puls and Powell, 1992).

Unless factory-cleaned filters are employed, the media should be "pre-conditioned" or "pre-wetted" in the field prior to use. A media-specific solvent (e.g., deionized or distilled water, nitric acid, or methanol) should be used to: 1) remove residues from manufacturing, packaging or handling that may leach into samples and 2) create a uniform wetting front to prevent channel flow and increase efficiency. The appropriate procedure depends on the design of the filter, the configuration of the equipment, and the parameters of concern. It is recommended that entities contact the filter media manufacturer prior to establishing the methods to be used.

## ***Filtration Procedure***

Generally, filtration techniques may be subdivided into two categories, in-line and "open system." In-line methods involve the use of positive pressure provided by a sampling pump to force the sample through an attached filter. The advantage of this technique is that samples remain isolated prior to atmospheric exposure. Stolzenburg and Nichols (1986) compared different filtering methods and found in-line techniques to provide the best results. Ohio EPA recommends that in-line techniques be used whenever possible. If bailers are used for sampling, in-line filters cannot be used unless a pressure or vacuum hand pump (i.e., peristaltic) is utilized to force the sample through.

"Open system" techniques require a transfer of the sample before filtration, thus allowing for additional exposure and agitation. Open system filtration should be conducted ***immediately in the field, at the wellhead, and prior to sample acidification and containerization***. As previously stated, upon sample removal, alteration occurs due to a change to more aerobic conditions. If filtration does not occur immediately, metals can begin to precipitate and, upon filtration, be removed, causing laboratories to underestimate actual concentrations. Agitation should be kept to a minimum, and the use of "double" filtration is not recommended. "Double" as used here refers to filtering a turbid sample twice using filters with progressively smaller pore sizes. This technique has been used for sediment-laden samples to speed up filtration; however, it can cause excessive agitation.

There are two main types of devices routinely used for "open system" filtration, vacuum and pressure. Vacuum "pulls" the sample through the filter, whereas, pressure "pushes" the sample

using compressed gas or a pump. These types offer varying degrees of portability and ease of decontamination. In addition, changes in pressure and aeration/oxygenation can alter sample representativeness. In fact, the vacuum system can cause extensive degassing, which can seriously alter metals concentrations (U.S. EPA, 1986a; EPRI, 1987; and Barcelona et al., 1985); therefore, vacuum is not recommended. The reason for the extensive alteration is that the application of a vacuum exacerbates the pressure decrease inherent with bringing a sample to the surface. For pressure filtration systems, only pure, inert gas should be used (i.e., nitrogen). If a pump is used as the driving mechanism, the peristaltic is commonly employed.

The filtration medium must be disposed between wells. If the ground water is highly turbid, periodic filter changes may be necessary (e.g., between samples). The filtration device, tubing, etc. must be appropriately decontaminated as sample-contacting equipment (see Decontamination Section).

## **SAMPLE PRESERVATION**

Preservation is an important step that must be conducted to stabilize the collected sample and prevent physical and chemical changes from occurring during transport to the laboratory and storage before analysis. Preservation is intended to maintain sample integrity by retarding biological action, preventing hydrolysis of chemical compounds and complexes, and reducing volatility of constituents (U.S. EPA, 1982). Appropriate techniques, found in Table 10.5, should be implemented immediately upon collection (and after filtration) to minimize changes that begin when a sample is exposed to the atmosphere.

### **pH and Temperature Control**

The most common preservation involves pH and temperature control. Acids are added to samples submitted for dissolved metals analysis because most metals exist in the dissolved state at low pH. If not preserved, most metals will oxidize and precipitate, which prevents representative analysis. Chemical preservatives can be pre-measured before entering the field and commonly can be obtained through the analytical laboratory. In addition, many laboratories place measured amounts in the requested sample bottles, so no field addition is needed. The most common method for temperature control is to place the collected samples in a portable cooler maintained at a temperature of 4° C with ice.

### **Containers**

Upon collection, samples should be contained properly to maintain integrity. Various fluorocarbons (i.e., Teflon), polyethylene plastic, or glass bottles with Teflon-lined lids are recommended for metals analysis. Samples to be analyzed for VOCs should be containerized in 40 ml glass vials. Clean containers can usually be obtained from the contracted laboratory. If cleaning is necessary, decontamination should be performed and appropriate blanks collected to verify cleanliness.

## Sample Labels

Samples should be properly identified with labels. The labels should be durable and remain legible when wet. The following information should be included:

- Sample identification number.
- Name of collector.
- Date and time of collection.
- Place of collection.
- Parameters requested for analysis.
- Chemical preservatives used.

**Table 10.5 Containers, preservation techniques, and holding times (Based on 40 CFR 136.3).**

| PARAMETER                                   | CONTAINER <sup>1</sup> | PRESERVATIVE <sup>2, 12</sup>                                    | MAXIMUM <sup>3</sup><br>HOLDING TIME |
|---|------------------------|--|--------------------------------------|
| <b>BACTERIAL TESTS</b>                      |                        |  |                                      |
| Coliform, fecal & total                     | P,G                    | Cool, 4°C; 0 .008% Na <sub>2</sub> O <sup>6</sup> <sub>3</sub>   | 6 Hours                              |
| Fecal Streptococci                          | P,G                    | Cool, 4°C; 0 .008% Na <sub>2</sub> O <sup>6</sup> <sub>3</sub>   | 6 Hours                              |
| <b>INORGANIC TESTS</b>                      |                        |  |                                      |
| Acidity                                     | P,G                    | Cool, 4°C  | 14 days                              |
| Alkalinity                                  | P,G                    | Cool, 4°C  | 14 days                              |
| Ammonia                                     | P,G                    | Cool, 4°C; H <sub>2</sub> SO <sub>4</sub> to pH<2                | 28 days                              |
| Biochemical oxygen demand                   | P,G                    | Cool, 4°C  | 48 hours                             |
| Biochemical oxygen demand, carbonaceous     | P,G                    | Cool 4°C   | 48 hours                             |
| Bromide                                     | P,G                    | None required  | 28 days                              |
| Chemical oxygen demand                      | P,G                    | Cool, 4°C; H <sub>2</sub> SO <sub>4</sub> to pH<2                | 28 days                              |
| Chloride                                    | PG,                    | None required  | 28 days                              |
| Chlorine, total residual                    | P,G                    | None required  | Analyze immediately                  |
| Color                                       | P,G                    | Cool, 4°C  | 48 hours                             |
| Cyanide, total and amenable to chlorination | P,G                    | Cool 4°C; NaOH to pH>12<br>0.6g ascorbic acid <sup>6</sup>       | 14 days <sup>9</sup>                 |
| Fluoride                                    | P                      | None required  | 28 days                              |
| Hardness                                    | P.G                    | HNO <sub>3</sub> to pH<2; H <sub>2</sub> SO <sub>4</sub> to pH<2 | 6 months                             |
| Hydrogen ion (pH)                           | P,G                    | None required  | Analyze immediately                  |

**Table 10.5 (Continued): Containers, preservation techniques, and holding times.**

| PARAMETER                      | CONTAINER <sup>1</sup> | PRESERVATIVE <sup>2,12</sup>                                | MAXIMUM <sup>3</sup><br>HOLDING TIME |
|--------------------------------|------------------------|---|--------------------------------------|
| Kjeldahl and organic nitrogen  | P,G                    | Cool, 4°C; H <sub>2</sub> SO <sub>4</sub> to pH<2           | 28 days                              |
| <b>METALS<sup>4</sup></b>      |                        |   |                                      |
| Chromium VI                    | P,G                    | Cool ,4°C   | 24 hours                             |
| Mercury                        | P,G                    | HNO <sub>3</sub> to pH<2                                    | 28 days                              |
| Metals, except above           | P,G                    | HNO <sub>3</sub> to pH<2                                    | 6 months                             |
| Nitrate                        | P,G                    | Cool, 4°C   | 48 hours                             |
| Nitrate-nitrite                | P,G                    | Cool, 4°C; H <sub>2</sub> SO <sub>4</sub> to pH<2           | 28 days                              |
| Nitrite                        | P,G                    | Cool, 4°C   | 48 hours                             |
| Oil and grease                 | G                      | Cool, 4°C; H <sub>2</sub> SO <sub>4</sub> or HCl to pH<2    | 28 days                              |
| Organic carbon                 | P,G                    | Cool, 4°C; HCl or H <sub>2</sub> SO <sub>4</sub> to pH<2    | 28 days                              |
| Orthophosphate                 | P,G                    | Filter Immediately; cool, 4°C                               | 48 hours                             |
| Oxygen, dissolved- probe       | G (Bottle and Top)     | None required   | Analyze immediately                  |
| Oxygen, dissolved- Winkler     | G (Bottle and Top)     | Fix on site and store in dark                               | 8 hours                              |
| Phenols                        | G on ly                | Cool, 4°C; H <sub>2</sub> SO <sub>4</sub> to pH<2           | 28 days                              |
| Phosphorus (elemental)         | G                      | Cool, 4°C   | 48 hours                             |
| Phosphorus, total              | P,G                    | Cool, 4°C; H <sub>2</sub> SO <sub>4</sub> to pH<2           | 28 days                              |
| Residue, total                 | P,G                    | Cool, 4°C   | 7 days                               |
| Residue, filterable            | P,G                    | Cool, 4°C   | 7 days                               |
| Residue, non-filterable (T.S.) | P,G                    | Cool, 4°C   | 7 days                               |
| Residue, settleable            | P,G                    | Cool, 4°C   | 48 hours                             |
| Residue, volatile              | P,G                    | Cool, 4°C   | 7 days                               |
| Silica                         | P                      | Cool, 4°C   | 28 days                              |
| Specific conductance           | P,G                    | Cool, 4°C   | 28 days                              |
| Sulfate                        | P,G                    | Cool, 4°C   | 28 days                              |
| Sulfide                        | P,G                    | Cool, 4°C, add zinc acetate plus sodium hydroxide to pH > 9 | 7 days                               |

**Table 10.5 (Continued): Containers, preservation techniques, and holding times.**

| PARAMETER  | CONTAINER <sup>1</sup> | PRESERVATIVE <sup>2, 12</sup>  | MAXIMUM <sup>3</sup><br>HOLDING TIME                 |
|--|------------------------|--|--|
| Sulfite  | P,G                    | None required  | Analyze immediately                                  |
| Surfactants  | P,G                    | Cool, 4°C  | 48 hours   |
| Temperature  | P,G                    | None required  | Analyze immediately                                  |
| Turbidity  | P,G                    | Cool, 4°C  | 48 hours   |
| <b>ORGANIC TESTS<sup>5</sup></b>                     |                        |  |  |
| Purgeable halocarbons                                | G, Teflon-lined septum | Cool, 4°C; 0.008%<br>Na <sub>2</sub> S <sub>2</sub> O <sub>3</sub> <sup>6</sup>                                  | 14 days  |
| Purgeable aromatic hydrocarbons                      | G, Teflon-lined septum | Cool, 4°C; 0.008%<br>Na <sub>2</sub> S <sub>2</sub> O <sub>3</sub> <sup>6</sup> HCl to pH<2 <sup>10</sup>        | 14 days  |
| Acrolein and acrylonitrile                           | G, Teflon-lined septum | Cool, 4°C; 0.008%<br>Na <sub>2</sub> S <sub>2</sub> O <sub>3</sub> <sup>6</sup> ; adjust pH to 4-5 <sup>11</sup> | 14 days  |
| Phenols <sup>13</sup>                                | G, Teflon-lined cap    | Cool, 4°C; 0.008%<br>Na <sub>2</sub> S <sub>2</sub> O <sub>3</sub> <sup>6</sup>                                  | 7 days until extraction,<br>40 days after extraction |
| Benzidines <sup>13</sup>                             | G, Teflon-lined cap    | Cool, 4°C; 0.008%<br>Na <sub>2</sub> S <sub>2</sub> O <sub>3</sub> <sup>6</sup>                                  | 7 days until extraction <sup>15</sup>                |
| Phthalate esters <sup>13</sup>                       | G, Teflon-lined cap    | Cool, 4°C  | 7 days until extraction,<br>40 days after extraction |
| Nitrosamines <sup>7,13</sup>                         | G, Teflon-lined cap    | Cool, 4°C; store in dark;<br>0.008% Na <sub>2</sub> S <sub>2</sub> O <sub>3</sub> <sup>6</sup>                   | 7 days until extraction,<br>40 days after extraction |
| PCBs <sup>13</sup>                                   | G, Teflon-lined cap    | Cool, 4°C  | 7 days until extraction,<br>40 days after extraction |
| Nitroaromatics & isophorone <sup>13</sup>            | G, Teflon-lined cap    | Cool, 4°C; 0.008%<br>Na <sub>2</sub> S <sub>2</sub> O <sub>3</sub> <sup>6</sup> ; store in dark                  | 7 days until extraction,<br>40 days after extraction |
| Polynuclear aromatic hydrocarbons <sup>13</sup>      | G, Teflon-lined cap    | Cool, 4°C; store in dark;<br>0.008% Na <sub>2</sub> S <sub>2</sub> O <sub>3</sub> <sup>6</sup>                   | 7 days until extraction,<br>40 days after extraction |
| Haloethers <sup>13</sup>                             | G, Teflon-lined cap    | Cool, 4°C; 0.008%<br>Na <sub>2</sub> S <sub>2</sub> O <sub>3</sub> <sup>6</sup>                                  | 7 days until extraction,<br>40 days after extraction |
| Chlorinated hydrocarbons <sup>13</sup>               | G, Teflon-lined cap    | Cool, 4°C  | 7 days until extraction,<br>40 days after extraction |
| TCDD <sup>13</sup>                                   | G, Teflon-lined cap    | Cool, 4°C; 0.008%<br>Na <sub>2</sub> S <sub>2</sub> O <sub>3</sub> <sup>6</sup>                                  | 7 days until extraction,<br>40 days after extraction |
| <b>PESTICIDES<sup>13</sup></b>                       | G, Teflon-lined cap    | Cool, 4°C; pH 5-9 <sup>8</sup>   | 7 days until extraction,<br>40 days after extraction |
| <b>RADIOLOGICAL TESTS</b><br>Alpha, beta, and radium | P,G                    | HNO <sub>3</sub> to pH<2   | 6 months   |

**Table 10.5 (Continued): Containers, preservation techniques, and holding times.**

1. Polyethylene (P) or Glass (G)
2. Sample preservation should be performed immediately upon sample collection. For composite samples, each aliquot should be preserved at the time of collection.
3. Samples should be analyzed as soon as possible after collection. The times listed are the maximum times that samples may be held before analysis. Samples may be held for longer periods only if data is available and kept on file to show that the specific types of samples under study are stable for longer time. Some samples may not be stable for the maximum period on the table. The sample/laboratory is obligated to hold the sample for a shorter time if knowledge exists to show that this is necessary to maintain sample stability.
4. Samples may need to be filtered immediately on site before adding preservative for dissolved metals. See filtration section of this chapter.
5. Guidance applies to samples to be analyzed by GC or LC or GC/MS for specific compounds.
6. Should only be used in presence of residual chlorine. Use ascorbic acid only in the presence of oxidizing agents. Maximum holding time is 24 hours when sulfide is present. Optionally, all samples may be tested with lead acetate paper before pH adjustment in order to determine if sulfide is present. If sulfide is present, it can be removed by addition of cadmium nitrate powder until a negative spot test is obtained. The samples is filtered and then NaOH is added to pH 12.
7. For analysis of diphenylnitrosamine, added 0.08%  $\text{Na}_2\text{S}_2\text{O}_3$  <sup>6</sup> and adjust pH to 7-10 with NaOH within 24 hours of sampling.
8. The pH adjustment may be performed upon receipt at the laboratory and may be omitted if the samples are extracted within 72 hours of collection. For the analysis of aldrin, added 0.08%  $\text{Na}_2\text{S}_2\text{O}_3$ .
9. Maximum holding time is 24 hours when sulfide is present.
10. Sample receiving no pH adjustment must be analyzed within seven days of sampling.
11. The pH adjustment is not required if acrolein will not be measured. Samples for acrolein receiving no pH adjustment must be analyzed within 3 days of sampling.
12. When any sample is to be shipped by common carrier or sent through the United States mails, it must comply with the Department of Transportation Hazardous Materials Regulation (49 CFR Subchapter C). The person offering such material for transportation is responsible for ensuring such compliance.
13. When the extractable analytes of concern fall within a single chemical category, the specified preservative and maximum holding times should be observed for optimum safeguard of sample integrity. When the analytes of concern fall within two or more chemical categories, the sample may be preserved by cooling to 4°C, reducing residual chlorine with 0.008% sodium thiosulfate, storing in the dark, and adjusting the pH to 6-9; samples preserved in this manner may be held for seven days before extraction and for forty days after extraction. Exceptions to this optional preservation and holding time procedure are noted in footnote 6 (regarding the requirement for thiosulfate reduction of residual chlorine), and footnotes 14, 15 (regarding the analysis of benzidine).
14. If 1,2-diphenylhydrazine is likely to be present, adjust the pH of the sample to  $4.0 \pm 0.2$  to prevent rearrangement to benzidine.
15. Extracts may be stored up to 7 days before analysis if storage is conducted under an inert (oxidant-free) atmosphere.

## Holding Times

Not all samples will maintain complete stability, regardless of the preservation technique. Therefore, a limit on when analysis should take place has been set for most parameters (see Table 10.5). These "holding times" specify the maximum allowable time between sample collection and laboratory analysis. If one is exceeded, the sample must be discarded and a new sample obtained. Therefore, it is important that the time of sampling and transportation to the lab be documented to ensure that the limits are met.

## Shipping

When samples must be shipped to a laboratory, an appropriate container must be used to protect and preserve them. Chests with ice or manufactured blue ice packets are commonly used. A manifest containing pertinent information and a chain-of-custody form must be included. Evidence tape also should be placed around the shipping container (and around each container, if desired), to guard against disturbance or tampering. It is important that, if samples are hazardous or potentially hazardous, they meet all federal and state transportation laws. At the state level, contact the Ohio Department of Transportation (ODOT) and the Public Utilities Commission of Ohio (PUCO) for additional information.

## DECONTAMINATION PROCEDURES

If non-dedicated sampling equipment is used, it must be cleaned between wells to prevent cross-contamination. All equipment, including field instruments, pumps, bailers, etc. should be properly decontaminated with pre-determined, adequate procedures. The decontamination area should be upwind of activities that may contribute dust or other contaminants to the solutions used. It is recommended that the process occur on a layer of polyethylene sheeting.

Table 10.6 outlines sequences and procedures that should be used (modified from ASTM 5088-90-1992). Procedures are based on equipment contact with collected samples. Sample-contacting equipment includes non-dedicated bailers and pumps (i.e., devices used for purging and sampling), sample containers, tubing, downhole field parameter probes, water level probes, non-dedicated filtration equipment, etc. In most instances, a distilled water rinse should be sufficient for field parameter measurement probes that are not lowered into wells. Many items are inexpensive and disposable (i.e., gloves, rope, tubing) and decontamination of these may not be needed.

**Table 10.6 Decontamination procedure for ground water sampling equipment.**

- Wash with non-phosphate detergent and potable water.
- Rinse with potable water.
- If analyzing samples for metals, rinse with 10% hydrochloric or nitric acid (note: dilute HNO<sub>3</sub> may oxidize stainless steel).
- Rinse liberally with deionized/distilled water (ASTM Type II or equivalent).
- If analyzing for organics, rinse with solvent-pesticide grade isopropanol, acetone, methanol, or hexane, alone or if required, in some combination. This solvent rinse should not be an analyte of interest.
- Rinse liberally with deionized/distilled water (ASTM Type II or equivalent).
- Air-dry thoroughly before using.
- Wrap with inert material if equipment is not to be used promptly.

## DOCUMENTATION

### FIELD SAMPLING LOGBOOK

A field logbook should be kept for all sampling events. It should document the following for each well sampled:

- Identification of well.
- Well depth.
- Static water level depth and measurement technique.
- Presence of immiscible layers and detection method.
- Thickness of immiscible layers.
- Well yield - high or low.
- Purge volume and pumping rate.
- Time well purged.
- Measured field parameters.
- Collection method for immiscible layers and sample identification numbers.
- Sampling device used.
- Well sampling sequence.
- Sample appearance.
- Types of sample containers and sample identification numbers.
- Preservative(s) used.
- Parameters requested for analysis.
- Field analysis data and method(s).
- Sample distribution and transporter.
- Field observations on sampling event.
- Name of collector(s).
- Climatic conditions including air temperature.
- Internal temperature of field and shipping (refrigerated) containers.
- Problems encountered and any deviations made from the established sampling protocol.

### CHAIN-OF-CUSTODY RECORD

A chain-of-custody record must be established to provide the documentation necessary to trace sample possession from time of collection to final laboratory analysis. The record (Figure 10.2) should account for each sample and provide the following information: (U.S. EPA, 1992).

- Sample number.
- Signature of collector.
- Date and time of collection.
- Sample type (i.e., ground water).
- Identification of well.
- Number of containers.
- Parameters requested for analyses.
- Preservatives used.
- Signature of person(s) involved in the chain of possession.

- Inclusive dates for time of possession.
- Internal temperature of shipping container when samples were sealed.
- Internal temperature of shipping container upon opening at laboratory.

## **SAMPLE ANALYSIS REQUEST SHEET**

A request sheet also should accompany samples on delivery to the laboratory. It should identify the samples, their chemical preservatives, and the designated analytical parameters. Figure 10.3 is an example of a typical sheet. The form should include the following information:

- Sample type (e.g., ground water).
- Sample identification number.
- Name of person receiving the sample.
- Date and time of sample collection.
- Date of sample receipt.
- Analyses to be performed, and method requested.
- Name of sampler.
- Internal temperature of shipping container upon opening at the laboratory.

## **FIELD QUALITY ASSURANCE/QUALITY CONTROL (QA/QC)**

To assure adequate QA/QC in the field, the sampling plan must be followed consistently. To verify if procedures are contaminating ground water samples, a variety of samples and blanks can be collected. The following are typical checks:

- **Field Duplicates** - Field duplicates are samples collected simultaneously with the primary samples at a specific location. Ultimately, upon analysis, both should yield the same results within an acceptable range. Variations could indicate problems with the sampling procedures or problems with the analysis. If strict protocols are followed, variability as a result of the field procedures should be minimal. Duplicates should be collected at a frequency of one per ten samples.
- **Trip Blanks** - Trip blanks are generally prepared by the laboratory before entering the field. Containers are filled with analyte-free, distilled, deionized water and sealed. These blanks are taken to the field and handled along with the collected samples, thereby acting as a control sample to determine potential VOC contamination from the containers themselves or the atmosphere. At least one trip blank should accompany each sampling event. Trip blanks are never opened in the field.
- **Equipment/Field Blanks** - Whenever non-dedicated sampling equipment is used, equipment/field blanks should be collected. An equipment/field blank is obtained by passing analyte-free, distilled, deionized water through a cleaned sampling apparatus (pump, bailer, filtration gear, etc.) and collecting it in a clean container. This blank is used to assess the effectiveness of the decontamination procedures implemented between sampling locations. Ideally, equipment blanks should be collected after sampling the well(s) that historically show(s) highest levels of contamination. They should be collected at a frequency of one blank per 10 samples.





All duplicates and blanks should be subjected to the same analysis as the ground water samples. The results are used to determine if proper procedures were followed. Blank contamination can result from improper decontamination of sampling equipment, poor sampling and handling procedures, contaminated rinse water or preservatives, or the interaction between sample and container. The concentration levels of any contaminants found should **not** be used to correct the ground water data. Blank contamination should trigger a re-evaluation of procedures to determine the source of the problem..

## **GROUND WATER SAMPLE ANALYSIS**

### **SELECTION OF ANALYTICAL METHOD**

The selection of the method for ground water analysis is determined by the parameters of interest and the purpose of the investigation. Several methods may exist for the same parameter. The results obtained can vary; therefore, specific methods may be preferred or mandated depending on the regulatory program. The selection should be an approved EPA method (see U.S. EPA, 1988). The specific requirements for analysis should be communicated to the laboratory.

The most important analytical requirement generally is the detection limit. For example, claims that no contamination is present in ground water samples are correct only to the quantitative extent that the analysis is capable of detecting the contaminant (Vitale et al., 1991). This level is known as the method detection limit (MDL). The MDL is the minimum concentration of a substance that can be measured and reported with a 99% confidence that the analyte concentration is greater than zero. Useless data may result if the detection limits are not low enough for the purpose of the investigation. For example, the primary objective often is to determine the risk to human health and the environment. In this case, the MDLs should be at or below human health-based criteria and environmental-based criteria.

Due to matrix interference and irregularities in instruments, the MDL may not always be obtained. In addition, the actual detection limit will be higher for samples that require dilution or reduced size to avoid saturation of the detector. The actual limit attained during the analysis should be reported with the data.

### **LABORATORY QUALITY ASSURANCE/QUALITY CONTROL (QA/QC)**

To obtain reliable results, appropriate laboratory procedures and methods must be followed. An extensive laboratory QA/QC program ensures the production of scientifically sound, defensible, documentable, and verifiable results. Whether Ohio EPA review is required depends on the regulatory program involved. For example, submittal of a laboratory QA/QC plan is not required for sites undergoing RCRA closure (Ohio EPA, DHWM Program); however, the owner/operator must demonstrate that the laboratory has a plan that contains the elements listed by U.S. EPA (1986b). A laboratory QA/QC plan must be approved for sites remediated under the CERCLA process (Ohio EPA, DERR program).

It is not the intent of this document to discuss laboratory QA/QC procedures. Procedures, methods, and levels of quality control are discussed in various U.S. EPA publications (1979a, 1979b, and

1986b). Laboratory QA/QC may include, but may not be limited to, qualifications, performance, matrix effects (e.g., blanks and matrix spikes), documentation, and record reporting. In addition, for sites under the CERCLA process, Ohio EPA-DERR (1990) has established set guidelines and specifications for preparing quality assurance project plans.

All laboratory QC data should be submitted. This data may be valuable for explaining outliers and questionable results. However, the laboratory QC results should not be used to alter the sample analytical data. A report of analytical data is incomplete without some verification of laboratory QA/QC.

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**TECHNICAL GUIDANCE MANUAL FOR HYDROGEOLOGIC  
INVESTIGATIONS AND GROUND WATER MONITORING**

**CHAPTER 11  
SUPPLEMENTAL METHODS**

**February 1995**

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## **CHAPTER 11**

### **SUPPLEMENTARY METHODS**

The cost of hydrogeologic investigations and ground water monitoring can be high, especially when attempting to locate and track contaminant plumes. The wastes produced during drilling require proper containment and disposal, which can add to project expense. Additionally, the difficulty of assessing appropriate monitoring well placement, especially in settings for which little hydrogeologic data is available, can result in investigations that are not cost-effective.

Supplementary techniques such as geophysics, soil gas surveys, and in-situ ground water sampling (e.g., using a hydropunch) can assist in delineating the extent of a plume. Geophysics also can be used to assist in defining hydrogeologic conditions. However, these tools should not be used as the primary means for site characterization. Conventional methods such as soil borings and installation and sampling of monitoring wells always are necessary to confirm site hydrogeology and/or monitor ground water quality.

### **GEOPHYSICS**

Geophysics provides an efficient and cost-effective means of collecting geologic and hydrogeologic information. It also can be used to locate buried drums and determine the presence and extent of contaminant plumes. Types of geophysical surveys include surface and downhole (or borehole). Surface surveys are more commonly used for site investigations.

When selecting a geophysical method, the following should be completed: 1) define the objective of the investigation, 2) review site-specific geology, 3) determine if cultural features are present that may interfere with the instrument(s), 4) determine site access, 5) consult with a person with expertise in geophysical data reduction and interpretation, and 6) determine cost.

Specialized education and training in physics and geology is necessary to conduct effective surveys and interpret the results. At a minimum, an investigator should be a qualified ground water scientist (see Chapter 1) and have experience in conducting and interpreting geophysical surveys. Because Ohio does not have a registration program for geophysicists or ground water scientists, it is recommended that appropriate proof of qualification and experience of all personnel involved accompany any report submitted.

This section discusses broad categories of methods and instruments. It is not the intent to discuss all that are available, but to provide enough information to show how certain ones can be efficient and cost-effective. It is also not the intent to provide specific procedures or guidelines for interpreting results.

### **SURFACE GEOPHYSICAL METHODS**

Surface geophysical methods utilize indirect measurements of material properties to define geology, hydrogeology, and waste placement. When performed properly and utilized early in the site characterization process, the methods can provide valuable information for placing monitoring wells. Measurements are taken at or near the surface and are classified by the physical property being measured.

The methods discussed here include ground penetrating radar, electromagnetics, resistivity, seismic, metal detection, magnetometric and gravimetric. These methods and their applications are summarized in Tables 11.1, 11.2, and 11.3. The techniques can provide extensive spatial data; however, each has limitations and may not be applicable in every situation. Site-specific geology, access, and cultural features affect instrument response and determine the success of a particular method. It may be desirable to utilize a variety of methods in case one fails or if there is a need to fill in data gaps.

## **Ground Penetrating Radar**

The ground penetrating radar (GPR) method involves the projection of high frequency radio waves into the subsurface. When the waves encounter an interface between materials of differing dielectric properties, they are reflected back. Travel times of the waves provide a profile of shallow conditions. The method generally provides high vertical resolution for characterizing geology and locating buried waste materials. Additionally, GPR can be valuable for identifying drilling or excavation locations because data can be collected rapidly and interpreted in the field. This method is generally less applicable for the delineation of contaminant plumes.

Detected interfaces, along with resulting changes in conductivity and dielectric properties, generally are due to the presence of bedding planes, cementation, moisture, clay content, voids, fractures, intrusions, and human-made objects (Benson et al., 1982). Natural changes in soil/rock conditions and material often result in different electrical properties and, as a result, cause varying reflection responses that show up on the radar profile.

The depth of GPR penetration depends on soil/rock properties and the radar frequency. In general, 3 to 30 foot penetration with GPR is common, although depths exceeding 100 feet have been reported (Benson, 1991). Best penetration occurs in dry, sandy, or rocky areas, while poor penetration occurs in moist, clayey, or conductive soils. Moisture has the greatest influence on penetration: the higher the water content, the lower the radar velocity. Because depth of formations generally is calculated from velocity, varying moisture content can cause inaccurate determinations of interface depths.

Low, medium, and high frequency GPR devices have been developed (Benson et al., 1982). The low frequency (80 - 125 MHz) instruments penetrate the deepest but provide low resolution. Objects must be larger than three feet in size to be detected. High frequency (500 - 900 MHz) instruments provide high resolution, but offer very small penetration. Medium frequency (250 - 500 MHz) devices provide excellent resolution for most situations.

Unwanted noise can degrade radar data and should be considered before any GPR study is undertaken. Additionally, it must be accounted for during data interpretation. Types of noise include:

- System noise.
- Overhead reflections from power lines, trees, etc.
- Surface features such as ditches, metal, etc.
- Natural subsurface features or buried trash.
- External electromagnetic noise from radio transmitters.

**Table 11.1 Typical applications of surface geophysical methods (Benson et al, 1982).**

| APPLICATION   | RADAR | EM  | RES | SEISMIC | MD  | MAG   |
|---|-------|-----|-----|---------|-----|-------|
| <b>NATURAL CONDITIONS</b>   |       |     |     |         |     |       |
| Layer thickness and depth of soil and rock  | 1     | 2   | 1   | 1       | N/A | N/A** |
| Mapping lateral anomaly locations   | 1     | 1   | 1   | 1       | N/A | N/A** |
| Determining vertical anomaly depths   | 1     | 2   | 1   | 1       | N/A | N/A   |
| Very high resolution of lateral or vertical anomalous conditions                    | 1     | 1   | 2   | 2       | N/A | N/A   |
| Depth to water table  | 2     | 2   | 1   | 1       | N/A | N/A   |
| <b>SUB-SURFACE CONTAMINATION LEACHATES/PLUMES</b>                                   |       |     |     |         |     |       |
| Existence of contaminant (Reconnaissance Surveys)                                   | 2*    | 1   | 1   | N/A     | N/A | N/A   |
| Mapping contaminant boundaries  | 2*    | 1   | 1   | N/A     | N/A | N/A   |
| Determining vertical extent of contaminant  | 2*    | 2   | 1   | N/A     | N/A | N/A   |
| Quantify magnitude of contaminants  | N/A   | 1   | 1   | N/A     | N/A | N/A   |
| Determine flow direction  | 2*    | 1   | 1   | N/A     | N/A | N/A   |
| Flow rate using two measurements at different times                                 | N/A   | 1   | 1   | N/A     | N/A | N/A   |
| Detection of organics floating on water table                                       | 2*    | 2*  | 2*  | N/A     | N/A | N/A   |
| Detection & mapping of contaminants within unsaturated zone                         | 2     | 1   | 1   | N/A     | N/A | N/A   |
| <b>LOCATION AND BOUNDARIES OF BURIED WASTES</b>                                     |       |     |     |         |     |       |
| Bulk wastes   | 1     | 1   | 1   | 2       | N/A | N/A   |
| Non-metallic containers   | 1     | 1   | 1   | 2       | N/A | N/A   |
| Metallic containers   |       |     |     |         |     |       |
| - Ferrous   | 2     | 1   | N/A | N/A     | 1   | 1     |
| - Non-Ferrous   | 2     | 1   | N/A | N/A     | 1   | N/A   |
| Depth of burial   | 2     | 2   | 1   | 2       | 2*  | 2*    |
| <b>UTILITIES</b>  |       |     |     |         |     |       |
| Location of pipes, cables, tanks  | 1     | 1   | N/A | 2       | 1   | 1     |
| Identification of permeable pathways associated with loose fill in utility trenches | 1     | 1   | N/A | 2       | 1   | 1     |
| Abandoned well casings  | N/A   | N/A | N/A | N/A     | 1   | 1     |
| <b>SAFETY</b>   |       |     |     |         |     |       |
| Pre-drilling site clearance to avoid drums, breaching trenches, etc.                | 1     | 1   | 2   | N/A     | 1   | 1     |

GPR=ground penetrating radar, EM=electromagnetics, RES=resistivity, MD=metal detection, MAG=magnetometric

1 Denotes primary use

2 Denotes possible applications, secondary use; however, in some special cases this method may be the only effective approach due to circumstances.

N/A Not applicable

\* Limited application

\*\* Not applicable in the context used in this document.

**Table 11.2 Surface geophysical methods for locating and mapping of buried wastes and utilities (Benson, 1991).<sup>a</sup>**

| <b>METHOD</b>      | <b>BULK WASTES WITHOUT METALS</b>  | <b>BULK WASTES WITH METALS</b>   | <b>55 GALLON DRUMS</b>                                      | <b>PIPES AND TANKS</b>   |
|--------------------|--|--|---|--|
| GPR                | Very good if soil conditions are appropriate; sometimes effective to obtain shallow boundaries in poor soil conditions | Very good if soil conditions are appropriate; sometimes effective to obtain shallow boundaries in poor soil conditions | Good if soil conditions are appropriate (may provide depth) | Very good for metal and non-metal if soil conditions are appropriate (may provide depth) |
| EM                 | Excellent to depths less than 20 feet  | Excellent to depths less than 20 feet  | Very good (single drum to 6-8 feet)                         | Very good for metal tanks  |
| Resistivity        | Good (sounding may provide depth)  | Good (sounding may provide depth)  | -N/A-   | -N/A-  |
| Seismic Refraction | Fair (may provide depth)   | Fair (may provide depth)   | -N/A-   | -N/A-  |
| Micro Gravity      | Fair (may provide depth)   | Fair (may provide depth)   | -N/A-   | -N/A-  |
| Metal Detector     | -N/A-  | Very good (shallow)  | Very good (shallow)   | Very good (shallow)  |
| Magneto-meter      | -N/A-  | Very good (ferrous only; deeper than metal detector)   | Very good (ferrous only; deeper than metal detector)        | Very good (ferrous only; deeper than metal detector)                                     |

<sup>a</sup> Applications and comments should only be used as guidelines. In some applications, an alternate method may provide better results.

**Table 11.3 Surface geophysical methods for evaluation of natural hydrogeologic conditions (Benson, 1991).<sup>a</sup>**

| <b>METHOD</b>         | <b>GENERAL APPLICATION</b>                              | <b>DEPTH APPLICATION</b>   | <b>MAJOR LIMITATIONS</b>   |
|-----------------------|---|--|--|
| GPR                   | Profiling and mapping; highest resolution of any method | to 100 feet (typically less than 30 feet)  | Penetration limited by soil type and saturation conditions   |
| EM (Frequency Domain) | Profiling and mapping, very rapid measurements          | to 200 feet  | Affected by cultural features (metal fences, pipes, buildings, vehicles)   |
| EM (Time Domain)      | Soundings   | to a few thousand feet   | Does not provide measurements shallower than about 150 feet  |
| Resistivity           | Soundings or profiling and mapping                      | No limit (commonly used to a few hundred feet)   | Requires good ground contact and long electrode arrays. Integrates a large volume of subsurface. Affected by cultural features (metal fences, pipes, buildings, vehicles). |
| Seismic Refraction    | Profiling and mapping                                   | No limit (commonly used to a few hundred feet)   | Requires considerable energy for deeper surveys. Sensitive to ground vibrations.   |
| Seismic Reflection    | Profiling and mapping                                   | Can use to a few thousand feet; depths of 50 to 100 feet are common in hydrogeologic studies | Sensitive to ground vibrations. Loose soils near surface limits the method. Very slow, requires extensive data reduction.  |
| Micro Gravity         | Profiling and mapping                                   | No limit (commonly used to upper 100 feet)   | Very slow, requires extensive data reduction. Sensitive to ground vibrations   |
| Magnetics             | Profiling and mapping                                   | No limit (commonly used to a few hundred feet)   | Only applicable in certain rock environments. Limited by cultural ferrous metal features.  |

<sup>a</sup> Applications and comments should be used as guidelines. In some applications, alternative methods may provide better results.

The picture-like output of the radar device can provide for direct analysis in the field. However, field interpretation can be hindered by problems that can show up in the data (Benson, 1991). Multiple bands often occur due to refractions and scattering, which can obscure layers. Overhead reflections can appear if an unshielded antenna was used. Also, system noise can clutter the output record.

## Electromagnetics

The electromagnetic method (EM) measures the electrical conductivity of soil, rocks, and fluid that fills pores. An alternating current is passed through a transmitter coil, which generates a magnetic field around the coil. When the coil is held near the ground, the magnetic field induces an electric field in the ground. The electrical field will travel at different strengths depending upon the ground conductivity. The field strength is measured in a passive receiver coil (Fetter, 1994). Changes in the phase, amplitude, and orientation of the primary field can be measured either with a frequency- or a time-domain system (Benson, 1991). The frequency-domain system measures changes in magnitude of the currents induced. With the time-domain system, the transmitter is cycled on and off, and the changes in the induced currents are measured as a function of time. These measured changes are related to the electrical properties of the earth. The specific conductance of the pore fluid often dominates the measurement.

Methods commonly used to obtain data from the EM device include profiling and sounding. **EM profiling** involves the acquisition of data by measuring lateral variations in conductivity to a given depth. It is more common due to the ease of its use. It allows for rapid determination of contaminant plumes through plotting of data and observation of conductivity anomalies from natural background. Data can be obtained at pre-assigned stations or with instruments that can create continuous profiles along a line of traverse. Using frequency-domain instruments, profiling station measurements may be made to approximately 200 feet. Continuous profiling data can be obtained to approximately 50 feet. Continuous measurements significantly improve lateral resolution for mapping small hydrogeologic features (Benson, 1991).

**EM sounding** measures the variations in vertical conductivity from a fixed point station. Sounding can be used to define vertical changes in geology, map soil/rock interfaces, and determine the depth of the water table. Spatial characteristics can be approximated by combining sounding data from a number of stations. The instrument is placed at one location and measurements are made at increasing depths by changing coil orientation and/or spacing. Data can be acquired at depths ranging from 2.5 to 200 feet by using a variety of commonly available frequency-domain instruments. The vertical resolution of frequency-domain sounding is relatively poor because measurements are made at only a few depths. Time-domain transient systems are capable of providing detailed sounding data to depths of 150 to more than 1000 feet (Benson, 1991).

The EM method is useful in helping define the following:

- Hydrogeologic conditions.
- Location of burial trenches and pits.
- Location of plume boundaries.
- Flow direction in the saturated and unsaturated zones.
- Rate of plume movement.
- Location of utility pipes, cables, and trenches.

Inorganic contaminant plumes are mapped by noting increases (anomalies) in conductivity due to increases in free ions introduced by the contamination. This contribution of electrolytes/colloids to the ground water plume often increases conductivity values from one to three orders of magnitude over background. If non-polar, organic fluids are present (generally as free product), conductivity will decrease as soil moisture is displaced. As a result, organic free product plumes will map as anomalous decreases in conductivity. Organic plume delineation with EM is difficult and not commonly attempted.

Soil and rock minerals, when dry, are characterized by low conductivities. On rare occasions, magnetite, graphite, and pyrite may occur in sufficient concentrations to increase natural conductivity significantly. Generally, conductivity is affected more by water content, porosity/permeability of the material, extent of pore space saturation, concentration of dissolved electrolytes and colloids, and the temperature and phase state (i.e., liquid, ice) of the pore water. Typical conductivity ranges have been determined for various soil and rock materials (Figure 11.1). Only ranges can be provided because conductivity can vary drastically within material types.

Typical EM noise or interference includes:

- Power lines.
- Atmospheric conditions.
- Steel drums, fences, vehicles, and railroad tracks.
- Buried utilities/pipes.

## **Resistivity**

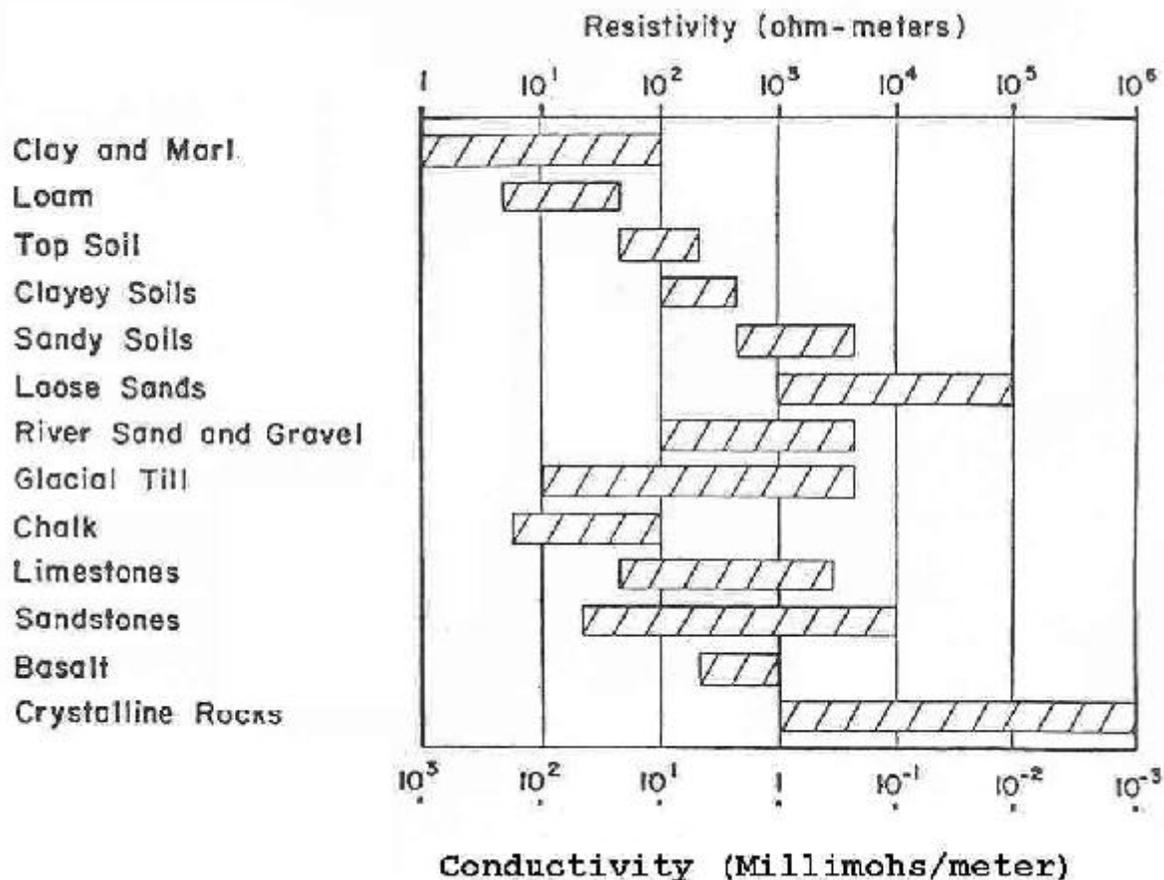
The resistivity method is opposite of the EM method and involves the measurement of the ability of soil, rock and ground water to resist the flow of an electrical current. Resistivity surveys are useful in providing supplemental information for:

- Location and direction and rate of movement of contaminant plumes.
- Location of burial sites (e.g., trenches, their depths and boundaries).
- Hydrogeologic conditions (e.g., depth to water or water-bearing zones, depth to bedrock, thickness of soil, etc).

The method involves the injection of electrical current through a pair of surface electrodes inserted into the ground. A second pair is used to measure the resulting potential field (voltage). Several electrode configurations are used. The three most common arrays are Wenner, Schlumberger, and the dipole-dipole. These arrays are described in Fetter (1994) and Sheriff (1989). Apparent resistivity is calculated based on the electrode separation, current applied, and measured voltage.

Figure 11.1 gives general ranges of resistivity in the natural environment. Soil and rock become less resistive (more conductive) as moisture/water content, porosity and permeability, dissolved solids, and colloid content increase. Clayey soils generally exhibit lower resistivity due to their high

moisture and clay mineral content. Gravel has a higher resistivity than silt or clay under similar moisture conditions, as the electrically charged surfaces of finer particles are better conductors (Fetter, 1994). Contaminant plumes that display high total dissolved solids (TDS) concentrations cause lower resistivity measurements.



**Figure 11.1 Range of electrical conductivities and resistivities in natural soil and rock** (Source: Benson et al., 1982.)

Various problems can hinder the collection of accurate resistivity data. Dry surface material (high resistivity) can make injection of current very difficult. Roads and parking lots composed of asphalt and concrete may prevent electrode insertion and, therefore, limit the lateral extent of the survey. Common problems include:

- Coupling between wires and reels.
- Poor electrical contact with the ground.
- Exceeding depth capabilities of instrument (power source and receiver sensitivity).

- Cultural noise, including stray currents, potential fields and electromagnetic currents as a result of power lines, man-induced ground currents, fences, railroad tracks, and buried metallic pipes.
- Heterogeneities in shallow conditions.

It is not uncommon for a variety of different geologic models to represent a single resistivity profile curve, and therefore, some preconception or data for subsurface geology is needed to verify the selected model. Resistivity surveys take more time than EM surveys, and space limitations also can hinder data collection. Success of the method is site-specific. In some cases, resistivity also outperforms EM and vice-versa. Like EM, profiling and sounding are the major methods for data acquisition.

**Resistivity sounding** is used to determine vertical changes in the geologic section. Data is collected at fixed stations as the distance between electrodes is successively increased. As a consequence, the apparent resistivity is determined as a function of the effective depth of penetration. Apparent resistivity is an attempt to account for spatial inhomogeneities and is a function of the electrode spacing. To interpret the data, the apparent resistivity values are plotted on log-log paper versus electrode spacing. The plots are compared to type curves or models to determine layer thicknesses, depths and true resistivities. These models are based on simple, uniformly layered ("layer cake") geologic conditions; therefore, they may oversimplify data interpretation for a more complex situation. **Resistivity profiling** involves moving an array of electrodes while keeping the array arrangement and spacing fixed (Sheriff, 1989). Lateral changes in resistivity are mapped, allowing for the delineation of contaminant plumes and of lateral changes in hydrogeologic conditions. For high resolution, stations should be spaced closely to increase accuracy. Electrode spacing can be varied to map lateral changes at varying depths, but this will slow the survey. Profiling can allow for rapid data interpretation by mapping apparent resistivity values and noting anomalous features relative to background. When mapping a plume, it is advantageous to conduct an initial sounding survey to determine plume depth and the appropriate electrode spacing, then continue with a profiling survey.

## **Seismic Methods**

Seismic methods are typically used to define natural geologic conditions, including top of bedrock; thickness, depth, composition, and physical properties of soil and rock; continuity of geologic strata; depth to water table, fracturing, faulting, and buried bedrock channels (Benson, 1991). Seismic methods have limited applications for determining buried wastes and cannot be used to locate contaminant plumes (see Tables 11.1- 11.3). Types of seismic methods include refraction and reflection.

### **Seismic Refraction**

Refraction surveys, the predominant seismic method in hydrogeologic studies, measure seismic wave velocities of materials. A source (e.g., sledge hammer, gun device, weight, or explosives) is used to create and emit waves into the subsurface. These waves travel at material-specific velocities, are refracted at various interfaces, and eventually are received by surface geophones

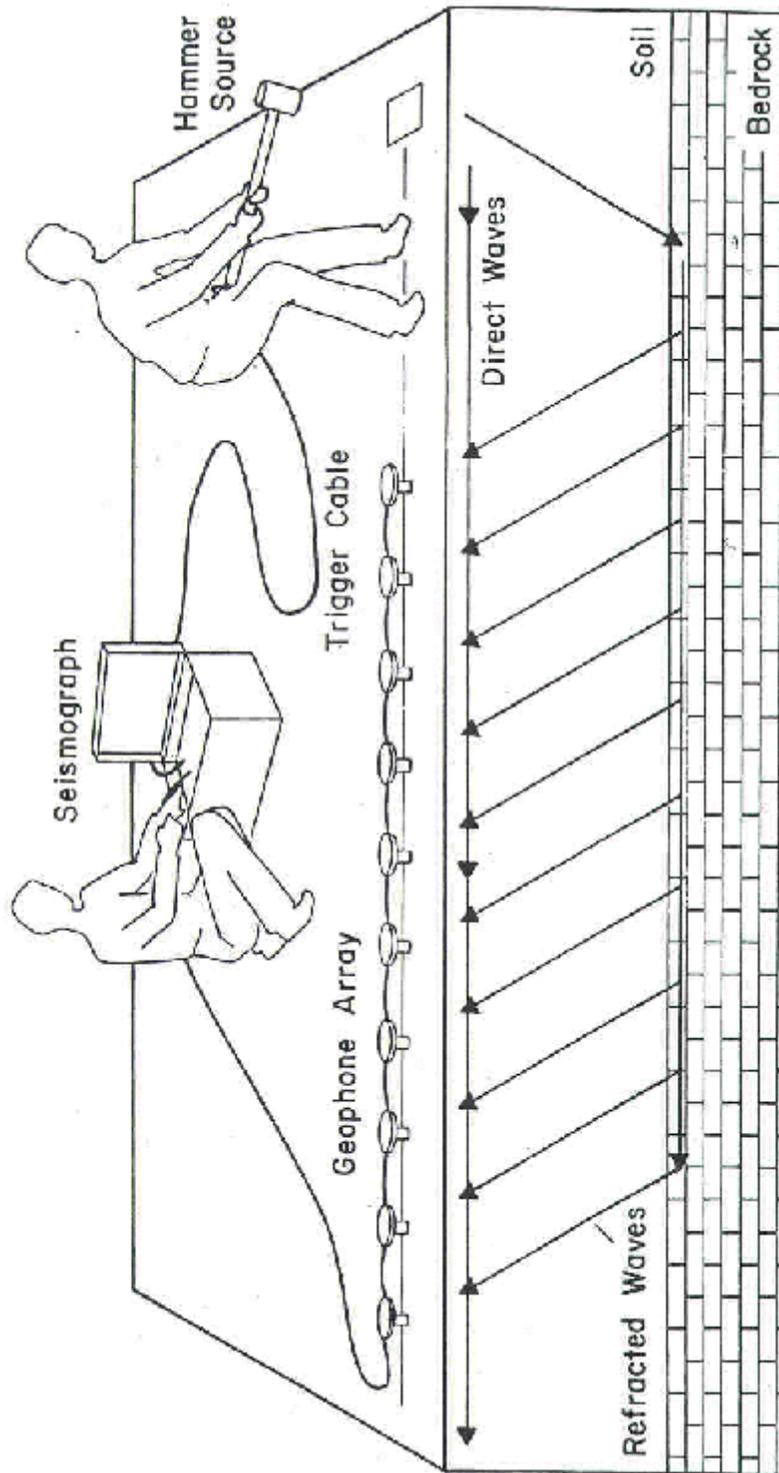
that convert them into an electrical signal that is displayed on a seismograph. Figure 11.2 shows a typical multi-channel refraction survey configuration.

A variety of elastic waves result from the source and show up on the seismograph output. Typically, the compressional (primary or P) wave is the only wave of concern. This wave travels fastest and is the first to arrive at the geophones, making its determination relatively easy. Physical properties determine the velocity at which the primary wave will travel through a particular geologic material or layer. For example, porosity, mineral composition, and water content affect material density and elasticity, which in turn affect velocity. Benson et al. (1982) provided common velocity ranges for various materials. Overlap between materials and their velocities prevent unique determination of material type based on velocity alone; however, comparisons with borehole and/or well log data can be used to make correlations to material type. Table 11.4 summarizes additional properties that affect relative velocities in geologic materials.

**Table 11.4 Properties that affect relative velocities in geologic material (based on Benson et al, 1982).**

| <i>HIGHER VELOCITY</i> | <i>LOWER VELOCITY</i> |
|------------------------|-----------------------|
| high density rock      | low density rock      |
| older rock             | younger rock          |
| igneous                | sedimentary           |
| solid rock             | cracked, fractured    |
| unweathered            | weathered             |
| consolidated           | unconsolidated        |
| saturated              | unsaturated           |
| sediments              | sediments             |
| wet soil               | dry soil              |

Once waves are introduced at the surface, the primary wave travels in the form of a direct wave and a refracted wave ( Figure 11.2). The closest geophones to the source measure the direct wave that travels at the velocity of the uppermost layer. If a more dense (higher velocity) layer exists below the upper layer, some of the waves will be bent or refracted as they enter the lower layer. One of the waves will be refracted perfectly parallel to the top of the lower layer. Refracted waves are continuously released back into the upper layer, which are then detected at the surface geophones (Figure 11.2). At a certain critical distance, the refracted wave traveling through the lower layer will arrive at a geophone before the direct wave that travels along the surface. Even though the refracted wave travels along a longer path, a majority of its transit occurs in the higher velocity lower layer. By measuring these first arrivals and their distances from the source, velocities, thicknesses, and depths of materials can be calculated.



**Figure 11.2** Field layout of a multi-channel seismograph showing the path of direct and refracted seismic waves in a two-layer soil/rock system (Source: Benson et al., 1982.)

In order to determine geologic conditions using refraction surveys, three fundamental assumptions must be met (Benson et al., 1982):

- Seismic velocities must increase with depth (generally, a valid assumption).
- Layers must display sufficient thickness to permit detection.
- Seismic velocities must differ enough to distinguish between individual layers.

Sufficient knowledge of site and regional geology is necessary to make adequate correlations between the data and actual conditions. In highly irregular, spatially variable, and heterogeneous geologic environments, data scatter and anomalies occur due to the variable seismic velocities within each "layer". For example, complicated interpretations can result when investigating poorly sorted glacial tills, perched water table conditions, bedrock formations with cementation differences, irregular bedrock surfaces, and highly dissolved limestone formations. Simple, uniform geology allows for easier interpretation and more accurate results.

Refraction surveys are often used to determine the depth of the water table, although the feasibility depends on site conditions. The water table can be readily identified in coarse-grained sand and gravel, where a distinct boundary between the saturated and unsaturated zones exists. In fine-grained sands, silts and clays, where natural capillary forces cause a very irregular and poorly defined saturated/unsaturated boundary, determination is difficult.

The depth of penetration is based on the length and spacing of the entire geophone line. Length in general should be 3 to 5 times the maximum depth of interest (Benson et al., 1982). Spacings of 5 to 50 feet are common for adequate resolution, but closer spacing may be necessary for higher resolution in shallow materials. Also, a greater energy source is needed as the desired depth of penetration increases. A sledge hammer can be utilized to reach depths of 30 to 50 feet (Benson et al., 1982). A drop weight or other mechanical impactors are sometimes used to reach depths from 150 to 350 feet. Special explosives may be necessary if greater depths are necessary.

Because refraction surveys measure ground vibrations, the method is very sensitive to background noise (moving vehicles, strong winds blowing through trees, field crew movement, etc.). Interference can be overcome by signal enhancement, which involves repeated hammer blows at the same station to build the true seismic signal above and beyond the signals produced by the noise.

### ***Seismic Reflection***

Seismic reflection surveys involve measuring the wave reflected back to the surface. By comparison, deeper investigations can be conducted with less energy than can the refraction method. The reflection method can provide information at depths less than 10 feet; however, it is more typically applied at 50 to 100 feet. The method can provide relatively detailed geological sections to a few thousand feet (Benson, 1991).

Seismic frequencies used for shallow studies should be relatively high (150 and 600 Hz) to improve vertical resolution. The ability to collect high frequency information may be limited by site conditions. Loose soil near the surface makes it difficult for the soil system to transmit high frequency energy. Because of the need for higher frequencies, attention must be given to selection of a source and its optimum coupling to soil or rock, as well as the geophone spacing. In general, the same source

used for the refraction method can be applied to the reflection method. The geophones should be closely spaced (1 to 20 feet) to provide good lateral resolution. The most common limitation of seismic reflection is acoustic noise from natural or cultural sources (Benson, 1991).

## **Metal Detection**

Metal detectors can locate any kind of metallic material, including ferrous (iron, steel) and non-ferrous (aluminum, copper). The tool is useful for locating shallow buried drums, trenches containing drums, underground storage tanks and metallic piping. It also can play an important safety role by locating utility pipes and cables prior to drilling or digging.

Types of metal detection devices include pipeline/cable locators, conventional "treasure hunter" detectors, and specialized detectors. Conventional detectors utilize small coils for detection of coin-sized objects. This limits their use to very shallow depths. Specialized detectors are designed to handle unique, site-specific problems. They are typically designed to enhance detection depths, increase area coverage, and continuously record data. They are expensive and require additional expertise to operate.

A metal detector responds to the electrical conductivity of objects. Metal objects typically display much higher conductivities than soil. Transmitting coils create a magnetic field that is in balance with the receiving coil. When metal comes in contact with the induced magnetic field emitted from the transmitting coil, a secondary field develops. This results in an imbalance between the transmitting and receiving coils. The instrument then indicates that a metallic object has been encountered (Benson et al., 1982).

Metal detector response is directly related to size and depth of the buried object. The larger the surface area of the object, the greater the depth of detection will be. Small metal objects, like quart-sized containers, can be detected at 2 to 3 feet (Benson et al., 1982). Larger objects, like 55 gallon drums, are typically detected at 3 to 10 feet. Piles of drums can be detected at 10 to 20 feet. Metal detector response is inversely proportional to the sixth power of the depth of the target ( $1/\text{depth}^6$ ). Therefore, if the depth of the target is doubled, the response will decrease by a factor of 64. Most objects, no matter how large, fall out of the range of metal detectors at depths greater than 20 feet (Benson et al., 1982). Coil response also affects metal detector response. Smaller diameter coils will limit detection depths, but enhance small object sensitivity. Large diameter coils will enhance detection depth, but decrease small object sensitivity.

Metal detection is extremely sensitive to noise. Any surface metallic objects can affect the instrument. Locations of fences, buildings, buried pipes, and metal objects should be identified. Furthermore, high concentrations of natural iron minerals in the soil can indicate a false target. Additionally, high concentrations of salt water, acids, and other conductive fluids can create detection problems. Many of these problems can be reduced when the transmitting and receiving coils are nulled or balanced before the survey begins. As a result, all background noise will be filtered.

## Magnetometry

Magnetic surveys have potential applications where adequate ferrous metals occur. A magnetometer is used to measure the intensity of the earth's magnetic field. This instrument is typically used to locate ferrous objects, boundaries of trenches buried with ferrous containers, and underground utilities (pipes and tanks) and the permeable pathways associated with them (Benson et al., 1982) (see Tables 11.1-11.3).

A natural magnetic field exists in and around the earth's surface. The intensity of this field varies considerably. In the U.S., it is typically around 50,000 gammas. The presence or absence of ferrous metals alters the intensity of the magnetic field. If natural magnetic properties are uniform, buried metallic objects display a local anomaly that is detected (Benson et al., 1982). Piles of buried drums can yield anomalies of 100 to 1000 gammas. The magnetometer is susceptible to a variety of cultural noise, which includes metal buildings and fences, overhead power lines, and buried utilities.

Total field and gradient are the two common types of magnetic measurements (Benson, 1991). Total field measurement responds to the total magnetic field of the earth, natural and cultural magnetics, and any changes caused by a target. However, measurement of such a large scale field can inhibit device effectiveness. This problem can be reduced by establishing a base station magnetometer to obtain background data and subtracting the values from measurements. This reduces the effects of natural noise and long-term changes of the earth's magnetic field, but does not reduce the effects of cultural noise (Benson, 1991). Total field magnetometer response is directly proportional to the mass of the ferrous object or target and inversely proportional to the cube of the distance to the target. A single drum can be detected up to 20 feet in depth and a massive pile of drums to 50 feet with a total field magnetometer (Benson, 1991).

If anomalies of interest are expected to be of similar magnitude to natural field variations, it is necessary to assess the site-specific noise and instrument repeatability by taking at least two readings at each station. Repeated measurements should agree within 1 gamma. Values that do not repeat within 10 gammas should not be used. Values that repeat between 1 and 10 gammas should be averaged.

Gradient measurements using a gradiometer also can be used to alleviate problems. This device is basically two magnetometers separated vertically (or horizontally) by a few feet. Gradient can also be obtained by taking two total field readings at different heights above the ground. Gradient measurements are insensitive to natural spatial and temporal changes in the earth's magnetic field and experience minimal effects from cultural features. A gradiometer only measures the difference between two total fields and, therefore, only responds to the local magnetic gradient (Benson, 1991). A gradiometer's response is inversely proportional to the fourth power of the distance to the target. Therefore, the device is less sensitive than a total field magnetometer. A gradiometer is better able to locate small targets, such as a barrel, and can detect a single drum up to depths of 10 feet, and massive piles of drums up to 25 feet (Benson, 1991).

## Gravimetry

Gravity instruments measure minute changes in the earth's gravity due to changes in density of subsurface materials. By mapping anomalous measurements across a site, an attempt can be made to interpret geologic conditions.

Gravity surveys can be used to locate bulk buried waste because of the density contrast with geologic materials, although alternate devices such as electromagnetics and radar are easier and more efficient to use. Benson (1991) refers to two types of surveys: regional and local. Regional surveys involve the collection of measurements over a large area with widely spaced stations (thousands of feet to miles) to determine large scale, regional features, often at great depth. Local surveys involve the acquisition of measurements in small areas with station spacings of 5 to 20 feet to locate shallow features such as buried valleys and fractures.

Gravimeters have been designed to measure in milligals, the unit measure of acceleration of gravity<sup>1</sup>. The instruments have been designed with thermostats to prevent drift due to changes in temperature. Ground noise, wind, and earth tides also may affect the measurements. About every hour, the instrument should be returned to an assigned base station and a measurement taken to record any drift that may be occurring. Corrections can then be applied to the data. The instrument should be handled carefully to prevent sudden jarring.

The data recorded in the field requires extensive reduction before any interpretations can be made. It must be corrected for earth tides, changes in elevation (all stations must be surveyed to 0.01 feet), latitude, and topography. This data can then be plotted as a gravity profile, from which interpretations are made. Careful interpretation is necessary because a variety of geologic situations can be represented by a single profile. Due to the extensive time and effort required to acquire the data and then reduce it, gravity studies are not typically applied to site-specific investigations.

## DOWNHOLE GEOPHYSICAL METHODS

Geophysical techniques provide an efficient and cost-effective means to obtain vertical profiles of a measured parameter within a borehole or well. Techniques for ground water investigations have been adapted from long-standing practices in the oil industry. A variety have been developed to determine subsurface lithology and physical properties (such as porosity, density, seismic velocity, and elastic moduli) and identify permeable or fluid-bearing zones. These methods or "logs" provide continuous measurements of properties along the entire length of a borehole. By comparing data for a borehole for which geology is unknown to data for a borehole for which a complete, detailed knowledge of geology is available, the geology of the unknown borehole can be determined.

Each technique has specific requirements and limitations that must be considered. For example, most logs provide measurements within a radius of 6 to 12 inches from the instrument (Benson, 1991). As the well diameter increases, instrument response may be greatly affected by the drilling method and components of well completion. Nuclear logs can be conducted in an open borehole

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<sup>1</sup>The earth's normal gravity is 980 gals.

as well as through steel or PVC well casing. Some techniques can only be conducted in open boreholes, which may limit their use in loosely consolidated, slumping materials where open conditions cannot be maintained. Certain instruments can only perform under saturated conditions, further limiting application. The presence of drilling muds and smearing of fine particles during drilling can affect instrument response and result in inaccurate interpretations. Table 11.5 summarizes the characteristics and use of commonly utilized downhole logging instruments, while Table 11.6 summarizes the common applications.

## **Nuclear Logs**

Nuclear logs measure radioactivity within the borehole, either due to natural radioisotopes within a formation or from transient response to radioactive sources contained within the probe. Logging tools commonly used include natural gamma, gamma-gamma, and neutron.

### ***Natural Gamma***

The gamma log measures the gamma radiation that is present naturally in the subsurface. Each material type displays relatively different amounts of radiation. Since clays and shales tend to concentrate radioactive elements due to ion exchange and adsorption, radiation is significantly higher than, for example, quartz sands or carbonates (Benson, 1991). The gamma log can be used in both open or cased boreholes above and below the water table. Though the technique can be used in cased boreholes, results may be significantly affected by attenuation due to casing materials, filter packs, and annular seals (Keys, 1990). These factors can be corrected to some extent, but the results are considered questionable (Collier and Alger, 1988).

### ***Gamma-Gamma (Density)***

The gamma-gamma log measures relative bulk density and can be used for identification and correlation of geologic materials. A radiation source in the probe emits gamma radiation. After attenuation and scatter into the surrounding material, gamma radiation is received by a detector on the same probe from which density determinations can be interpreted. Gamma radiation attenuation is assumed to be proportional to bulk density of the material it passes through (Keys, 1990). The gamma-gamma log also can be used in both open and cased boreholes, above and below the water table. However, as with the gamma technique, the results from the cased boreholes may be questionable. Its small radius of investigation (6 inches) limits the usefulness of the data.

### ***Neutron-Neutron (Porosity)***

The neutron-neutron log provides a measurement of the relative moisture content of the material above the water table and porosity below the water table. This log also utilizes a radiation source and a detector. The neutron interactions with the subsurface material measure the amount of hydrogen present, which is a direct indication of water content (Keys, 1990). This device can be used above and below the water table, in cased and uncased boreholes.

**Table 11.5 Downhole geophysics, characteristics and use (Benson et al., 1991).**

| <b>DOWNHOLE LOG</b>        | <b>PARAMETER MEASURED (OR CALCULATED)</b>                       | <b>CASING UNCASSED/PVC/STEEL</b> | <b>SATURATED</b> | <b>UNSATURATED</b> | <b>RADIUS OF MEASUREMENT</b>          | <b>AFFECT OF HOLE DIAMETER, AND MUD</b>          |
|----------------------------|---|----------------------------------|------------------|--------------------|---------------------------------------|--|
| Natural Gamma              | Natural Gamma Radiation   | Yes Yes Yes                      | Yes              | Yes                | 6-12 inches                           | Moderate   |
| Gamma-Gamma                | Density   | Yes Yes Yes                      | Yes              | Yes                | 6 inches                              | Significant                                      |
| Neutron                    | Porosity Below Water Table - Moisture Content Above Water Table | Yes Yes Yes                      | Yes              | Yes                | 6-12 inches                           | Moderate   |
| Induction                  | Electrical Conductivity   | Yes Yes No                       | Yes              | Yes                | 30 inches                             | Negligible                                       |
| Resistivity                | Electrical Resistivity  | Yes No No                        | Yes              | No                 | 12 inches to 60 inches                | significant to minimal depending upon probe used |
| Single Point Resistance    | Electrical Resistance   | Yes No No                        | Yes              | No                 | near borehole surface                 | significant                                      |
| Spontaneous Potential (SP) | Voltage - Responds to Dissimilar Minerals and Flow              | Yes No No                        | Yes              | No                 | near borehole surface                 | significant                                      |
| Temperature                | Temperature   | Yes No No                        | Yes              | No                 | within borehole                       | N/A  |
| Fluid Conductivity         | Electrical Conductivity   | Yes No No                        | Yes              | No                 | within borehole                       | N/A  |
| Flow                       | Fluid Flow  | Yes No No                        | Yes              | No                 | within borehole                       | N/A  |
| Caliper                    | Hole Diameter   | Yes Yes Yes                      | Yes              | Yes                | to limit of sensor typically 2-3 feet | N/A  |

**Table 11.6 Summary of log application (Keys and MacCary, 1971).**

| <b><i>REQUIRED INFORMATION ON THE PROPERTIES OF ROCKS, FLUID, WELLS, OR THE GROUND WATER SYSTEM</i></b> | <b><i>WIDELY AVAILABLE LOGGING TECHNIQUES THAT MIGHT BE UTILIZED</i></b>   |
|---|--|
| Lithology and stratigraphic correlation of aquifers and associated rocks                                | Electric, sonic, or caliper logs made in open holes; nuclear logs made in open or cased holes  |
| Total porosity or bulk density  | Calibrated sonic logs in open holes, calibrated neutron or gamma-gamma logs in open or cased holes                                     |
| Effective porosity or true resistivity  | Calibrated log-normal resistivity logs   |
| Clay or shale content   | Gamma logs   |
| Permeability  | No direct measurement by logging. May be related to porosity, injectivity, sonic amplitude, and fractures                              |
| Secondary permeability-fractures, solution openings   | Caliper, sonic, or borehole televiewer or television logs  |
| Specific yield of unconfined aquifers   | Calibrated neutron logs  |
| Grain size  | Possible relation to formation factor derived from electric logs   |
| Location of water level or saturated zones  | Electric, temperature, or fluid conductivity in open hole or inside casing, neutron or gamma-gamma logs in open hole or outside casing |
| Moisture content  | Calibrated neutron logs  |
| Infiltration  | Time interval neutron logs under special circumstances or radioactive tracers  |
| Direction, velocity, and path of ground water flow  | Single-well tracer techniques-point dilution and single-well pulse; multiwell tracer techniques  |
| Dispersion, dilution, and movement of waste   | Fluid conductivity and temperature logs, gamma logs for some radioactive wastes, fluid sampler   |
| Source and movement of water in a well  | Injectivity profile; flowmeter or tracer logging during pumping or injection; temperature logs   |
| Chemical and physical characteristics of water, including salinity, temperature, density, and viscosity | Calibrated fluid conductivity and temperature in the well; neutron chloride logging outside casing; multi-electrode resistivity        |
| Determining construction of existing wells, diameter and position of casing, perforations, screen       | Gamma-gamma, caliper, collar, and perforation locator; borehole television   |
| Guide to screen setting   | All logs providing data on the lithology, water-bearing characteristics, and correlation and thickness of aquifers                     |
| Cementing   | Caliper, temperature, gamma-gamma; acoustic for cement bond  |
| Casing corrosion  | Under some conditions, caliper or collar locator   |
| Casing leaks and (or) plugged screen  | Tracer and flowmeter   |

## **Non-Nuclear or Electric Logging**

Non-nuclear or electric logging encompasses logs in which a record of potential differences in electric current is measured. In order for the systems to provide useful data, the pore fluid must be conductive. This may not always be the case. Electric logging tools commonly used include induction, resistivity, single-point resistance, spontaneous potential, and acoustic.

### ***Induction***

The induction log measures the electrical conductivity of the subsurface material. Conductivity variations result from changes in porosity, permeability, rock type, and fluid content. Changes in materials due to variations in conductivity can be identified. This log can be utilized without direct electrical contact with the formation, which allows for its use in both saturated and unsaturated conditions. It also can penetrate PVC well casing (Benson, 1991). Specific conductance of the pore fluid has a major influence on instrument response. Therefore, the induction log can be used to identify inorganic contaminant plumes or organic plumes containing inorganic constituents.

### ***Resistivity***

The resistivity log provides measurements of the apparent resistivity of the material surrounding a borehole (Benson, 1991). Resistivity is the reciprocal of conductivity and, therefore, this log measures the same properties and has the same applications as the induction log. Direct electrical contact is needed. Therefore, the technique can only be used in uncased boreholes in saturated materials.

### ***Single-Point Resistance***

The single-point resistance log provides a record of the resistance between surface and downhole electrodes of the instrument. Resistance logs are used primarily for lithologic determination, correlation, and identification of fractures and washout zones (Benson, 1991). Single-point logs do not provide a quantitative measure of resistance for the surrounding material. The resistance log is limited to use in uncased boreholes in saturated materials.

### ***Spontaneous-Potential***

The spontaneous-potential log (SP) is a record of the natural potential or voltage that develops between the borehole fluid and the surrounding materials. Spontaneous-potential is a function of fluid chemical activities, temperature, and the type and quantity of clay present, and is not related to porosity and permeability (Keys, 1990). Electrochemical and electrokinetic or streaming potentials, caused by water moving through permeable material, are the primary sources of spontaneous-potential. Oxidation-reduction potential is another source (Keys, 1990). Measurements are subject to considerable noise from the electrodes, hydrogeologic conditions, and borehole fluid (Benson, 1991). Though quantitative results are not provided, the SP may be useful in determining lithology, oxidation-reduction conditions, and fluid flow (Benson, 1991). The SP is limited to use in uncased boreholes under saturated conditions.

## ***Acoustic***

Acoustic logging includes techniques that use a transducer to transmit a sonic wave through the fluids in a borehole and the surrounding rock. The techniques can provide information on porosity, lithology, cement, and the location and character of fractures. Types described by Keys (1990) include velocity, wave, cement bond, and televue. All require fluid in the borehole to couple the signal to the surrounding rock. They differ in the frequencies used, the way the signal is recorded, and the purpose of use. ***Velocity logs*** can be used to help identify lithology and measure porosity. These logs are generally limited in use to consolidated deposits and uncased, fluid-filled boreholes. ***Cement bond logs*** provide information on the quality of the bond between the borehole and cement and the casing and cement. ***Wave form logs*** have not been extensively used in hydrogeologic studies; however, they are needed to accurately interpret cement bond logs. A ***televue*** is a logging device that can provide high-resolution information on the location and characterization of secondary porosity (e.g., fractures and solution channels). The technique can also provide information on the strike and dip of planar features.

## **Physical Logs**

Physical methods include temperature, conductivity and caliper logging. Use of these logs often is necessary to properly interpret other geophysical logs.

### ***Temperature***

The temperature log provides a continuous recording for any fluid that a sensor probe contacts. It can provide information on movement of water through a borehole, trace movement of injected waste or water, and correct other logs sensitive to temperature. Types of logs that are common are temperature and differential temperature. The differential log is a record of the rate of change per depth (Keys, 1990).

### ***Fluid Conductivity***

Fluid conductivity logs provide data related to dissolved solids concentration in the fluid column. Conductivity is sensitive to temperature. If accurate conductivity values are needed, a temperature log record should also be taken to correct the data. Although the quality of the fluid in the borehole column may not reflect the quality of the adjacent interstitial fluids, the information may be useful when combined with other logs (Keys, 1990).

### ***Fluid Flow***

Flow measurements with logging probes can be performed by mechanical, tracer and thermal methods. The most common flow logging probe used is an impeller-type device.

### ***Caliper***

The caliper log provides a measure of the diameter of the cased or uncased borehole. This log is essential in interpreting other logs that are affected by changes in borehole diameter (Keys, 1990).

It also can provide information for locating slumping or cavities and fractures in the open borehole walls. In cased wells, the caliper log can be useful for determining construction details and may reveal accumulation of minerals or corrosion of the casing itself (Benson, 1991).

## **DATA REQUIREMENTS**

If a regulated entity utilizes surface or downhole geophysical methods, it is important that the entire process be documented and the appropriate data submitted for Agency review. Some of the important features that should be presented are as follows:

- Objective of the study, including description of the targets of interest.
- Description of chosen technique(s) and the decision-making process.
- Description of site location and setting, both culturally and geologically.
- Description of survey set-up and data collection.
- Summary of the collected data (including raw and corrected).
- Summary of data reduction.
- Interpretation of the data, including any correlations made from existing data.
- Development of appropriate tables, maps, and data plots and their interpretation.
- Documentation of all problems encountered.

## **SOIL GAS SAMPLING AND ANALYSIS**

Soil gas sampling and analysis can be a rapid and cost-effective approach for preliminary delineation of the areal and/or vertical extent of subsurface contamination by volatile organic compounds (VOCs). Information can be obtained that is useful in developing ground water and soil sampling and analysis programs. Gasoline and many other organic liquids contain VOCs that can be emitted as vapors. If such a liquid is released into the subsurface, vapors emitted will occupy the void spaces between the individual grains within the formation. Soil gas surveys involve sampling and analyzing gases that occupy the pore spaces in the vadose zone. Conventional activities such as ground water sampling of monitoring wells and performance of soil borings always will be necessary to confirm and/or monitor subsurface contamination.

When an organic liquid is released into the subsurface, it generally migrates downward under the force of gravity until it reaches the water table. Depending on the characteristics of the liquid, it may float on the surface, sink to the bottom of the water-bearing zone, and/or dissolve into the ground water. Also, the contaminant may, in part, become adsorbed to sediments as it migrates through the vadose zone. Soil gas sampling can be used, in appropriate situations, to detect volatile organic vapors derived from all of these potential sources. The technique is most effective for contaminated soils and water table aquifers and is relatively ineffective for contaminated ground water overlain by extensive confining layers. Soil gas surveying can be used to: 1) detect and identify specific VOCs in the subsurface, 2) determine the concentrations of each component in the gas phase, 3) identify sources and extent of multiple spill events, 4) predict the extent of soil and/or ground water contamination, 5) interpret mode of occurrence of contaminants (liquid, dissolved), 6) identify fuel products (diesel vs. gasoline), 7) help guide the placement of borings and monitoring wells and 8) initially monitor the progress of in-situ bioremediation systems. Benefits of soil gas

surveys include low cost, rapid sampling, quantitative analysis of VOCs, thorough site coverage, and timely results.

## FACTORS OF CONCERN IN SURVEY DESIGN

Site-specific physical factors such as soil characteristics, geologic heterogeneity, depth to water table, and existence of natural or cultural confining zones affect vapor transport and, hence, the usefulness of soil gas surveys. Chemical and physical factors and concentrations of contaminants affect the degree to which compounds partition into the vapor phase. Changes in barometric pressure, temperature, and moisture content can affect soil gas flux and subsequent interpretation of the data. Also, use of proper sampling and analysis protocol and appropriate instruments with detectors sensitive to the contaminant of interest is required to detect volatiles (Crockett and Taddeo, 1987). Failure to understand and consider these factors when designing soil gas surveys and interpreting the data can result in erroneous conclusions. Table 11.7 summarizes the factors.

**Table 11.7. Factors affecting concentrations of soil gas vapors.**

|  |
|--|
| <b><i>CHEMICAL/BIOLOGICAL CHARACTERISTICS</i></b>  |
| <ul style="list-style-type: none"> <li>B Volatility of compounds (solubility and vapor pressure)</li> <li>B Mobility in subsurface</li> <li>B Concentration gradients</li> <li>B Persistence in subsurface (half life, biodegradable capacity, interaction with other chemicals, etc.)</li> </ul>                      |
| <b><i>HYDROGEOLOGIC CONTROLS</i></b>   |
| <ul style="list-style-type: none"> <li>B Properties of the soil media: moisture content, total porosity, air porosity, grain size distribution, organic carbon content, Redox potential.</li> <li>B Heterogeneity of the subsurface materials</li> <li>B Fluctuating water table</li> <li>B Perched aquifer</li> </ul> |
| <b><i>ANTHROPOGENIC CONTROLS</i></b>   |
| <ul style="list-style-type: none"> <li>B Paving and buildings</li> <li>B Utility conduits</li> <li>B Pumping centers</li> </ul>  |
| <b><i>METEOROLOGICAL CONTROLS</i></b>  |
| <ul style="list-style-type: none"> <li>B Barometric pressure</li> <li>B Precipitation regime</li> <li>B Temperature</li> </ul>   |

## Chemical/Biological Characteristics of Contaminants

To apply soil gas surveying, the dissolved and/or liquid contaminant must have entered into the gas phase. This limits application to investigation of the presence of contaminants such as solvent chemicals and petroleum hydrocarbons, which are characterized by high vapor pressure, low molecular weights, and low aqueous solubilities.

These compounds can readily partition out of the liquid and/or ground water and into the soil gas phase as the result of their high gas/liquid partitioning coefficients. In general, the greater the amount of contaminant present, the greater the opportunity for volatiles to exist in soil pores; however, the relationship is not necessarily directly proportional. The amount of an organic compound that can be volatilized is limited (under static conditions) by factors controlling the equilibrium between the liquid and gas phase. Additionally, soil gas evolving from light non-aqueous phase liquids (LNAPLs) exhibit higher contaminant concentrations than soil gas coming from a contaminant in the aqueous phase.

When dealing with a pure product, the likelihood that the compound will enter into the vapor phase can be predicted by the vapor pressure of the target compound. According to Kerfoot (1988), the minimum vapor pressure of the target compound should be approximately 3 pounds per square inch (psi). Likewise, Henry's Law can be used to determine the likelihood. Henry's Law constants are a function of the aqueous solubility, vapor pressure, and molecular weight of a compound. According to Marrin (1987), compounds characterized by constants less than 0.1 mmHg M<sup>3</sup>/mol will not partition adequately to be detected in soil gas. Crockett and Taddeo (1987) indicated that chloromethanes and chloroethenes have Henry's Law constants ranging from 0.1 to 2.0 X 10<sup>-2</sup> atm M<sup>3</sup>/mole (0.76 to 15.2 mmHg M<sup>3</sup>/mol) and are suitable for soil gas surveys. The constants for benzene, toluene, and xylene range from 5 to 9 X 10<sup>-3</sup> M<sup>3</sup>/mole (3.8 to 6.8 mmHg M<sup>3</sup>/mol), indicating that these compounds also can be detected by soil gas analysis; however, it must be noted that many factors can influence these idealized approximations. For example, compounds characterized by boiling points below 110° C are most mobile in soil gas (Thompson and Marrin, 1987). Vapors from hydrocarbons with boiling points greater than 150° C are usually detected only in the immediate vicinity of the source because of their low diffusion coefficients and tendency to adsorb onto soils.

For a soil gas survey to be successful, the target compounds must be persistent in the subsurface. Chemicals such as benzene, toluene, and xylene can be altered by biological action or chemically transformed into non-volatile or water-soluble compounds that are not amenable to being detected. Petroleum hydrocarbons are particularly susceptible to biodegradation in the upper portions of the soil profile where oxygen is present. Soil gas measurements for petroleum releases should be collected as close to the water table as possible (Thompson and Marrin, 1987). However, in the immediate vicinity of a strong hydrocarbon source, such as a leaking underground storage tank, vapors are generally detectable at or very near the ground surface. According to Marrin and Kerfoot (1988), halogenated hydrocarbons can biodegrade under anaerobic conditions. Compounds with minimal halogens can biodegrade under both anaerobic and aerobic conditions. Chlorinated hydrocarbons such as tetrachloroethylene (PCE) and trichloroethylene (TCE) can be biologically dehydrated in the subsurface to produce more volatile compounds (e.g., dichloroethene isomers and vinyl chloride).

## **Site Physical Factors**

Successful detection of volatiles by soil gas sampling requires transport of VOCs over some distance. The distance capability is dependant on the chemical/physical properties of the contaminant, and hydrogeologic and soil conditions.

The predominant transport mechanisms for soil gas are diffusion and convection. Diffusion is the result of thermal motion of molecules subject to a concentration gradient. Convection is the result of a pressure gradient causing mass flow in a gaseous phase. Both processes are independent of topography or hydraulic gradient. The soil gas concentration tends to decrease with increasing distance both horizontally and vertically away from the source. Studies have shown that concentrations drop more rapidly horizontally than vertically (Crockett and Taddeo, 1987). Though vertical transport by diffusion predicts a linear increase in VOC concentration with depth, hydrogeologic/geologic heterogeneities, soil porosity, moisture content, and sorption equilibria within the subsurface can affect VOC vapor gradients. During the upward migration of soil gas, the vapor may encounter a clay or human-made structure that may cause it to diffuse horizontally and result in a plume that is slightly larger than the source. Vapor transport through wet clays is limited compared to transport across a dry porous sand (Crockett and Taddeo, 1987). Paved areas can cause near-surface concentrations to be significantly higher because they prevent off-gassing. Also, migration pathways can be directly influenced by anthropogenic structures such as utility conduits, which are typically backfilled with permeable sand and gravel.

According to Marrin (1988), soil gas surveys are most applicable where the water table is 15 feet or greater in depth. Shallow conditions present a difficulty because the concentration gradient in soil gas can be very steep and slight variations in the ground water elevation can result in large variations in VOC concentrations. If the water table is close to the surface, it is difficult to acquire samples that are reliable and representative. If samples must be acquired from 2 feet or less, there is an increased likelihood that they will be diluted by air or affected by barometric pressure. Tillman et al. (1989b) indicated that it is possible to sample at too great a depth. If this occurs, then accumulations of vapors, such as those that may occur above a contaminated perched water table, may be missed. Slight variations in depth of samples collected close to the water table can produce large apparent concentration variations. Less variability in results is apparent with increased distance above the water table.

## **Site Meteorological Factors**

Meteorological changes such as barometric pressure, temperature, and moisture content can affect soil gas flux; therefore, these effects need to be understood in the acquisition and interpretation of data. A high pressure system during sampling creates a lower volatile flux at shallow depths than during a period of low pressure. Freezing and thawing conditions can have an effect on flux. Soil gas can become concentrated beneath the frozen cap. The temperature of soil gas can affect the rate at which volatilization occurs in the subsurface. Studies have shown that VOC concentrations can increase during early afternoon and decrease in late afternoon, roughly correlating with daily temperature changes (Karably and Babcock, 1989). Increased moisture content can increase the rate of movement of volatiles through soils because water tends to displace non-ionic species from the adsorption site. However, according to Tillman et al. (1989a), a period of heavy rainfall often causes a decrease in the gas flux due to the near-surface saturated conditions and the stripping of

soluble components out of the soil gas. To eliminate the effects of meteorological changes, soil gas samples should be taken over the shortest period of time possible.

## **SAMPLING AND ANALYSIS TECHNIQUES**

Appropriate methods for soil gas sample acquisition and analysis depend on site conditions and survey objectives. Before methods are selected, contaminant properties, site-specific hydrogeologic conditions, human-made interferences, and why and how the data will be utilized should be understood clearly (Crockett and Taddeo, 1987). Accurate detection of VOCs requires use of proper protocol and appropriate instruments with detectors sensitive to the contaminant of interest. The selection of techniques influences the subsequent interpretation of the data. In addition, a decision must be made regarding the development of a long-term soil gas monitoring program (i.e., permanent stations).

Soil gas sampling techniques fall into two categories, active and passive. The techniques selected should be dependent on the objective of the study. Techniques have not been standardized or adequately evaluated. It is therefore imperative that those conducting surveys are experienced with the methods and are familiar with site conditions.

### **Active Methods**

Active sampling methods provide an instantaneous picture of the soil atmosphere at a particular location. Examples of active techniques include head space measurements from subsurface structures, head space measurements from soil samples, and sampling soil gas from driven probes or surface flux chambers. The methods are summarized below and additional references for the techniques are provided.

#### ***Head Space Measurements, Subsurface Structures***

Head space measurements from subsurface structures involve collecting grab samples or utilizing a portable hydrocarbon analyzer in wells, storm sewers, underground utility lines, or other human-made structures. This technique can be used during the first phase of an investigation. The results obtained can assist in developing protocol for subsequent work. The limitations of this technique include interference from methane in sewer lines and diffusion of volatile hydrocarbon species out of unsealed structures. In addition, negative test results are inconclusive.

#### ***Head Space Measurements, Soil Samples***

Head space measurements of an undisturbed soil sample ( e.g., from a hand auger, driven tube, or split spoon) can also be used. Containers must be properly decontaminated and meet the same standards as containers submitted for laboratory analysis. Several approaches can be taken. The container can be half-filled with soil, sealed, and allowed to equilibrate with the ambient temperature. Measurements can be taken from volatilization of the gas into the vacant space using a portable detector (Holbrook, 1987). Other techniques involve placing the sealed container in a hot water bath (70° C) to volatilize the organic compounds (Jermakian and Majka, 1989).

Head space measurements from soil samples typically are simple and quick to perform. They can be used to analyze soil gas from discrete or composite samples at incremental depths down to the water table. This technique has been used to collect shallow soil gas to assess deeper sources of vapors. Devitt et al. (1987) recommended this technique when the sampling crew has a modest level of technical expertise or when sophisticated sampling equipment is neither available or cost-effective. Limitations include:

- Primarily suited for measuring adsorbed organics rather than free organics in the interstitial pore spaces.
- Loss of volatile hydrocarbons when the sample is removed from the ground or transferred for analysis.
- Loss of volatile hydrocarbons due to degradation of organic compounds from the time delay between sampling and analysis.

Soil type, head space volumes, temperature, handling techniques, and storage times need to be held constant in order to compare relative concentration levels between samples.

### ***Driven Probes***

Soil gas can also be sampled by driving a hollow probe and evacuating a small amount of vapor. Openings in the tube near the leading edge allows for soil gas to enter. The sample can be extracted by inserting a needle through the evacuation line and drawing gas from the stream (Figure 11.3). Samples can be analyzed in the field by gas chromatography (GC) or transported for laboratory analysis

Both large-volume and small-volume probes have been used. The internal volume of the probe significantly affects the measurement process and the utility of the resulting data (Devitt et al., 1987). Small probes can be used to attempt to measure "true" soil gas concentrations. The small volume permits the air inside the probe to be purged and a small (e.g, 1 mL) sample to be collected without substantially altering the gas equilibrium. The use of a large probe typically involves sampling several liters of soil gas. This may not permit a representative sample to be collected under most conditions, but allows for the soil gas to be concentrated prior to analysis or for multiple aliquots to be extracted.

The large probes are typically used for investigations that seek to determine relative concentrations or that are concerned with whether or not contamination affects a given area. Devitt et al. (1987) cited various researchers and how they applied both small and large probes.

Use of driven probes is best suited for shallow sampling. Probes can be installed through landscaped areas, through concrete or asphalt covers, or inside buildings with relatively little disturbance of the surrounding area. The technique is relatively sensitive and can be used to measure subsurface gas concentrations while avoiding surface interference. Samples also can be obtained below impermeable layers. The technique is well suited for ground water investigations, except in the presence of wet or ayey soils or near surface rock strata. The method is labor- and time-intensive, and sampling ports can clog, making sample extraction difficult.

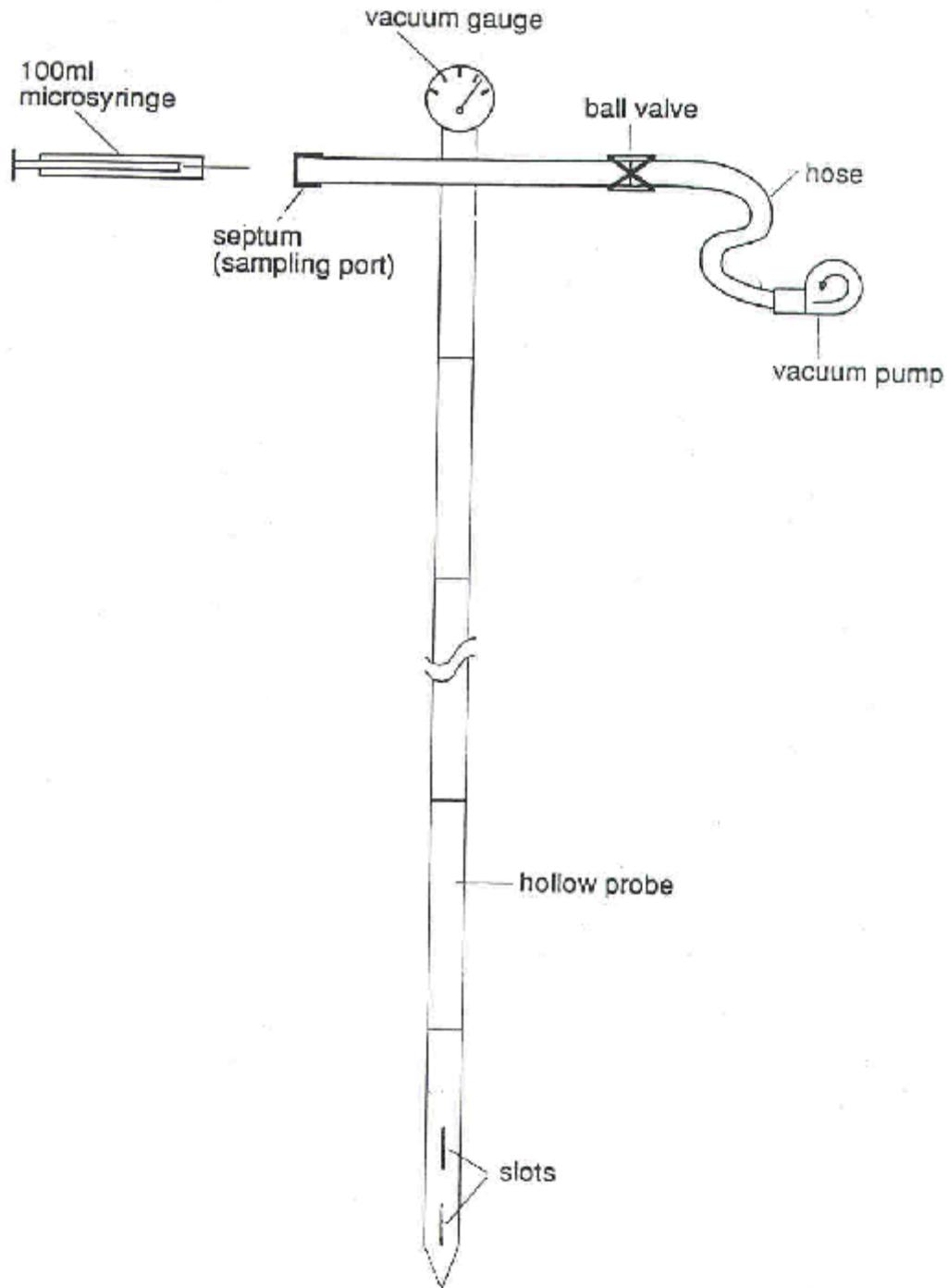


Figure 11.3 Schematic diagram of driven probe, soil gas sampling apparatus (Source: "Sampling Soils in Tight Formations" by R.W. Greensfelder, M. Singh and G. Davitt. Proceedings of the Conference on Petroleum Hydrocarbons and Organic Chemicals in Ground Water, Prevention, Detection and Restoration, p. 99 (Figure 1). 1991. Reprinted from the Proceedings of the Conference on Petroleum Hydrocarbons and Organic Chemicals in Ground Water, Prevention, Detection and Restoration with permission of the National Ground Water. Copyright 1991.)

## **Surface Flux Chambers**

A device enclosed in a surface flux chamber is used to sample gaseous emissions from a known surface area. The air is passed through a chamber and the gas exiting the chamber is analyzed or collected for later analysis. Best results are obtained by using sophisticated sampling techniques (e.g., stainless steel evacuation) and/or sensitive detection systems (e.g., GC) (Devitt et al., 1987).

This technique is particularly applicable to measuring population exposures, because gaseous emissions are being measured at the surface. Limitations include:

- C Dilution of sample, which decreases the sensitivity of the method.
- C Caliche, semi-impermeable soils, and/or soils saturated with water block the migration of soil gas.
- C Concentrations of soil gas collected at the surface generally are lower than the subsurface soil gas concentrations, making contaminant detection difficult.

## **Passive Sampling Methods**

Passive methods involve leaving an accumulator device in the ground for a series of days or weeks to measure some function of an average concentration over a period of time. These techniques do not provide equivalent measurements. Many do not provide reliable and representative samples. For example, passive sampling may not yield the highly quantitative results critical to a proper interpretation. The use of passive devices requires site disruption and much greater turnaround time for sample acquisition. Also, passive methods usually dictate a geometric grid arrangement of sampling points, except for sites where potential sources are obvious. Some techniques may cause dilution of samples by mixing with the air or cause contamination of the sample from the sampling apparatus.

An example of a passive technique involves use of a sorbent sampler. The device is buried underground and used to collect gas over a given period of time (2 to 6 weeks), after which the devices are removed and analyzed in the laboratory. Devitt et al. (1987) discussed sorbent systems designed by various researchers.

Sorbent samplers provide integrated samples that compensate for fluctuations in soil gas concentration. Sorbent sampling is best suited for cases where concentrations are expected to be very low (Devitt et al., 1987). The sampling duration can be varied to ensure that a sufficient sample is collected to allow for analytical detection. Therefore, this technique is useful for determining whether contamination exists, but does not provide information on the concentration.

## **ANALYSIS TECHNIQUES**

A wide variety of techniques exist to analyze soil gas. These range from handheld devices that measure total levels of VOCs to laboratory gas chromatographs that measure minute quantities of

individual constituents. The selection of a method is dependant on the objective of the survey and the compounds of interest.

**Handheld analyzers** can be used to measure gross levels of VOCs and using such a device is often one of the first steps of an investigation. The technique is quick, simple, and economical and can save substantial amounts of time and money by providing input data for selection of additional sampling strategies (Devitt et al., 1987). However, because of their high sensitivity to ambient changes, the data obtained from a handheld analyzer cannot be used as a mapping tool (Tillman et al., 1989b). Also, negative test results are inconclusive.

The use of a **gas chromatograph (GC)** is a more definitive approach to identifying individual components of soil gas. Samples can either be analyzed in the field using a portable GC unit or taken to a laboratory for analysis by a laboratory-grade unit. The use of portable GCs generates data on the same day the sampling is completed; however, field GC analysis often is slow overall and may not provide the low detection limits that laboratory technology provide. Mobile labs with laboratory-grade GCs provide top quality results and allow field analysis.

Selection of an appropriate detector also is critical to a successful survey. The detector must be sensitive to the volatiles to be analyzed and offer appropriate detection limits. A variety of detectors that measure different classes of VOCs can be used with the gas chromatograph. These include a flame ionization detector (FID), a photoionization detector (PID), and an electron capture device (ECD). A FID can be used when the objective is to detect the presence of petroleum hydrocarbons. An ECD can be used if the objective is to measure the existence of chlorinated hydrocarbons. A PID can be used to measure some components of both hydrocarbon and chlorinated hydrocarbons. If the objective is to determine the presence of the full range of EPA Volatile Priority Pollutants, then both the GC/FID and the GC/ECD analysis must be conducted.

## **INTERPRETATION OF DATA**

To obtain maximum benefits from soil gas data, proper interpretation based on experience and knowledge of the underlying principles is essential (Crockett and Taddeo, 1987). One of the most common mistakes is to extend the interpretation beyond the scope of the survey design (Marrin, 1988). For example, a survey designed to locate contaminant source areas probably is not appropriate for delineating contaminant plume characteristics at the same location. Soil gas surveying is effective only for specific types of contaminants and must be interpreted with careful regard to the physical chemistry of the contaminant and the hydrogeologic environment (Marrin and Kerfoot, 1988).

Quantitative relationships between VOC concentrations in soil gas and ground water can be difficult to establish due to variability in subsurface conditions across a site (Marrin, 1988). Even under the most homogeneous conditions, correlation coefficients can only be calculated on an order-of-magnitude basis. Heterogeneities in the subsurface (i.e., moisture content, air-filled porosity, grain size distribution, pavement) cause differences between soil gas and ground water plume characteristics; however, the lack of statistical correlation does not mean that soil gas analyses are not indicative of ground water conditions (Marrin, 1988).

Using soil gas contours to define the boundary of a contaminant plume in ground water rarely is successful because compounds characterized by low to moderate air/water partitioning coefficients are not present at high enough concentrations in soil gas to be detected and because compounds with high partitioning coefficients have usually diffused in soil gas beyond the ground water plume (Marrin, 1988).

## **THE IN-SITU GROUND WATER SAMPLER**

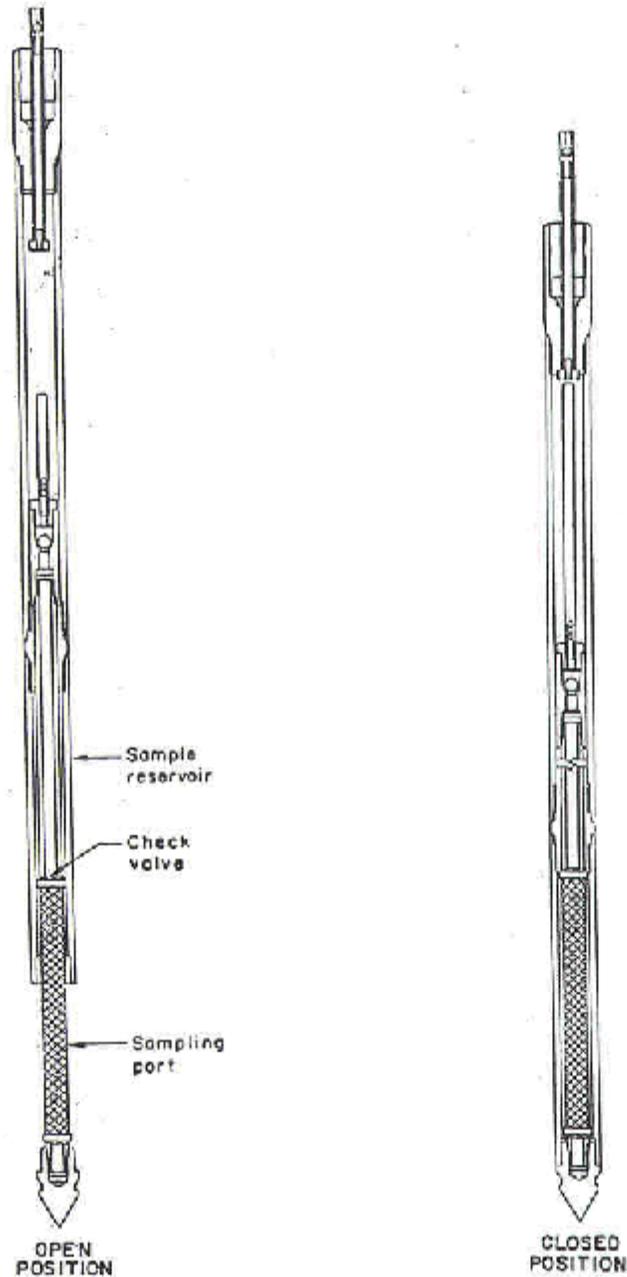
Soil gas analysis and geophysical techniques often fail in defining the presence/absence or extent of ground water contamination due to hindrances from site conditions, geology, and cultural noise, etc. To alleviate these problems, a tool has been devised to collect ground water samples from the subsurface without the time, effort, and cost of installing monitoring wells. The tool, the Hydropunch™ (Patent #4669554), provides a sample that, upon laboratory analysis, may help determine the extent of contamination. The term "hydropunch" has become a generic term for all in-situ ground water sampling devices.

The use of the hydropunch or any related device is accepted as a reconnaissance tool when determining the extent of ground water contamination. Installation and sampling of monitoring wells may not be most desirable nor cost-effective when conducting such investigations. On the other hand, the hydropunch or related device is not accepted as the sole means of documenting the extent of a plume. The device can only be used for the initial determination of the existence of contamination. In addition, monitoring wells should be installed (based on the results) to further verify and monitor the contamination. In effect, a hydropunch should act as a screening device (like soil gas or geophysics) to aid in effective monitoring well placement.

### **DESCRIPTION AND USE**

The hydropunch is a stainless steel or fluorocarbon sampling tube (Figure 11.4) that is attached to a small diameter pipe and either driven or pushed hydraulically to the desired depth. As the tool is advanced, it remains in the closed position, which prevents soil or water from entering. Once the desired level is reached, a sampling chamber is opened to the water-bearing zone by retracting the pipe approximately 1.5 feet. In the open position, ground water can flow freely into the sample chamber. When full (500 ml), the sampler is pulled to the surface. As the device is retracted, check valves close and trap the water in the sample container (Edge and Cordry, 1989). No development is needed because the device allows for an isolated sample to be collected from a discrete zone and a screen prevents the infiltration of sediments.

Samples collected from the device should be handled with the appropriate quality assurance/quality control (QA/QC) procedures to ensure adequate analytical results can be obtained. All applicable protocols and procedures outlined in Chapter 10 of this document should be followed and documented. Additionally, hydropunch equipment should be properly decontaminated between locations and zones, if necessary. The methods recommended in Chapter 6 for subsurface sampling equipment should be used.



**Figure 11.4 Hydropunch in open and closed positions. The open position is for sampling and the closed position is for driving.** (Source: "Cone penetrometer tests and hydropunch sampling: A screening technique for plume definition" by M. Smolley and J.C. Kappmeyer. *Ground Water Monitoring Review*, Vol. 11, No. 2, p. 104 (Figure 4), 1991. Reprinted from *Ground Water Monitoring Review* with permission of the National Ground Association. Copyright 1991.)

The hydropunch is typically used in conjunction with a cone penetrometer. The cone penetrometer involves the use of hydraulic rams in conjunction with a heavy truck or drilling rig to push a 1.5 inch diameter cone attached to a series of rods into the ground. Changes in the force acting on the cone are detected and measured, with the resulting data correlated to soil stratigraphy. Cone penetrometers generally work best in soft, fine- to medium- textured soils (Edge and Cordry, 1989). The cone can be replaced with the hydropunch sampler to collect ground water samples. Edge and Cordry (1989) found from field experience that this combination of technology can produce a sample from depths of 15 to 70 feet within an hour. They estimated that the use of the hydropunch costs one-half to one-tenth that of installing, developing, and sampling a monitoring well. At the same time, no drill cuttings or development water is produced and the surrounding environment is disturbed only to a minimal extent.

When a cone penetrometer is not practical or its availability is limited, the hydropunch can be used with conventional drilling methods. It can be directly connected to drill rods and advanced ahead of the borehole bottom to collect samples unaffected by the drilling process. In addition, numerous samples can be collected as the borehole is advanced, allowing determination of water quality at various depths. Edge and Cordry (1989) estimated that use of the hydropunch with the hollow stem auger can provide a cost savings of one-half of monitoring well installation costs.

The resulting hole from the penetrometer or drilling method should be properly abandoned with bentonite or a cement/bentonite grout mixture. Refer to Chapter 9 of this document for recommended procedures.

## **CONSIDERATIONS FOR IMPLEMENTATION**

Edge and Cordry (1989) and Smolley and Kappmeyer (1991) reported a variety of field considerations affecting the use of the hydropunch, including the following:

- The time to fill the sampler chamber upon opening to the water bearing zone varies according to the relative permeability of the geologic material. Fill times of approximately 45 minutes for low permeability clays and 5 minutes for more permeable materials can be expected.
- The hydropunch may not be efficient when penetrating deposits with cobbles . As a rule of thumb, the device can be used in the same environments in which a 2-inch split-spoon sampler can be utilized.
- The appropriate mesh size of the hydropunch screen should be considered to prevent sediment from entering the sample chamber and causing the check valves to malfunction.
- Approximately 5 feet of hydrostatic head is needed above the sampling port to fill the probe, which limits its use to thin water-bearing zones.
- When conducting shallow studies or when collecting successive samples from a single borehole, use of two or more hydropunches may be desirable. This may be necessary to increase efficiency by allowing one device to be decontaminated while the other is in use.
- The 500 ml sample size may not be sufficient when analyzing for certain parameters (e.g., metals, BOD, etc.).

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**TECHNICAL GUIDANCE MANUAL FOR HYDROGEOLOGIC  
INVESTIGATIONS AND GROUND WATER MONITORING**

**CHAPTER 12  
GROUND WATER QUALITY DATA ORGANIZATION AND  
INTERPRETATION**

**February 1995**

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## **CHAPTER 12**

### **GROUND WATER QUALITY DATA ORGANIZATION AND INTERPRETATION**

Large amounts of ground water quality data can be generated during a hydrogeologic investigation and/or ground water monitoring program. Proper interpretation of the data is necessary to enable sound decisions. It is important that the data be: 1) organized and presented in a manner that is easily understood and 2) checked for technical soundness, statistical validity, proper documentation, and regulatory or programmatic compliance.

Project goals and data evaluation procedures often are dictated by regulatory requirements. For example, an owner or operator of an interim status land-based hazardous waste management unit or a solid waste landfill must use statistics in his/her monitoring program to determine whether contaminants have been released to ground water. The methodology used to evaluate risk to human health and/or the environment also may depend on the regulatory program. Additionally, methods utilized to interpret data may be ordered on a site-specific basis.

#### **VALIDATION**

Validation is crucial for the correct assessment of ground water quality data. Data must be systematically compared against a set of criteria to provide assurance that the data are adequate for the intended use. Validation consists of editing, screening, checking, auditing, verification, certification, and review (Canter et al., 1988).

The methods used to define site hydrogeology and collect ground water samples need to be scrutinized. In addition, data should be evaluated using field and trip blank(s) (see Chapter 10) to help verify that sampling techniques were appropriate. Laboratory data validation is completed by a party other than the laboratory performing the analysis. U.S. EPA guidance for validation of chemical analyses (U.S. EPA, 1988a, b) stressed the importance of evaluating analytical methods and procedures such as sample holding times, instrument calibration, method blanks, surrogate recoveries, matrix spikes, and field duplicates.

#### **ORGANIZATION AND INTERPRETATION TOOLS**

Ground water quality data should be compiled and presented in a manner convenient for interpretation. Presentation methods include tabular, map, and graphic. Interpretation techniques include statistics and modeling. The appropriate tools depend on the goals of the monitoring program.

#### **TABULAR**

Tables of data are the most common form in which the chemical analyses are reported. Tables generally are sorted by well, type of constituent, and/or time of sampling. For most constituents, data are expressed in milligrams per liter (mg/l) or micrograms per liter ( $\mu\text{g/l}$ ). Data should be organized and presented in tabular form or as dictated by regulatory or program requirements. Reports from the laboratory also should be submitted. Some Ohio EPA programs are beginning

to require ground water quality data to be submitted in a computer-based format. However, before submitting data in an electronic format, regulated entities should check with the appropriate program to determine the preferred media. Chapter 2 summarizes the Agency's organization and authority to require monitoring.

## MAP

Isopleth maps are contour maps constructed by drawing lines representing equal concentrations of dissolved constituents or single ions (Figure 12.1). These maps, when combined with site-specific geologic/hydrogeologic characteristics (see Chapter 3), are useful in tracking plumes. However, their applicability depends on the homogeneity of ground water quality with depth and the concentration gradient between measuring points. Restricted sampling points in either the vertical or horizontal direction limit usefulness (Sara and Gibbons, 1991). Questionable data or areas lacking sufficient data should be represented by dashed lines.

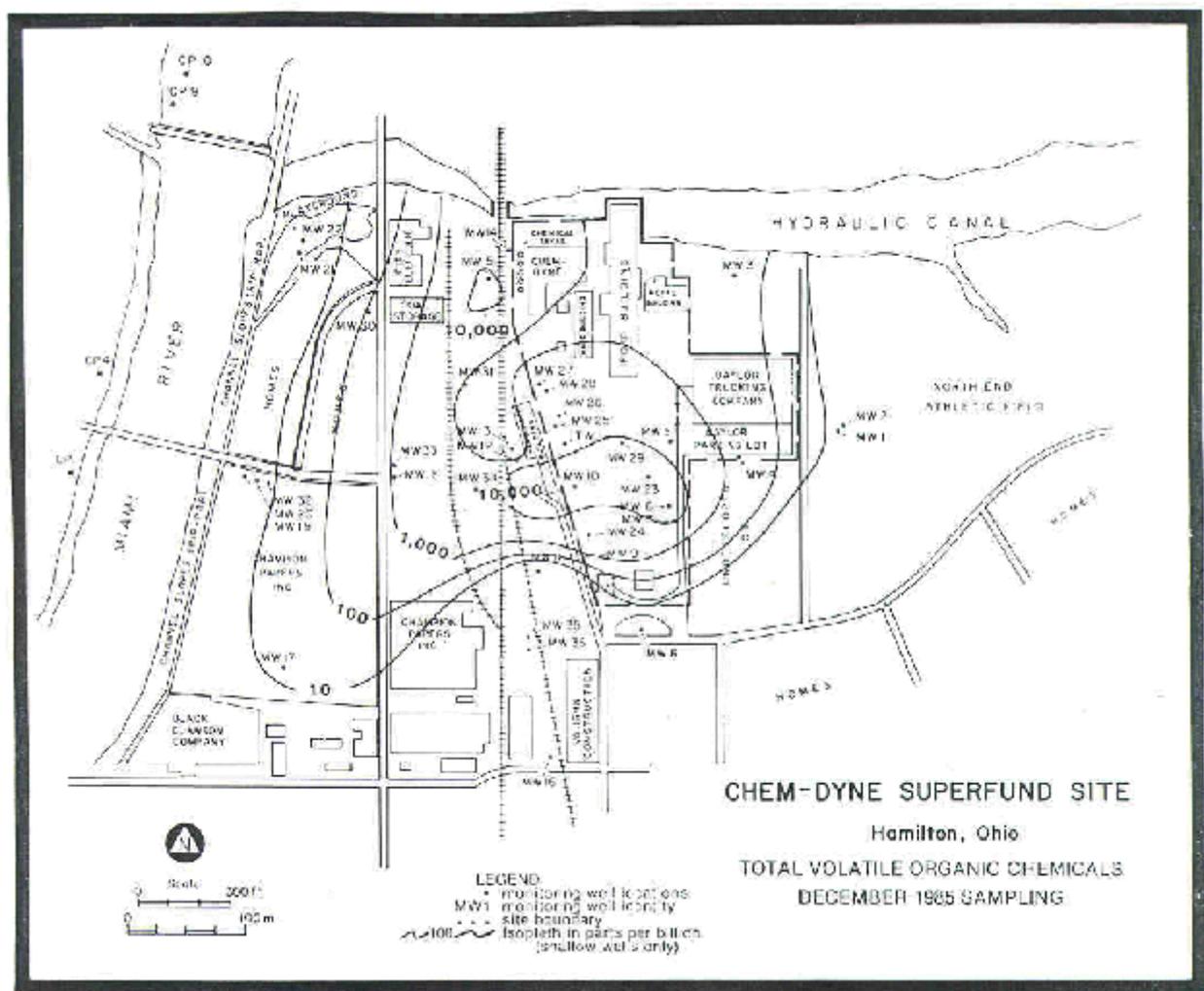


Figure 12.1 Contours of total VOC concentrations (ppb) at the Chem-/Dyne site in Hamilton, Ohio for shallow well data. December 1985 (Source: U.S. EPA, 1989b).

## **GRAPHICAL**

Graphical presentation can be helpful in visualizing areal distribution of contaminants, identifying changes in water quality with time, and comparing waters of different compositions. Typical methods include, but are not limited to, bar charts, XY charts, box plots, trilinear diagrams, and stiff diagrams.

### **Bar Charts**

Bar charts display a measured value on one axis and a category along the other. Historically, bar charts used in water quality investigations were designed to simultaneously present total solute concentrations and proportions assigned to each ionic species for one analysis or group of analyses. These charts displayed total concentrations and were based on data reported in milliequivalents per liter (meq/l) or percent meq/l. Analytes of ground water contamination studies are present as both ionic and non-ionic species and data are reported in units of mg/l or  $\mu\text{g/l}$ . For such studies, bar charts can be constructed to display concentrations of constituents for single or multiple monitoring wells and/or sampling events. The design and number of the charts should depend on the investigation. Figure 12.2 presents several examples of bar charts that may be useful.

### **XY Charts**

XY charts differ from bar charts in that both axes show measured parameters. Plots of changes in dissolved constituents with time is one example of an XY chart that is extremely useful when evaluating contaminant releases or remedial progress. Even with a relatively slow rate of flow, long-term monitoring can detect gradual changes. Time-series formats can be used to compare individual parameters for a single well with time, multiple parameters for a single well with time (Figure 12.3), or illustrate changes with time for multiple wells for a common parameter (Sara and Gibbons, 1991). It is important that care be used when evaluating data with different levels of quality assurance/quality control. Regulated entities are encouraged to supply data in graphical form showing each parameter for each well plotted against time.

### **Box Plots**

Box plots can be used to compare ground water quality data (generally for the same parameter) between wells. The plots are constructed using the median value and the interquartile range (i.e., 25 and 75 cumulative frequency as measured central tendency and variability) (U.S. EPA, 1992a) (Figure 12.4). They are a quick and convenient way to visualize the spread of data. Complicated evaluations may dictate use of a series of plots. For example, box plots may be constructed using data from wells screened in a particular saturated unit to show horizontal changes in water quality.

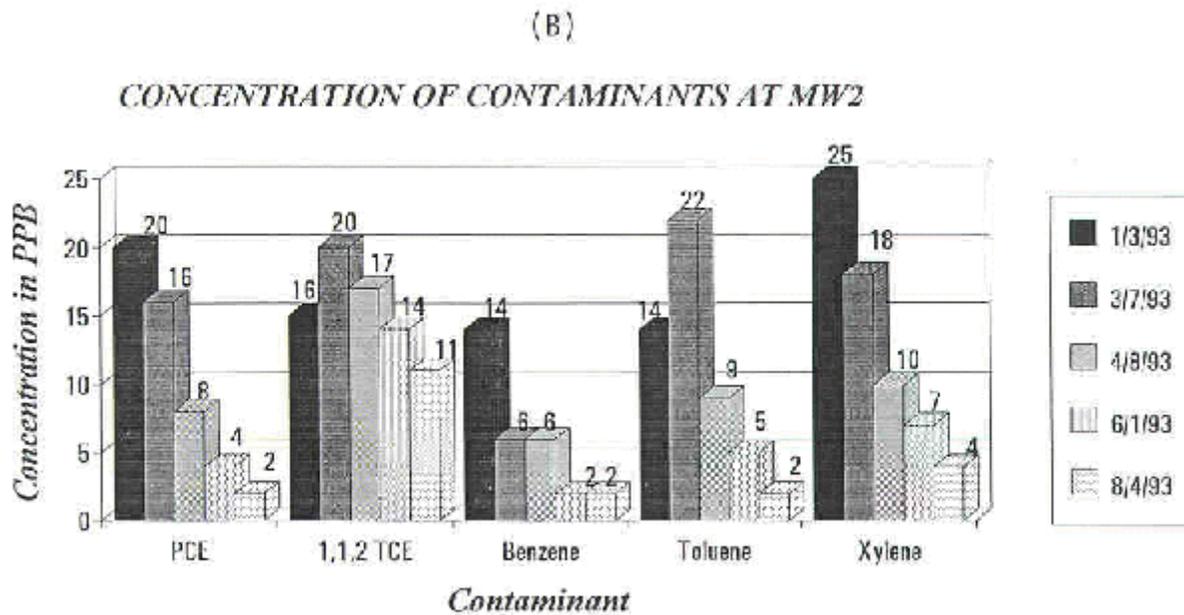
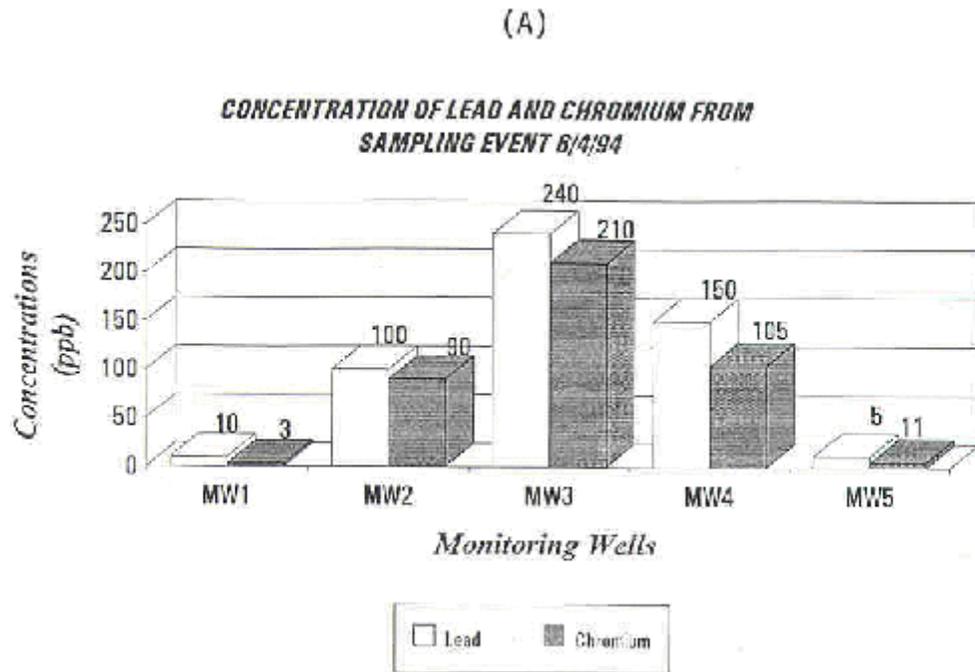


Figure 12.2 Bar Charts. A) Shows concentrations of lead and chromium for one sampling event. B) Shows concentrations of several constituents at one well over multiple sampling events.

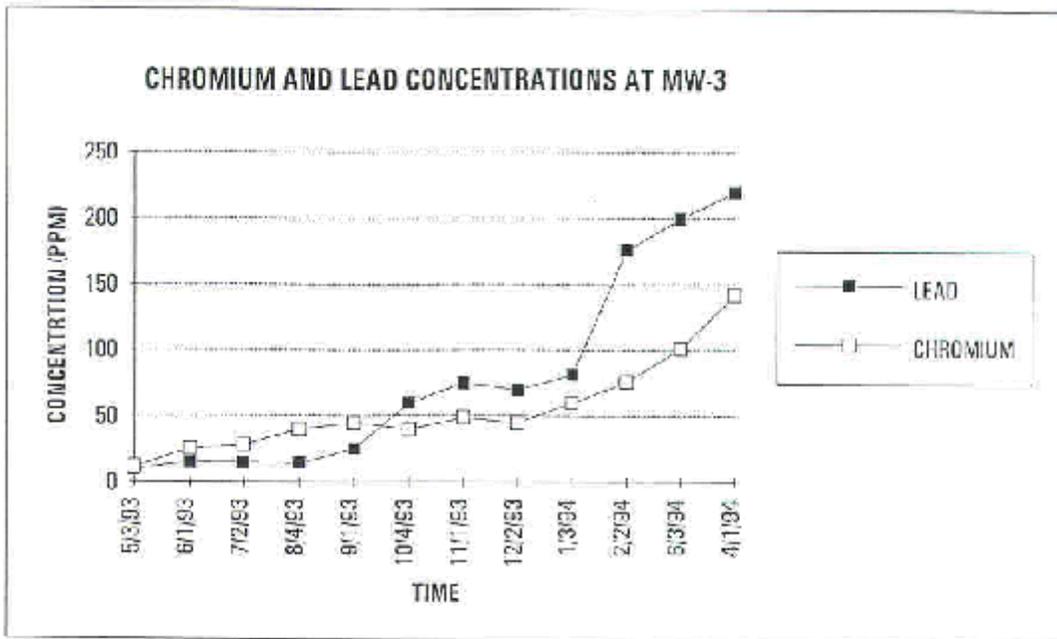


Figure 12.3 Chromium and lead concentrations over time.

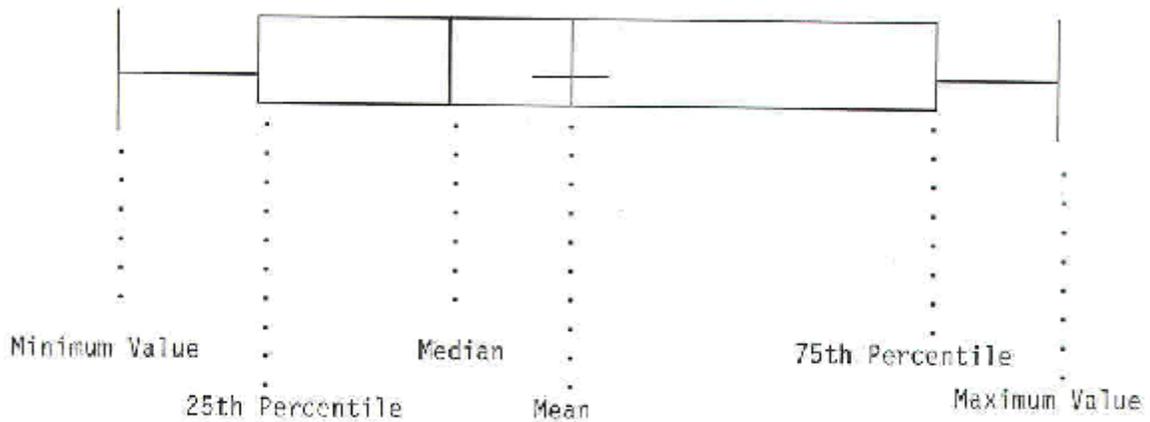


Figure 12.4 Example of a box plot

## Trilinear Diagrams

Trilinear diagrams are often used in water chemistry studies to classify natural waters (Sara and Gibbons, 1991). They can show the percentage composition of three ions or groups of ions and often are in the form of two triangles bracketing a diamond-shaped plotting field (Figure 12.5). These diagrams are useful in determining the similarities and/or differences in the composition of water from specific hydrogeologic units and are convenient for displaying a large number of analyses. The diagrams may help show whether particular units are hydraulically separate or connected and whether ground water has been affected by solution or precipitation of a salt.

The value of trilinear diagrams may be limited for some investigations. Composition is represented as a percentage. Therefore, waters of very different total concentrations can show identical representation on the diagram. Because non-ionic solutes (e.g., silica and organics) are not represented (Hem, 1985), trilinear diagrams often are not used when evaluating the presence or absence of contaminants.

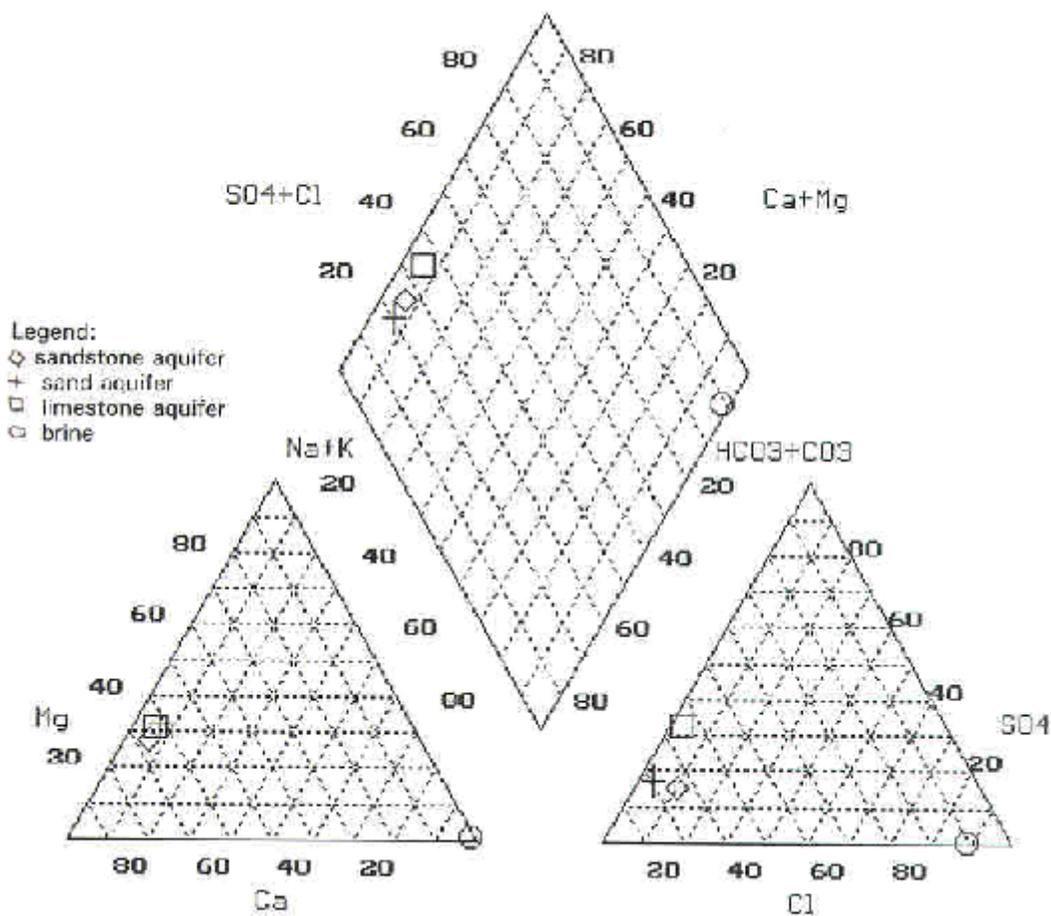


Figure 12.5 Trilinear diagram.

## **Stiff Diagrams**

Stiff diagrams are another graphical representation of the general chemistry of water. A polygonal shape is created from four parallel horizontal axes extending on either side of a vertical axis. Cations are plotted on the left of the vertical axis and anions are plotted on the right (Fetter, 1994). The diagrams can be relatively distinctive for showing water composition differences or similarities. The width of the pattern is an approximation of total ionic strength (Hem, 1985). One feature is the tendency of a pattern to maintain its characteristic shape as the sample becomes diluted. It may be possible to trace the same types of ground water contamination from a source by studying the patterns. In the case presented in Figure 12.6, seepage of salt water from a brine disposal pit was suspected. Samples analyzed from the pit and the wells demonstrated the same pattern, showing evidence of contamination (Stiff, 1951).

## **STATISTICS**

Ground water quality data also can be evaluated by statistical analysis. This tool can be used to compare upgradient versus downgradient or changes with time. Various regulatory programs may require use of statistics. The reader is referred to Statistical Analysis of Ground Water Monitoring Data at RCRA Facilities (U.S. EPA, 1989a), the addendum to that document (U.S. EPA, 1992b), and Chapter 13 for appropriate methodologies.

## **MODELING**

Ground water modeling is a tool that can assist in the determination of extent and rate of contaminant migration. Models can be used throughout the investigation and remedial processes. Information on modeling can be found in Chapter 14.

## **DATA INTERPRETATION OBJECTIVES**

The mechanism to interpret ground water quality data can vary depending on project objectives and regulatory or program requirements. Data often are evaluated to: 1) determine if a site/facility has impacted ground water (detection monitoring), 2) determine the rate, extent, and concentration of contamination (assessment monitoring), 3) determine the source of contamination, 4) gauge the effectiveness of remedial activities, and/or 5) monitor for potential health or environmental effects. Data must always be evaluated in conjunction with site hydrogeology, contaminant characteristics, and past and present land use.

## **IDENTIFICATION OF RELEASES TO GROUND WATER**

Methods to identify whether contaminants have been released to ground water include professional judgment and statistical analysis.

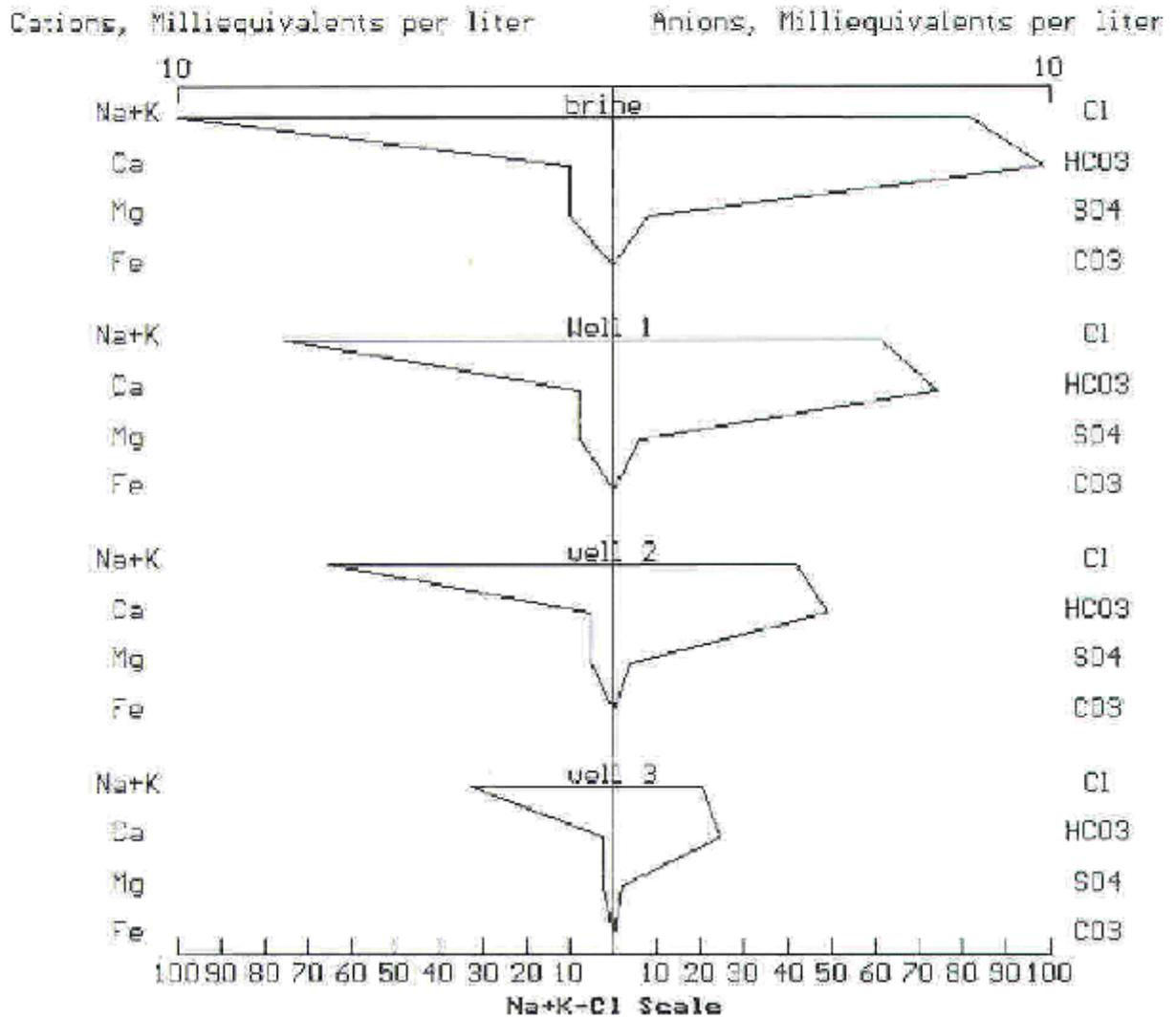
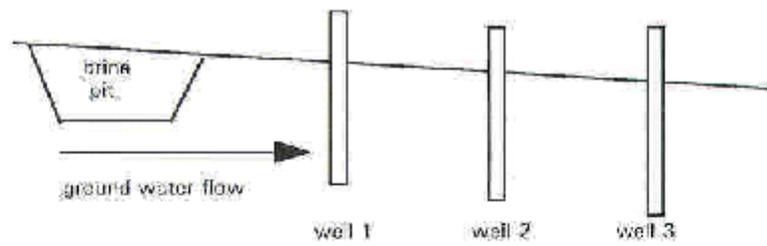


Figure 12.6 Stiff pattern demonstrating seepage of a salt from a brine disposal pit.

**Professional judgment** involves the use of education and experience. In some cases, a simple visual inspection of downgradient versus upgradient/background data can show obvious differences in chemical quality. The tabular and graphical presentations discussed earlier in this chapter can be used for this evaluation.

When evaluating potential ground water contamination, water quality data often are compared to primary and secondary drinking water standards. As important as it is to protect public health by identifying an exceedance, formulating a conclusion that ground water has been contaminated based solely on the exceedance is not appropriate. Certain inorganic constituents, such as iron and sulfate, can occur naturally in Ohio's ground water at levels above standards; therefore, exceedance for these constituents may not imply contamination. Conversely, values lower than a standard do not necessarily imply that contamination has not occurred. In general, the mere presence of organics, which usually are not naturally occurring, indicates contamination. Data for wells downgradient from a pollution source should be compared to data from an upgradient/background well that has not been affected by the source. If an upgradient/background well does not exist, then the results can initially be compared to known local or regional background values. However, utilization of regional values for evaluating potential contamination should be a part of initial investigations only. Further evaluation should be based on site-specific background sampling. In any ground water contamination investigation, it is essential to obtain background concentrations for chemical constituents of concern, particularly those that may be common to both the local ground water quality and the potential or known contaminant source.

Whether a release has occurred also can be evaluated by **statistical analysis** if adequate data are available. The U.S. EPA (1989a, 1992b) documents and Chapter 13 should be used to determine appropriate methods and application. While statistics are useful to determine if a release occurred, professional judgment still needs to be exercised to ensure that the results represent actual conditions. For example, the results may show either a "false positive" or "false negative" due to naturally occurring variations such as geologic heterogeneity and/or seasonal variability. Determining whether a release has occurred or whether the analysis has triggered a "false positive" generally requires additional investigation.

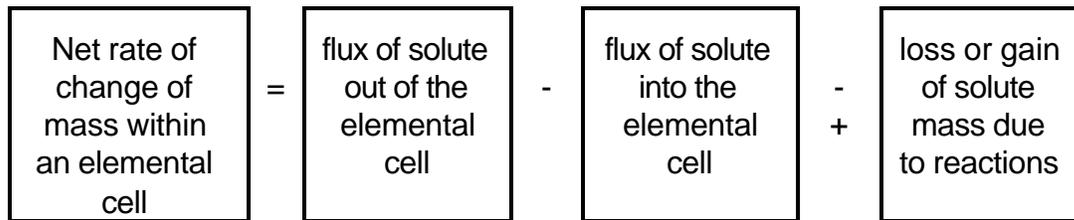
## **RATE OF CONTAMINANT MIGRATION**

A simple and straight forward method does not exist for determining the rate of contaminant migration. In general, the rate can be estimated by a form of Darcy's Law (see Chapter 3) if it is assumed that the dissolved solute travels at the average linear ground water velocity. The rate of advancement of a dissolved contaminant can be substantially different, however. Mobility of a contaminant can be altered due to adsorption/desorption, precipitation, oxidation, and biodegradation. Mobility of a solute can be affected by the ratio of the size of the molecule to the pore size. The calculated velocity also would not account for a contaminant moving faster than the average linear velocity due to hydrodynamic dispersion. Dispersion affects all solutes, whereas<sup>1</sup> adsorption, chemical reactions, and biodegradation affect specific constituents at different rates. Therefore, a contaminant source that contains a number of different solutes can result in several plumes moving at different rates.

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<sup>1</sup> See Chapter 5 for additional explanation on how these parameters influence ground water flow paths.

The equation governing the movement of dissolved species can be developed by utilizing the conservation of mass approach. The equation in statement form, as described by Canter et al. (1988), is:



The mass of solute transported in and out of the cell is controlled by advection and dispersion. Loss or gain of solutes within the cell may be caused by chemical, biological, or adsorption/ desorption reactions. A generalized three-dimensional solute transport equation considering dispersion, advection, and reactions in a homogeneous environment takes the form as (modified from Freeze & Cherry, 1979):

$$\frac{MC}{Mt} \cdot \left[ \frac{M}{M_x} \left( D_x \frac{MC}{M_x} \right) \% \frac{M}{M_y} \left( D_y \frac{MC}{M_y} \right) \% \frac{M}{M_z} \left( D_z \frac{MC}{M_z} \right) \right] \quad \text{Dispersion}$$

$$\& \left[ \frac{M}{M_x} (\bar{v}_x C) \% \frac{M}{M_y} (\bar{v}_y C) \% \frac{M}{M_z} (\bar{v}_z C) \right] \quad \text{Advection}$$

$$\pm F(c) \quad \text{Reaction}$$

Where:

- $C$  = the concentration of the polluting substance;
- $D_x, D_y, D_z$  = the coefficients of hydrodynamic dispersion in the x, y, z directions;
- $v_x, v_y, v_z$  = velocity vector components in the x, y, and z directions; and
- $F(c)$  = chemical reaction function.

Attempts to quantify contaminant transport generally rely on solving conservation of mass equations. There are essentially two kinds of models available for solving mass transport equations, analytical and semi-analytical, and numerical. Analytical models are developed by considering ideal conditions or using assumptions to simplify the governing equation. These assumptions may not allow a model to reflect conditions accurately. Additionally, even some of the simplest analytical models tend to involve complex mathematics. Numerical modeling techniques incorporate analytical equations that are so complex they necessitate use of computers capable of multiple iterations to converge on a solution (Canter et al., 1988). The numerical approach depends on tedious sensitivity analyses to develop information on the nature of the parameter interaction. Analytical models are used to verify the accuracy of numerical solutions where appropriate. Additional information on numerical, computer-oriented models can be found in Chapter 14.

## EXTENT OF CONTAMINANT MIGRATION

The areal or vertical extent of contaminant plumes may range within wide extremes depending on local geologic/hydrogeologic conditions. Determination of extent generally involves sampling monitoring wells at increasing distances and depths from the source. Data for wells downgradient

of the site/facility are compared to background data by visual inspection and/or statistical analysis. All downgradient locations at which significant differences are noted are considered to be within the contaminated area. The use of isopleth maps and time-series formats assist in the determination of extent. Modeling (Chapter 14) can be used to help estimate rate and extent and determine optimum locations for monitoring wells.

## **SOURCE OF CONTAMINATION**

Ground water quality data often are evaluated to determine the source of contamination. In general, isopleth and ground water contour maps are utilized in conjunction with knowledge of area-specific geologic/hydrogeologic characteristics, contaminant properties, and past and present land use to pinpoint the source.

## **PROGRESS OF REMEDIATION**

When gauging the effectiveness/progress of remedial action, changes in water quality can best be illustrated by time-series presentations and a series of isopleth maps prepared throughout the proceedings. The data should be compared to background or standards developed by risk assessment.

## **RISK ASSESSMENT**

Clean-up goals often are established by means of a risk assessment. Both human health and environmental assessments can be conducted. The appropriate methodology depends on the regulatory program involved. Therefore, prior to conducting a risk assessment, the appropriate Ohio EPA Division should be consulted.

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**TECHNICAL GUIDANCE MANUAL FOR HYDROGEOLOGIC  
INVESTIGATIONS AND GROUND WATER MONITORING**

**CHAPTER 13  
STATISTICS FOR GROUND WATER QUALITY COMPARISON**

**February 1995**

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## CHAPTER 13

### STATISTICS FOR GROUND WATER QUALITY COMPARISONS

The statistical evaluation of data resulting from the chemical analysis of ground water is required by Ohio's regulations for Part B permitted hazardous waste land disposal facilities [OAC 3745-54-97(G)], Part A permitted hazardous waste land disposal facilities [OAC 3745-65-93], and permitted municipal solid waste [OAC 3745-27-10(C)(6)], residual waste [OAC 3745-30-08(C)(5)], and industrial waste landfills [OAC 3745-29-10(C)(6)]. Additionally, statistics can be employed for wastewater facilities (including non-toxic flyash, bottom ash, foundry sand and coal storage piles) and in corrective actions at regulated and unregulated hazardous waste sites. This chapter is intended to address only those statistical evaluations performed for Part B permitted hazardous waste land disposal facilities, permitted municipal solid, residual, and industrial waste landfills, and wastewater facilities. This chapter pertains to Part A permitted hazardous waste land disposal facilities only if the owner/operator has entered into an agreement with the Director of Ohio EPA to utilize methods identified in OAC 3745-54-97 in place of those specified in OAC 3745-65-93. Regarding the methods mandated by OAC 3745-65-93 (i.e., the Student's T-test and the Average Replicate Test), the reader is referred to the U.S. EPA's Technical Enforcement Guidance Document (U.S. EPA, 1986).

Statistical analyses are used to compare the chemical ground water quality of a monitored zone downgradient of the waste management unit with either: 1) a standard set in a permit, 2) the chemical ground water quality from a background (or upgradient) well screened in the same monitored zone and unaffected by facility operations, or 3) historic concentrations from the same well. These comparisons provide reliable determinations as to whether a waste management unit has influenced the quality of the ground water. Statistics can also be used to define the extent of ground water contamination. If no statistically significant difference is observed between a downgradient well and background, the well is statistically considered beyond the plume of contamination.

U.S. EPA has issued the Guidance Document on the Statistical Analysis of Ground Water Monitoring Data at RCRA Facilities, (U.S. EPA, 1989) and an addendum to the same document (U.S. EPA, 1992). The Ohio EPA recommends the methods outlined in the U.S. EPA guidance. Additionally, U.S. EPA has developed a data management tool designed to facilitate the storage, analysis and reporting of data collected through ground water monitoring programs. The statistical portion of the program incorporates the most frequently used statistical methods for ground water monitoring. This tool is called the Ground Water Information Tracking System with Statistical Analysis Capability (GRITS/STAT or GRITS).

This chapter supplements and clarifies the U.S. EPA's guidance with regard to the number of different statistical methods required per facility, independent samples, determination of a background data set, initial year sampling frequency, and corrections for seasonal fluctuations. In addition, fixed and variable requirements or assumptions of the most frequently used statistical methods are discussed. These assumptions include minimum sample size, distribution, variance, treatment of non-detects, and comparison and experimentwise errors. Finally, recommendations for submittals of statistical information are outlined. It is recommended that the U.S. EPA guidance documents be reviewed before reading this chapter.

## BASIC STATISTICAL ASSUMPTIONS

Whether starting from scratch with a new database or building on an established database, the first steps in determining whether a statistically significant difference has occurred should be the same. Before choosing the statistical method, an evaluation must be made as to whether the available site-specific data meet a few basic assumptions necessary for a particular test to perform with the greatest accuracy and power, power being the probability that the test will correctly identify contamination when it is present. Assumptions basic to all methods include independence of samples, determination of the background data set, sampling frequency, and corrections for seasonality.

### INDEPENDENT SAMPLES

**Statistical analysis is based on the assumption that all data points are generated independently of each other.** For ground water samples to be independent of each other, enough time must pass between sampling events to ensure that the previously sampled ground water has left the vicinity of the monitoring well and that "new" ground water is being sampled. At the same time, the sampling interval must be short enough to provide "immediate" detection of contamination.

Ohio Hazardous Waste Regulations, OAC Rule 3745-54-97(G)(1), 98(D) and 99(F) and (G), require the collection of independent samples for permitted facilities. Wastewater policy and solid waste regulations do not state specifically that independent samples must be collected, but solid waste regulations do state that the sample number must be appropriate for the statistical method chosen (OAC Rule 3745-27-10(C)(9)). To perform a valid statistical test, including the collection of independent samples, the time interval between sampling events should be based on the average linear velocity of ground water for the zone being sampled. The sampling interval is determined after evaluating the monitored zone's effective porosity, horizontal hydraulic conductivity, hydraulic gradient, and the fate and transport characteristics of potential contaminants. U.S. EPA (1989) outlined the method used to determine the sampling interval necessary to obtain an independent sample.

For wells recovering reasonably quickly, it may be possible to collect multiple independent samples in one scheduled event by purging a well thoroughly, collecting the first independent sample, then repurging the well and collecting the second independent sample, etc., until all necessary samples have been collected. If a regulated entity proposes this option, it must supply data indicating the recharge rate of the well. However, to develop a representative background ground water quality database, temporal and seasonal water level (and parameter) variations must be accounted for. In other words, just because there is adequate recharge does not mean that the complete background data set may be collected at one sampling event.

Generally, replicate samples are unacceptable for statistical analysis because the information they provide indicate only the accuracy of the laboratory, not the ground water quality. When more than one sample is collected for the same parameter from the same bailer or same aliquot of ground water, the samples are considered replicate samples. Replicates are not recommended as they offer less variability than independent samples. If, however, replicates have been obtained as part

of the original background data for hazardous waste Part A Interim Status ground water monitoring, and the Ohio EPA approves the use of this data as background for Part B permitted status statistical analyses, the replicate values should first be averaged and the means used in the statistical analyses.

## **DETERMINATION OF BACKGROUND DATA SET**

**For all statistical methods employing the use of pooled background data, the background data set should be such that it reflects naturally occurring changes in hydrogeology.** A moving background data set is recommended using data from only the eight most recent sampling events. This will help minimize temporal variability (Sara, 1991). During the initial year of monitoring, only the background or upgradient well(s) should be used as background when comparing up to downgradient values. In subsequent years, the background levels, whether using up to downgradient or intra-well comparisons, should be modified during each monitoring event so that the eight most recent values are used. When intra-well comparisons are being performed (e.g., control chart) the background database must be from an uncontaminated well.

## **SAMPLING FREQUENCY**

***Minimum sampling frequency shall be consistent with the appropriate statistical method chosen.*** The Ohio hazardous waste rules require ***at least*** semi-annual sampling for detection monitoring (OAC Rule 3745-54-98(D)), while solid waste rules (OAC Rule 3745-27-10(D)(5)) require ***at least*** semi-annual monitoring for the initial year. However, to determine initial background values, sampling must be appropriate for the statistical method chosen (OAC Rule 3745-54-97(G)). The hazardous or solid waste permit should outline the sampling frequency necessary to achieve the minimum sample size, which may oblige the permittee to sample ***more than*** what appears to be regulatorily required.

## **CORRECTIONS FOR SEASONALITY**

***Only when strong empirical evidence is present to indicate that seasonality exists should corrections for seasonality be made.*** If seasonality is present in a data set, Ohio hazardous and solid waste regulations require procedures be used to control or correct for it. The following methods are available: 1) Two-way ANOVA, which attributes variations to seasonal as well as spatial differences, 2) U.S. EPA (1989) provided a simple method for calculating the monthly or quarterly effects attributable to seasonal variations, and 3) Seasonal Kendal Test (Gibbons, 1994). Tolerance intervals tend to be self-correcting for seasonality since seasonal effects show up in both upgradient and downgradient wells.

## **STATISTICAL ASSUMPTIONS THAT VARY WITH METHODS**

Once the basic assumptions have been met or the data set has been transformed to meet the basic assumptions, a statistical method may be chosen. The next step in making the choice is to determine the best fit between the site-specific data available and the specific assumptions that allow each method to perform with the greatest accuracy and power. Assumptions that vary

between methods include minimum sample size, determination of distribution, homogeneity of variance, treatment of non-detect parameter levels, and experimentwise and comparisonwise errors. Another factor to take into account for each of the following assumptions is, as the-site specific database changes over time, it may be necessary to change to a different statistical method.

## MINIMUM SAMPLE SIZE

Statistical methods must employ a certain minimum sample size to yield both statistically and hydrogeologically valid results. The term "sample size" reflects the number of observations for each parameter taken per well. Minimum sample size requirements are provided below for common methods. Although it is possible to perform the calculations and obtain mathematically valid results using fewer independent samples for some statistical methods, the minimum sizes are designed to yield hydrogeologically valid results. Permit applicants should be aware that during the initial year of monitoring, the *minimum* sampling frequency is semi-annual and that more frequent sampling may be necessary, depending on the statistical method chosen, the hydrogeologic environment, and the objectives of the study. Over time, the minimum sample size may be met, allowing the use of a different statistical method.

- **ANOVA (*Parametric or normally distributed*):** The minimum sample size for analysis of variance (ANOVA) should result in at least ten (10) degrees of freedom for error (or within groups) variance. The number of degrees of freedom is the number of ways the sample may be changed without having to produce any change in the constraining factors. For ANOVA, the total number of wells should be equal to or greater than two (2). The degrees of freedom are calculated using the equation  $N-p$ , where:

$N$  = total number of observations; and  
 $p$  = total number of wells.

**Example:** Quarterly sampling from four (4) wells will give twelve (12) degrees of freedom ( $N-p=16-4=12$ ).

U.S. EPA (1989) recommends that  $N - p$  be greater than 5 with  $p \geq 2$ , and with at least three (3) observations per well. However, if  $p$  (the number of wells) = 2, then the test is essentially equal to the t-test. Care should be exercised with small sample sizes because they may lead to false positives (statistical test indicating contamination when none exists) and false negatives (statistical test indicating no contamination exists when, in fact, there is contamination). It is better to recommend a minimum of 10 degrees of freedom, with the number of wells being equal to/greater than 2 ( $N - p \geq 10, p \geq 2$ ).

- **ANOVA (*Non-parametric or non-normal distribution*):** The minimum sample size required for Non-parametric ANOVA (ANOVA based on ranks) is at least three (3) wells with at least three (3) observations in each well ( $N-p=9-3=6$ ). Ohio's solid waste regulations require that a minimum of four (4) independent samples be taken from each well during the initial 180 days of monitoring, so there will be at least four (4) independent observations per well initially.

- **Tolerance Interval:** The minimum sample size for constructing a Tolerance Interval is at least eight (8) independent background observations from each well. Tolerance interval calculations can be made with as few as three (3) observations; however, this would result in a large upper tolerance limit due to the increased tolerance factor (K) associated with smaller sample sizes.
- **Prediction Intervals:** The minimum sample size for constructing prediction intervals should result in at least ten (10) degrees of freedom. Degrees of freedom for tolerance intervals are calculated using the equation  $n - 1$ , where  $n$  = number of observations in the background data (so at least 11 independent samples are needed). While eight (8) samples may be used, ten (10) or more are recommended. The prediction limit should be recalculated at least annually to update the background for upgradient changes.
- **Control Charts:** The minimum sample size required for control charts is eight (8) observations in **each** well. This requires that eight **independent** samples be collected over a one year period for each well.

## DETERMINATION OF DISTRIBUTION

Normal distribution is based on the Central Limit Theorem, which states that sums and averages of random variables tend to be normally distributed. Normality deals with average behavior and average variability of behavior. Distribution is important in ground water monitoring because determination of population characteristics are being made based on limited information contained in a set of data. The most common example of normal distribution is the bell-shaped curve. The assumption that all samples are independent is required.

If data is normally distributed, parametric methods of analysis may be applied. When data is neither normally or log-normally distributed, non-parametric methods are most commonly be used. Parametric methods may be applied to non-normally distributed data and non-parametric tests may be applied to normal data. Non-parametric methods are more efficient, or powerful, when data is normally distributed than parametric methods when if data is not normal.

Skewness measures the degree of symmetry of the sample distribution. Normal data has a skewness coefficient of 0. If the data is neither normally or log-normally distributed, is positively skewed, and an indication exists that the distribution is skewed to the right, the statistician should proceed as if the data was log-normal using non-parametric tests or try another type of transformation. Parametric tests lose power when the skewness coefficient is  $> 1.0$ . If the same case exists and the data is negatively skewed, indicating a shift to the left, Cohen's adjustment for non-detect data or non-parametric tests should be used. If the skewness is equal to zero, a perfect bell-shaped curve exists.

Kurtosis is the area under the distribution curve. The greater the spread of the data distribution, the lower and broader the peak of the distribution curve will be. Kurtosis measures the degree of peakedness of the sample distribution. It is measured relative to the normal distribution curve. Normal kurtosis is  $= 0$ . As the kurtosis coefficient becomes greater, the peakedness decreases and the curve spreads out, indicating a broader distribution of values. As the kurtosis coefficient

decreases (below 0), the peak of the distribution curve becomes higher and more peaked, indicating that the distribution is centered around a narrow range of values (Ott, 1977).

## TRANSFORMATION OF DATA TO ACHIEVE NORMAL DISTRIBUTION

It is critical in any statistical evaluation to determine whether the data is normally distributed. If the original data does not have a normal distribution, transformations should then be attempted to achieve normality, as most statistical tests have the underlying assumption that the data has a normal distribution. The most accepted method is log-transformation. Log-transformations are most useful when the ratio of the largest to the smallest value in a data set is greater than 20. While U.S. EPA (1992) gives log transformations as the default method, the Ohio EPA recommends both original and log-transformed data be evaluated to find the best fit. Transformations other than logging the data, such square root, reciprocal and cube root, while less standard, may also be applied. If normality cannot be achieved, Non-parametric tests should be used.

## NORMALITY TESTS

Many different tests are available to determine if data is normally distributed. The following discussion will describe the minimum requirements necessary to perform the eight most common normality tests, Shapiro Wilk, Shapiro Francia, Chi Squared, Coefficient of Variation, Probability Plots, Kolomorgorov-Smirnov, Skewness Coefficient, and Kurtosis. All of these tests are available in GRITS.

- **Shapiro Wilk:** Shapiro Wilk is considered the best numerical test of normality. It is the most powerful for detecting departures from normality in the tails of a sample distribution. It is useful for sample sizes ranging from 3 to 50 and data must be log-transformed before performing the test
- **Shapiro Francia:** While Shapiro Francia has the same benefits as Shapiro Wilk, it is best used for sample sizes larger than 50. It also should be used on log-transformed data.
- **Chi Squared ( $X^2 = Mean^2$ ):** Chi Squared is not the most powerful test, as it does not indicate *how* the data is not normal. If the departure from normality is in the tails instead of the middle of the data, Chi Squared may not register it as significant.
- **Coefficient of Variation:** This test is easy to calculate: if  $S/X > 1$  ( $S/X =$  Standard Deviation/ Mean), the distribution is not normal. While this test is good for small sample sizes, it is not a reliable indicator of model appropriateness. Its true purpose is to estimate skewness, not normality.
- **Probability Plots/Correlation Coefficient:** This method measures the strength of the linear relationship between two variables, normal distribution, and the test group. The test group value should, if normal, fall in a straight line with the proportion of observations less than or equal to each observed value. The correlation coefficient is = 1.) If no relationship exists between the two groups, the correlation coefficient = 0. This test is a good indicator of skewness and the presence of outliers.

- **Kolmogorov-Smirnov Test (Cheeney, 1983):** The Kolmogorov-Smirnov test graphically evaluates the fit of the distribution (the goodness of fit).
- **Kurtosis:** Kurtosis measures the thickness of the tails in a distribution. Normal distribution has a kurtosis of 0.
- **Skewness Coefficient:** The skewness coefficient measures the degree of symmetry in the distribution. Normal distribution has a coefficient of 0. Parametric tests lose power when the skewness coefficient is  $> 1.0$ .

## HOMOGENEITY OF VARIANCE

Variance is the variation or skewness between the parameter levels in the wells being compared, typically downgradient and background wells. It estimates the amount of spread or variability of the data. Homogeneity of variance assumes that all the wells being compared have the same skewness or variance. If this assumption is not true, if the wells do not have close to the same distribution, then the ability of a method to detect differences between the group means is reduced. Methods such as ANOVA assume homogeneity of variance; however, in reality this situation almost never exists. Limitations and uses are described below for the two most commonly used methods of evaluating homogeneity of variance: Box Plots and Levene's Test. Box Plots are covered briefly in Chapter 12. Both tools are available in GRITS.

- **Box Plots** provide a quick way to visualize the spread of data using a graphical display. If the longest and shortest box lengths differ by a ratio of greater than 3, Levene's test should be performed for homogeneity of different groups. Box plots are a pre-requisite to performing Parametric ANOVA.
- **Levene's Test** evaluates the homogeneity of variance between compliance wells and **pooled** background wells. It may be used with either a normal or non-normal data distribution. Variances of different wells are assumed to be approximately equal. Central to the test is the calculation of the F-statistic, which is the detection of differences among group means. If the F-statistic is not significant, variances are approximately equal. If the F statistic is significant, the groups do not have equal variance, and the non-parametric Kruskal Wallis test should be employed. Levene's test may be used as a One-way Parametric ANOVA test.

## TREATMENT OF VALUES BELOW THE DETECTION LIMIT (NON-DETECTS)

If there are less than or equal to 15% non-detects in the total number of measurements analyzed for each parameter, the value of each non-detect should be substituted with one-half the practical quantification limit (PQL) for the parameter (Gibbons, 1992). If 15 to 50% non-detects are present, either use a non-parametric ANOVA test or adjust the original data and proceed with a parametric test. If a method involving intervals is being employed, use either Cohen's or Aitchison's Adjustments. Cohen's Adjustment assumes that the non-detects indicate a low but positive concentration. Aitchison's adjustment assumes that the non-detects represent a true zero

concentration. When 50 to 90 % of the results are non-detects, switch to non-parametric rank methods or use Poisson-based non-parametric prediction or tolerance intervals. (However, Wilcoxin Rank Sum is most powerful at 15% <ND < 50%.) If there are 90-99% non-detects, use the Poisson-based non-parametric prediction or tolerance intervals. If 100% of the samples are non-detect, do not employ statistics.

In order to choose between Cohen's and Aitchison's adjustments, consideration should be given as to whether contamination is present. If so, Cohen's Adjustment may be preferred. Additionally, parameter characteristics should be considered. Non-detects for naturally occurring parameters may indicate a low but positive concentration. In this case, Cohen's Adjustment should be used. If the parameter is a common lab contaminant, Aitchison's Adjustment should be chosen.

## ERRORS

Two types of errors, experimentwise and comparisonwise, are common when performing statistical analysis. Comparisonwise error is based on the false positive rate associated with a single well comparison. Experimentwise error is based upon the total number of statistical tests being performed.

### Comparisonwise Error

There are two types of statistical comparisons, paired and multiple. A paired comparison compares one upgradient well with one downgradient well. Multiple comparisons exist when downgradient data is pooled and then compared with upgradient data. Examples of paired comparisons using parametric tests would be the Student t and Average Replicate tests. The Wilcoxin Rank Sum test is a paired comparison test that works well when the data is not normal (non-parametric) and when a large number (even greater than 50%) of non-detects are present, as it is based on ranks rather than actual concentrations.

Multiple comparisons arise where there are multiple compliance wells and multiple parameters per well. If one test is run in every well for each parameter, a large number of tests will be needed. The larger the number of tests, the greater the chance of error. In particular, with increasing comparisons, a corresponding increase in the false positive error rate occurs (i.e., for every 100 tests, 5% of the tests should be expected to be false positives).

### Experimentwise Error

Statistics are based on the null hypothesis, that is that there is no real difference between the value of a sample in the population sampled and the hypothesized value of the sample; in other words, the assumption is that there will be no contamination. There are two types of errors associated with accepting this hypothesis:

- **Type 1 or False Positives ("Hanging the Innocent"):** Rejection of a true null hypothesis. If there is indeed no contamination (a true null hypothesis) and the statistical test indicates that contamination exists, a false positive has occurred.

- **Type 2 or False Negatives (“Freeing the Guilty”)**: Acceptance of a false null hypothesis. If the null hypothesis is false, meaning there is indeed contamination, and the statistical test indicates no contamination, a false negative has occurred.

The goal is to minimize both Type I and Type 2 errors. When using ANOVA, the experimentwise error level (Type I, or false positive error) should be less than or equal to five (5) percent for each testing period. This means that, for the upgradient to downgradient well group comparisons, the Type 1 (alpha) error level should be less than or equal to five (5) percent. For individual well comparisons, the error level (Type I error) should be less than or equal to one (1) percent. If there are more than five downgradient wells, each individual well comparison must be made at the one percent error level. The experimentwise five percent error should not be divided by the number of downgradient wells because this may result in an individual error level of less than one percent. If the false positive rate increases, the statistical test will become less powerful.

The power of a statistical test indicates its sensitivity and the probability that the test will indicate actual contamination. The goal is to have the power be as high as possible. If the basic assumptions of each test are met, the maximum power will be employed. The power to detect differences tends to increase as the alternative mean moves farther from the null hypothesis (or as the value from an individual well moves further from the mean of the background database).

## METHODS

The following section provides a very general discussion of specific uses and problems associated with the most common statistical methods not addressed in U.S. EPA (1989). This document, along with its Addendum, provide a further discussion of each method as well as sample calculations.

Each constituent that must be statistically analyzed may require a different statistical method; for example, inorganic parameters such as chloride or certain metals may be detected during every sampling event with very few non-detects, thereby allowing analysis using a parametric method. Other parameters with a large percentage of non-detect values may require a non-parametric approach. All statistical assumptions (e.g., data distribution, normality, variance) must be tested and validated upon the designated data set prior performing the statistical test. The statistical test must be appropriate for each constituent's data set.

### ANOVA

**ANOVA (parametric one way)** compares background values to several compliance wells at once. It is a powerful test when only a small amount of data is available. It is also recommended when ground water velocity is higher than average due to the fact that simultaneous testing of multiple compliance wells requires many independent samples. The purpose of ANOVA is to assess whether the average concentration (mean) at any compliance well is significantly higher than mean background level. **Two-way ANOVA** is used to correct for seasonal variations. Both are available in GRITS/STAT.

Problems associated with ANOVA are: 1) pooling of downgradient data results in a slower detection of a release; 2) ANOVA commonly indicates a statistically significant difference when small consistent spatial differences in ground water geochemistry exist (which often occurs across a waste disposal facility); 3) both parametric and non-parametric ANOVA assume homogeneity of variance, a condition that almost never exists in reality; 4) ANOVA does not adjust for multiple comparisons due to multiple constituents which results in an increased rate of false positives and negatives (Gibbons, 1993); and 5) ANOVA is not good at detecting a narrow plume that may affect only 1 out of 10 or 20 monitoring wells.

**ANOVA (non-parametric)** analysis includes the Kruskal Wallis and Wilcoxin Rank Sum tests, which are based on ranking the order of the combined background and compliance data, followed by a comparison of the relative rank of each group. This test is very powerful when the distribution of the data set is non-normal. Non-parametric ANOVA may be used whenever parametric ANOVA is appropriate. Non-parametric methods are more powerful if data is normally distributed than parametric methods are if data is not normal. Many of the same problems exist with non-parametric ANOVA as did with parametric ANOVA (i.e. assumption of homogeneity of variance). In addition, the non-parametric method requires more observations than the parametric ANOVA. It, too, is available in GRITS/STAT.

## TWO-SAMPLE TESTS

**Wilcoxin Rank Sum and T-Test** are examples of two-sample tests. The Wilcoxin Rank Sum test is based on a comparison of 1 background to 1 compliance well, while the T-test compares a pooled background data set with 1 compliance well. The Wilcoxin Rank Sum test does not require normality of distribution, while the T-test does. The power of the two tests is greatest when the percent of non-detects is between 15 and 50%. Both are available in GRITS/STAT.

## INTERVALS

Due to the fact that the width of tolerance, prediction and confidence intervals (limits) may be very different for the same data set, it is important to distinguish the purpose for using intervals before choosing the type of interval to be used. Typically, based on the same data, tolerance intervals (TI) will have the widest limits followed by prediction (PI), then confidence (CI). (TI > PI > CI).

Tolerance and prediction intervals are calculated by comparing background or intra-well data against downgradient sample values. Confidence intervals are computed by comparing downgradient values against a fixed standard such as an ACL or MCL. When using tolerance and prediction intervals, significant evidence of contamination is indicated by any value from either a downgradient or compliance well exceeding the upper 95% tolerance or prediction limit. Statistical evidence of contamination using confidence intervals is indicated when the lower limit of the interval is above the fixed standard. Parametric tolerance and prediction intervals must be normally or log-normally distributed. Typically, log-normal data is used.

The important difference between tolerance and prediction intervals is the definition of "population" or "k". Tolerance intervals assume a 95% confidence level of including **a specified portion** of the entire distribution of measurements from which the background data were drawn. For prediction

intervals, the 95% confidence level is related to containing all of the next k measurements, where k is relatively small. Tolerance intervals are used when comparing data with MCLs, while confidence intervals are used most often with ACLs. This is due to the fact that tolerance intervals are more stringent and should be used when quantifiable health-based risk levels are available.

The following is a discussion of the uses and problems associated with tolerance intervals performed on background and compliance limits, parametric and poisson-based prediction intervals, and parametric and poisson-based confidence intervals. All the intervals are available on GRITS/STAT with the exception of the Poisson-Based Intervals.

### **Tolerance Intervals**

- ***Tolerance Interval On Background*** are used in detection ground water monitoring when comparing the upper limit of uncontaminated background data to individual compliance points. If any single compliance well exceeds the upper 95% tolerance limit, there is significant evidence of contamination.
- ***Tolerance Interval On Compliance Limits (MCL or ACL)*** are Poisson-Based Intervals. This test is most powerful when non-detects are greater than 50%, computed on either parametric or non- parametric data. This method is used in compliance ground water monitoring when comparing the upper limit of a compliance well's data and the fixed Ground Water Protection Limit set in the permit, either the MCL, risk-based limit, or ACL. If the tolerance limit exceeds the standard, significant evidence exists that more than 5% of all compliance well values exceed the tolerance limit. This test is also used in intra-well comparisons when comparing present data with upper limits derived from past data from the same well.

### **Prediction Intervals**

- ***Parametric Prediction Intervals*** are the most powerful when non-detects comprise less than 50% of the data set. The main problem associated with this method is the determination of "K". Cameron (1995) defined K as the number of samples collected from one well during the time between the last sampling event and the next time the data must be statistically analyzed. If statistics are required annually and four sampling events occurred during the year, then  $K = 4$ . Parametric prediction intervals are the most powerful when performed on parameters naturally detected in ground water such as inorganics or geochemical parameters. This method is especially useful when only a few compliance data points are available, as in the early stages of detection monitoring. One of the benefits of this method is that it effectively limits the false positive rates without sacrificing false negative rates.
- ***Poisson-Based Prediction Limits (Non-Parametric)*** use original measurements, not ranks. The Poisson intervals are useful for rare event data, when a large percentage of the values are non-detect. They are commonly used for intrawell comparisons when computing the upper interval limit from past data to predict expected values of future well samples.

## Confidence Intervals

- **Parametric Confidence Intervals** indicate the proportion, over time, that repeated random intervals will cover the desired parameter value. Normal or log-normal data is necessary to perform this test. Parametric confidence intervals are useful if none of the on-site wells are truly upgradient. This method should **only** be used in compliance monitoring when comparing the value from a well to a fixed limit (most commonly ACL) derived from **on-site** background data. However, it is not the preferred method for statistical analysis of ground water when the comparison is being made to a health-based standard because this method only estimates the approximate level of the true concentration range. It should **never** be compared to a MCL.
- **Poisson-Based Confidence Intervals (Non-Parametric)**, while requiring more compliance observations than its parametric counterpart, does not always need as large a background data set as the parametric confidence interval. Again, it should **only** be used when comparing a value to a fixed limit derived from site-specific data.

## CONTROL CHART METHOD

The control chart method, mentioned specifically in the hazardous waste (permitted) and solid waste regulations, is based on normally distributed data but does not require it. As mentioned above, control charts require eight independent samples over a one (1) year period from each well. Unlike the other methods, which compare sample results from upgradient to downgradient wells, the control chart method evaluates the change in concentration of a parameter **in a single well** over time. The control chart method should be used only for initially **uncontaminated** wells. Before performing this method, a demonstration must be made, using another statistical method, to provide evidence that no contamination is present in the well. Caution is needed when approving this method for sites already in operation where contamination may have occurred previously (U.S. EPA, 1992a).

The control chart method is useful for analyzing inorganics or geochemical parameters having few non-detects. Use of this method avoids problems arising from concentration differences due to spatial or hydrogeologic variability. It is available in GRITS/STAT.

## STATISTICAL DATA SUBMITTALS

To facilitate correct interpretation of the statistical data, by both Ohio EPA and the regulated entity, the Agency recommends that certain information be submitted with any statistical evaluations. Evidence should be provided that the statistical methods used:

- were as specified in the permit, if applicable.
- were conducted separately for each constituent.
- were completed within the time frame specified in the permit, if applicable.

- were appropriate for the distribution of the constituents.
- were done at a Type 1 error level of .01 for each testing period for individual well comparisons; and .05 for multiple comparisons (with the exception of tolerance, confidence, prediction intervals and control charts).
- accounted for data below the limit of detection as specified in the permit, if applicable.
- included procedures to control or correct for seasonal, spatial and temporal variability, as necessary.

Example calculations for each statistical method should be provided.

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**TECHNICAL GUIDANCE MANUAL FOR HYDROGEOLOGIC  
INVESTIGATIONS AND GROUND WATER MONITORING**

**CHAPTER 14  
GROUND WATER MODELING**

**February 1995**

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## CHAPTER 14

### GROUND WATER MODELING

The use of ground water models to simulate ground water flow and contaminant transport has greatly increased over the past decade. Ground water models represent or approximate a real system and are tools that help in the organization and understanding of hydrogeologic data or the prediction of future hydrogeologic events. Models are not a substitute for field investigations, but should be used as supplementary tools. Results are dependent on the quality and quantity of the field data available to define input parameters and boundary conditions (Wang and Anderson, 1982). Results should always be evaluated in context with the fundamental assumptions of the model and the adequacy of the input data.

The purpose of this chapter is to briefly describe the modeling process. Because major decisions are frequently based on modeling results, it is essential that Ohio EPA review is thorough. To facilitate such a review, the effort must be documented in great detail. This chapter identifies the documentation needed. It is assumed that the reader has some prior experience with the concepts and use of models.

#### GENERAL PROCESS

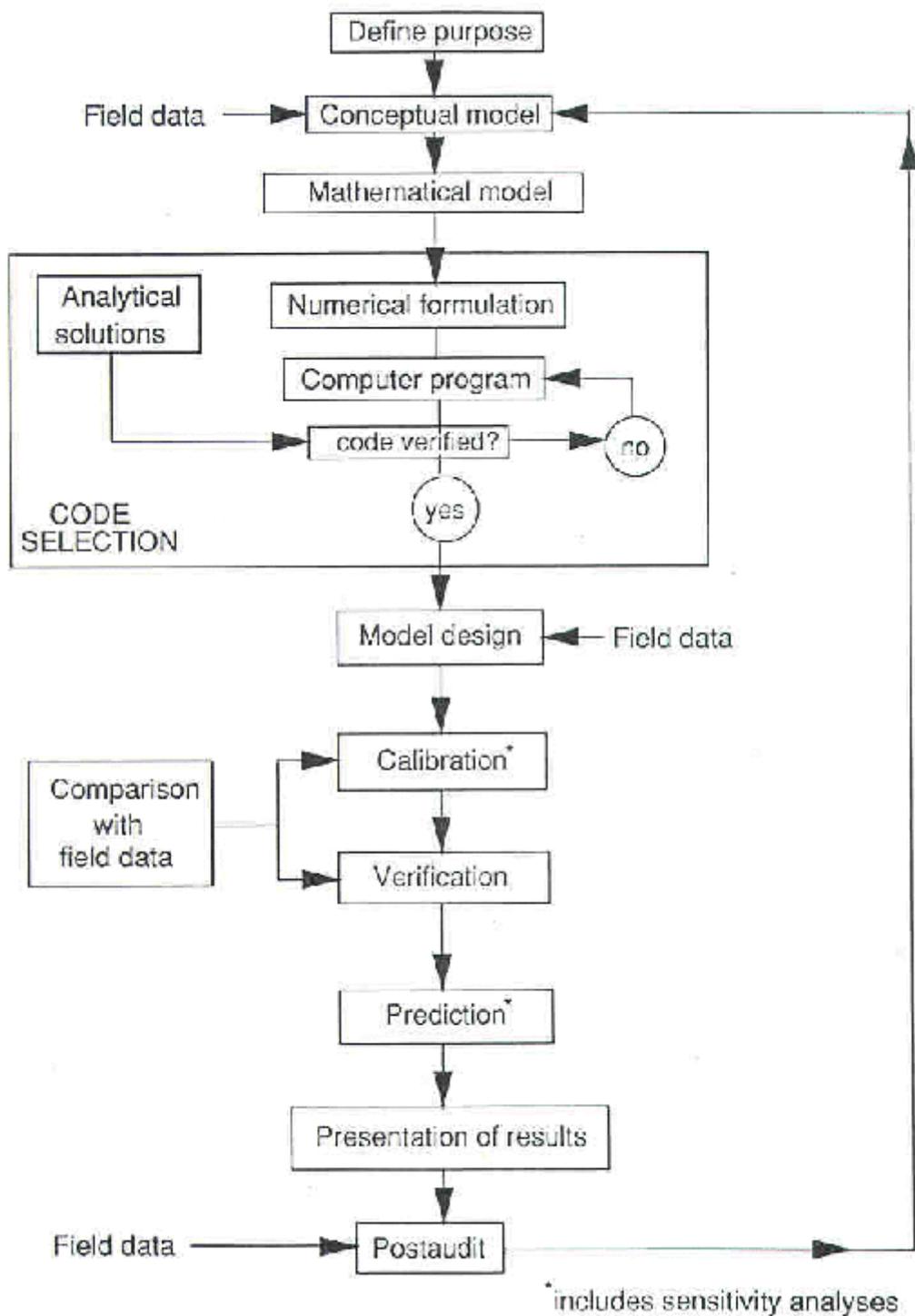
The following paragraphs outline the general process that can be used to ensure that modeling is conducted and documented appropriately. Figure 14.1 charts the basic steps.

#### DEFINE THE PURPOSE

The purpose of the modeling effort should be clearly defined and understood. Ground water models are typically utilized to:

- Determine ground water movement, flow direction, velocity and discharge rates.
- Interpolate between known measurement points in a system.
- Identify data gaps during site characterization.
- Help in the placement and design of a monitoring well network.
- Aid in the development and management of ground water supply systems.
- Determine potential impacts of contamination to nearby wells or surface water.
- Assist in the identification of parties potentially responsible for ground water contamination.
- Aid in the design of ground water remedial action.
- Predict future ground water flow, elevation, and contamination.

For additional information on model uses, see Boutwell et al. (1985), U.S. EPA (1988), van der Heijde (1987), and Wilkinson and Runkle (1986).



**Figure 14.1 Steps in a protocol for model application** (Source: *Applied Ground Water Modeling. Simulation of Flow and Advective Transport* by M.P. Anderson and W.W. Woessner. Copyright © 1992 by Academic Press. Printed with permission.)

## CONCEPTUAL MODEL

The most critical step in any modeling project is the development of a conceptual model (Bear et al., 1992). A conceptual model is a simplified description and schematic that outlines the components of the system to be modeled. The model must be based on a thorough understanding of site hydrogeologic conditions derived from field investigations and regional data obtained from academic or government studies (see Chapter 3).

A conceptual model should incorporate regional hydrogeologic setting, boundary and initial conditions, areas of recharge and discharge (sources and sinks), distribution of water-bearing units, composition of matrix material, interaction/connectedness between water-bearing units, potentiometric surfaces, temporal influences, thickness of water-bearing zones, and distribution of hydraulic parameters. For contaminant transport modeling, additional factors should be incorporated, including distribution of effective porosity, contaminant sources, concentration distributions, source/sink water quality, and the physical and chemical properties of the contaminants that may affect their movement. Conceptual models should be continually refined as more data is obtained.

Of particular importance is establishment of boundary and initial conditions, which can be a difficult task. Types of boundaries include constant head, impermeable, constant flow, and variable head. Examples of boundaries are surface water bodies, rivers, geologic structures, injection barriers, and ground water divides. Boundaries should be chosen at locations that have no significant effect on the area of interest in the model. Various scenarios can be evaluated during calibration by moving the boundaries and comparing the effects. For further information, see Franke et al. (1987), Franke and Reilly (1987) and Anderson and Woessner (1992).

## MATHEMATICAL MODEL

Mathematical models are used to simulate the components of the conceptual model and include a single equation or set of governing equations that represent the process(es) occurring (e.g., ground water flow, solute transport, etc.). The equations used are generally solved analytically or numerically (Bear et al., 1992). **Analytical** models use exact, closed-form, calculus-based solutions to solve the equations for partial differential flow and solute transport. Often, the conceptual model simulated by analytical models is greatly oversimplified. For example, boundaries are assumed to be fully-penetrating and may be represented as straight lines, the aquifer is assumed to be homogeneous and isotropic, and ground water flow is assumed to be at steady-state. As a result, the model may not accurately describe the real flow system.

Where the ground water system is complex--and where sufficient data exist to simulate the complexities in detail--a **numerical** model may be able to simulate the system with much greater accuracy. Numerical models solve the partial differential flow or solute transport equations through numerical approximations using matrix algebra and discretization of the modeled domain. Generally, they can model irregular boundaries, layered aquifers, variations in input parameters such as hydraulic conductivity and recharge, vertical flow gradients at recharge and discharge areas, transient flow conditions, and other complexities. Although a number of numerical techniques exist, only finite-difference and finite-element techniques have been widely used in the United States (Anderson and Woessner, 1992). The U.S. EPA (1991) identified less common solution techniques

as: 1) collocation, 2) boundary (integral) element, 3) particle mass tracking, and 4) method of characteristics (MOC) (Huyakorn and Pinder, 1983).

Recently, a number of ground water flow models have come into popular use that are based on the ***analytic element technique*** (Strack, 1989). This technique applies specific analytical solutions to various "elements" in an aquifer, such as streams, lakes, wells, and areas of recharge. The individual solutions then are superposed to obtain a solution (of hydraulic head) for any location. One attractive feature of this technique is its lack of a fixed grid, which allows the user to extend the model any distance to incorporate regional features without sacrificing accuracy in the area of interest. However, the method's applicability currently is limited to steady-state, two-dimensional ground water flow regimes.

## **COMPUTER CODE SELECTION**

Computer programs or codes have been developed to solve flow equations with the analytical and numerical solutions described above. This simplifies the modeling process by allowing choice of a code that meets objectives and site complexity. Codes have varying degrees of complexity and useability.

A code should be chosen based on its applicability to the conceptual model, availability of the required input data, and the defined purpose of the modeling effort. The code should satisfy fundamental assumptions and the boundary and initial conditions of the area to be modeled. The U.S. EPA (1991) identified four categories of codes: 1) porous media flow, 2) solute transport, 3) geochemical, and 4) specialized (such as fractured rock, heat transport, and multiphase flow). Selection of code type should be determined by the purpose of the modeling effort and the ability to obtain site-specific data. Compilations of codes and their appropriate uses have been developed by van der Heijde and Beljin (1988), van der Heijde et al. (1989), and Graves (1986). The International Ground Water Modeling Center (Colorado School of Mines, Golden, Colorado 80401), provides an information clearinghouse for modeling software. Also, the Center for Subsurface Modeling Support (U.S. EPA, Robert S. Kerr Laboratory, P.O. Box 1188 Ada, OK 74820) provides software and maintains databases of current models. Additionally, several vendors can provide both public and private domain codes.

It is important that the chosen code utilize appropriate governing and process equations in order to simulate the natural system accurately. In principle, ground water flow and contaminant transport systems are three-dimensional and should be modeled as such unless appropriate justification is made. Bear et al. (1992) provided a discussion on evaluating the appropriateness of two- and three-dimensional modeling. For example, regional studies often assume 2-D horizontal flow because of the large ratio between horizontal length and thickness of the aquifer. This observation is also valid when small changes exist in the thickness of a confined aquifer or the saturated thickness of an unconfined aquifer. Horizontal flow assumptions fail in regions where a large vertical component exists (i.e., near rivers, springs, and partially penetrating wells), and 3-D flow should be assumed. However, the effects of vertical flow on a model's accuracy decrease with distance from the feature causing the vertical flow. As a general rule, the effects become negligible at a distance equal to 1.5 to 2 times the aquifer thickness. The 2-D approach is difficult to justify in contaminant transport modeling. Contaminants often only travel through a small fraction of the aquifer thickness, and heterogeneity causes velocity differences that alter the rates of advance and spreading.

Contaminant transport modeling should include simulation of advective flow, which is typically the major component of contaminant transport. Mechanical dispersion and diffusion also can play a role, and these parameters are often lumped into a single dispersion value (Faust and Mercer, 1980). Transformation processes (e.g. biodegradation, sorption, hydrolysis, etc.) can change the physical or chemical state of contaminant(s). When modeling contaminant movement, all applicable transport processes should be considered. Excluding or combining any of the processes must be justifiable.

It is important that any computer code used be documented and verified. **Documentation** generally involves an explanation that includes the fundamental assumptions and limitations of the code, the mathematical solution techniques utilized, and the code structure. In addition, documentation should include instructions on how to use the model, input data requirements, and an explanation of the output. **Verification** is a process whereby the code is shown to produce reliable and accurate results consistently. It is necessary to verify that the flow equations are appropriate for the model and are accurately solved by the code. In addition to documentation and verification, it is important that the chosen code has had considerable peer review. Modelers often choose to employ a general but widely used model rather than one that is specialized and less well known because the general model's code has been widely tested in numerous settings and should be relatively free of "bugs."

## **DESIGN/SETUP**

### **Input Parameters**

All data collected to define the conceptual model should be organized and incorporated into a database that is input to the computer model. Additional data may be necessary to meet the requirements of the chosen code. This new data may require modification of the conceptual model as data gaps are filled.

### **Grid Design**

Most numerical methods require the development of a grid overlay. The input parameters and grid form the database on which the ground water system is defined. The formation and input of this database is specific to the computer code chosen. Fine, closely spaced grid patterns produce more accurate results. On the other hand, the finer the grid pattern, the longer the computer run time. Faust and Mercer (1980) provided the following general guidelines:

- Locate "well" nodes near pumping wells or well fields.
- Locate boundaries accurately. For distant boundaries, the grid may be expanded, but large spacings next to smaller ones should be avoided.
- Grid spacing should be finer in areas where there are large spatial changes in transmissivity or hydraulic head. Large changes in hydraulic head typically occur in recharge and discharge areas, and may be especially significant near pumping wells.

- Align axes of the grid with the major directions of anisotropy (i.e., orient grid with major trends).

In addition, when expanding finite difference grids beyond the interior nodes (area of modeling interest) to the boundaries, as a rule of thumb, grid spacing should not be more than 1.5 times the previous nodal spacing (Anderson and Woessner, 1992).

### **CALIBRATION (with Sensitivity Analysis)**

Once the database has been developed, the code is run and a series of output data is produced. A process of calibration now begins to "fine tune" the input database until a "reasonable" match can be made to existing or preexisting conditions. This generally involves the comparison of water table or potentiometric surface measurements (field data) to the values produced by the model. Since the input parameters (i.e., hydraulic conductivity, transmissivity, dispersivity, etc.) are highly variable, sometimes suspect, and limited spatially, these values are typically adjusted and extrapolated through an iterative process until an acceptable "match" is made with known head values. This process is often referred to as the inverse problem, because the solution (head values) is known and is used to define input parameters. It is not uncommon to make 25 to 100 (or more) simulations before calibration is achieved. It is important to remember that the parameters obtained through calibration may be a non-unique solution, may have errors, or are completely unobtainable (McElwee, 1982) (see also Khan 1986a, 1986b). Therefore, accurate knowledge of site hydrogeology becomes very important to develop a realistic model.

A sensitivity analysis should be conducted in conjunction with calibration. One parameter (such as hydraulic conductivity) is adjusted over a reasonable range and the resulting flow regime is analyzed to see how it has been affected. By simulating ranges, the modeler can determine which parameters have the greatest effect on the particular model. In addition to input parameters, sensitivity to changes in boundary conditions should also be determined (Wang and Anderson, 1982). For further information on sensitivity analysis, see Anderson and Woessner (1992), Aquado et al. (1977), Gillham and Farvolden (1974), McElwee (1982, 1984), Sykes et al. (1985), and Wilson and Metcalf (1985).

As calibration proceeds, data gaps often become evident. The modeler may have to redefine the conceptual model, collect more data, and update the database for a new set of simulations. When the best calibrated match is achieved, a final input data set should be established and demonstrated to be reasonable and realistic. This demonstration should include a quantitative statistical comparison of results to field conditions. The degree of accuracy and how precise the match should be is governed by the defined purpose of the modeling effort. It is up to the modeler to document that the calibrated model is acceptable.

### **HISTORY MATCHING ("Verification")**

Once a model has been calibrated and final input values have been determined, a process known as "history matching" (also known as "verification") should be initiated. This process analyzes the ability of the model to reproduce an historical data set under conditions different from the original conditions. It generally involves matching simulated values to values measured from historical field data. If historical data are insufficient for this purpose, the modeler may instead simulate a specific

stress on the system that can be reproduced in actuality (such as increasing or decreasing pumping rates at various wells). Field data then should be collected while the simulated stress is reproduced, and should be compared to the simulated values. If a reasonable match can be made between the simulated and measured values, the model is considered "verified." As with calibration, the modeler should include a quantitative comparison of the simulated and measured values with a degree of precision appropriate to the defined purpose of the model.

If the first effort at history matching/verification produces an unacceptable match between simulated and measured values, the input data and conceptual model should be reevaluated. Many times, adjusting the input parameters within acceptable ranges (e.g., hydraulic conductivity, recharge rates, river conductance, etc.) may produce a better match. In other cases, a reevaluation of the conceptual model could reveal problems with boundary conditions and the underlying assumptions of the ground water system, or it could show that the model applied was inappropriate. If redesigning fundamental model components still fails to produce an acceptable simulation, it may be necessary to collect more field data to locate the flaws in the conceptual model. Again, whenever significant adjustments are made, the processes of calibration and history matching must be repeated.

It may not be possible to complete the history matching process for a given site or hydrogeologic system if no historic data sets exist and/or aquifer testing is not feasible due to the hazardous nature of the ground water and the problems and liabilities of waste production upon its extraction. Unfortunately, a model that has not been subjected to history matching/verification inspires little confidence. While it is almost impossible to prove that **any** model accurately represents the actual system, history matching improves our confidence that one does (Konikow and Bredehoeft, 1992). Therefore, models that are not subjected to history matching should be used only for **general** interpretations. Using them to make detailed determinations of flow systems or to make long term predictions is unacceptable. Moreover, the modeler should prepare a well-documented justification for using an unverified model. The justification should be based on consideration of the following factors: 1) the goal of the model application, 2) the complexity of the hydrogeologic system, 3) the quality and abundance of field data that help constrain the model, and 4) the results of a detailed sensitivity analysis.

## **PREDICTION**

Upon completing adequate calibration and history matching, the model can be used to predict future scenarios for the ground water flow or contaminant transport system as natural- or man- induced stresses are applied to the system. If long-term action is necessary, it may be useful to refine and update the model as additional data is collected and future stresses are observed (see Post-Audits section). Konikow (1986) stated that "there is no sure way to reliably predict the future since there are severe limits on the adequacy of available data to describe aquifer properties, historical stresses, responses, and by an inability to predict future stresses." Extreme caution is required. As the time span of prediction increases, the uncertainty also increases.

## PRESENTATION OF RESULTS

Complete documentation of the application of a mathematical model to simulate a hydrogeologic system is important to show that a quality effort was made. This will facilitate peer review and also enable further scientific verification by allowing the model to be reproduced by future modelers. Results should be presented in a clear and concise manner and include appropriate documentation. The following provides an outline of components that should be incorporated into a report:

- **Purpose** - The purpose and specific goals or objectives of the modeling effort should be clearly stated.
- **Hydrogeologic Setting** - A narrative, with appropriate cross-sections and maps of the hydrogeologic system, should be provided.
- **Conceptual Model** - A detailed conceptual model should be presented.
- **Data Collection** - Methods and techniques for collecting, analyzing and interpreting data should be explained. Levels of confidence for system parameters should be discussed. Any data gaps and simplifying assumptions should be discussed. Data set strengths and deficiencies should be noted.
- **Model Description** - The rationale for the choice of a particular computer code or analytical equation should be documented. Simplifying assumptions of the model should be discussed and related to the problem to be simulated, along with the impact these assumptions may have on the results. A description of where assumptions and actual field conditions do not coincide should be presented. It should be shown that the model chosen is appropriate for the system in question. Any modifications to the code should also be discussed.
- **Assignment of Model Parameters** - All input data, including initial conditions, boundary conditions, and hydraulic and transport parameters, should be defined. The reasons for selecting initial and boundary conditions should be justified. Assigned values throughout the modeled area should be presented. Data can be presented on cross-sections and maps showing flow boundaries, topography and surface water features, water-table/potentiometric surfaces, bedrock configuration, saturated thickness, transmissivity/hydraulic conductivity, specific storage, cross sections, etc.
- **Model Calibration** - Specific goals and procedures of calibration, results of the final calibrated model, departure from the calibration targets, the effects of the departure on the model results, and the overall water and/or chemical balance of the model should be presented and discussed.
- **Sensitivity Analysis** - All sensitivity analyses should be presented and interpreted. Input parameters that have the greatest impact on results should be described.
- **Additional History Matching** - Goals and procedures of any additional history matching should be presented and discussed. Documentation of historical data or an applied

stress for model comparison should be presented. Additional sensitivity analyses on these new comparisons should be documented.

- **Data Pre- and Post-Processing** - All pre- and post-processing of model input and output data should be described and any computer codes utilized should be documented. The modeler(s) should describe the data manipulation process and why it was conducted.
- **Model Prediction**- All output from predictive simulations should be presented and interpreted in detail. The modeler(s) should cover model water balance, highlighting salient features such as pumpage, recharge, leakage, etc. All predictions should be presented in the context of the fundamental assumptions of the model. Limitations of and confidence in predictions should also be stated.
- **Sources of Error** - All known problems and errors should be evaluated and discussed by utilizing ranges and expressing levels of confidence for all predictions made. Konikow (1988) identified several common types of predictive errors that occur in modeling.
- **Model Results/Summary** - The physical reality of the model should be discussed by comparing the model with actual physical and chemical conditions. The limitations of the modeling effort and all assumptions should be discussed. Also, the degree of uncertainty and appropriate uses of the results should be presented.
- **Model Records** - The entity should keep on file, and be able to provide upon request, input and output data sets for model runs (in digital form or hard copy), including final calibration, additional history matching, and all predictions. The original model documentation and a copy of the source code used should also be available upon request.
- **Post Audit**- If a model will be used to make long-term decisions that extend beyond its predictive limit, the report should include a plan for future post-audits to check the model in time and space to be certain that past decisions are still appropriate.

## POST AUDIT

A sufficiently calibrated and history-matched model uses historical data to predict the future; however, it is difficult to predict the magnitude, location, and duration of future stresses. As a result, post-audits of predictive simulations often show the flow system did not behave as predicted. Post-audits utilize the additional field data collected after the model study is completed to evaluate the accuracy of the prediction. The new data should then be used to recalibrate the model to update and improve the simulation. These periodic updates allow appropriate "corrective actions" to be made (e.g., modifications to an extraction well system). Anderson and Woessner (1992) and Konikow (1986) provided discussions on post-audit methods that can be utilized to re-calibrate a model. Many investigators have suggested not extending transient predictive simulations into the future for more than twice the number of years for which there is transient calibration and verification data (Faust et al., 1981).

## ALTERNATIVE APPROACHES

Most computer models utilize a deterministic approach where all data is input as single, "best estimate" values. Single value inputs result in single value outputs. When modeling on a site-specific scale, where extensive data has been collected and spatial characterization is well established, a deterministic approach is generally appropriate and acceptable. Simulations with appropriate calibration, sensitivity analysis, and history matching can produce an adequate representation of the real hydrogeologic system. If the modeling effort utilizes very limited data or where a larger, regional scale is involved, a stochastic (statistical) approach may be an acceptable alternative. This approach utilizes hydraulic parameters having a probability distribution that results in all output having the same probability distribution. This method characterizes parameter uncertainty by incorporating uncertainty into the parameters and database utilized in the simulations.

One common stochastic approach is to use Monte Carlo simulations. This method entails repeatedly solving a deterministic problem using different sets of randomly generated parameter values that represent the distributions that would be measured in the field (Bair et al., 1991). All simulations are then compiled and statistically evaluated to interpret the real system. The Monte Carlo method has been utilized by Bair et al. (1991) and Ahlfeld and Hyder (1990) to delineate wellhead protection areas. First-order analysis and perturbation analysis are additional stochastic approaches that can be utilized to account for uncertainty in the input parameters. Freeze et al. (1990) provided a summary and additional references for these approaches.

When a lack of data and a high degree of data uncertainty exists, calibration and additional history matching can be long, tedious or impossible. The stochastic approach allows the uncertainty factor to be maintained throughout the modeling process, allowing for potentially more realistic interpretations of the results by providing ranges of scenarios applicable to the real system. Too often, the data uncertainty factor is lost when deterministic approaches are utilized at sites for which limited data is available. The results become "fact" without acknowledgement of the limitations dictated by the input parameters and the underlying assumptions.

## COMMON MISUSES AND MISTAKES

The following is a list of common misuses and mistakes related to ground water flow modeling (from Bear et al., 1992):

- ***Improper conceptualization of the considered problem:***
  - wrong assumptions related to the significant processes, especially in cases of contaminant transport. These may include the type of sink/source phenomena, chemical and biological transformations, fluid-solid interactions, etc.
  - selecting a model that involves coefficients that vary in space, but for which there are insufficient data for model calibration and parameter estimation.
  - improper delineation of the model's domain.
  - wrong selection of model geometry: a 2-D horizontal model, or a 3-D model.

- improper selection of boundary conditions.
- wrong assumptions related to homogeneity and isotropy of geologic material.
- ***Selection of an inappropriate code for solving the model:***
  - code is more powerful/versatile than necessary.
  - code is less powerful/versatile than necessary.
  - code has not been verified and tested.
- ***Improper model application:***
  - selection of improper values for model parameters and other input data.
  - misrepresentation of aquitards in a multi-layer system.
  - mistakes related to the selection of grid size and time steps.
  - making predictions with a model that has been calibrated under different conditions.
  - making mistakes in model calibration and other history matching.
  - improper selection of computational parameters (closure criterion, etc.).
- ***Misinterpretation of model results:***
  - mass balance is not achieved.
  - applying the model beyond its true predictive capabilities.

## **ADDITIONAL SOURCES OF INFORMATION**

A variety of sources are available that explain the many intricate components of the modeling process, including Anderson and Woessner (1992), Bear et al.(1992), Botha and Pinder (1983), Faust and Mercer (1980), Fetter (1988), Freeze and Cherry (1979), Freeze et al. (1990), Huyakorn and Pinder (1983), Lapidus and Pinder (1982), Pinder (1984), Prickett (1975), Prickett and Lonquist (1971), Tsang (1991), and Wang and Anderson (1982).

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