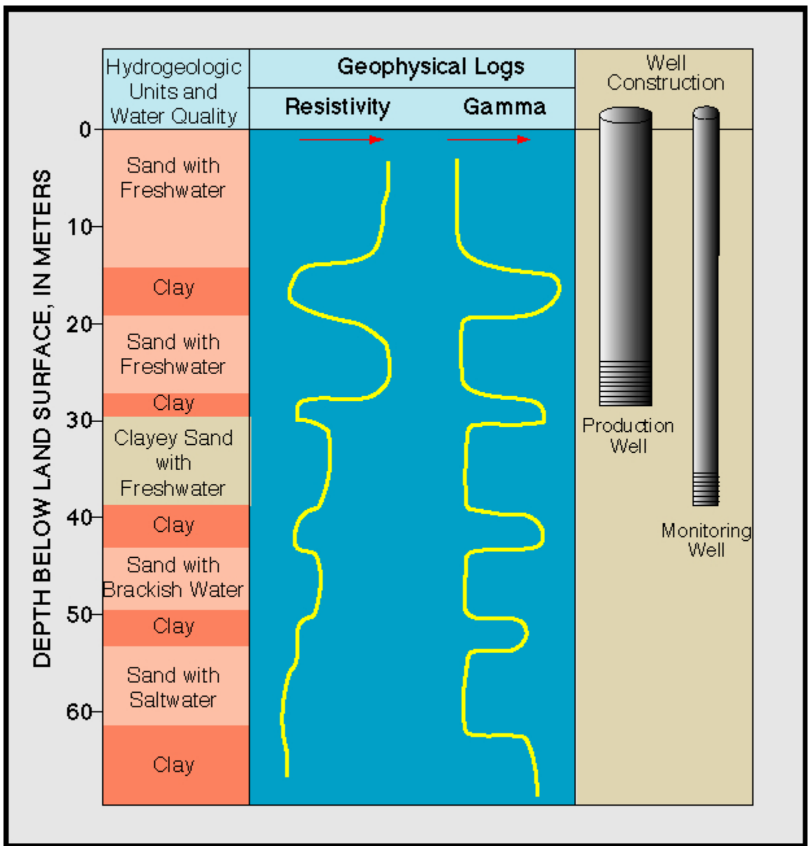
State of Ohio
Environmental Protection Agency

Division of Drinking and Ground Waters

Technical Guidance Manual for Ground Water Investigations

Chapter 16

Application of Geophysical Methods for Site Characterization



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August 2008

Governor : Ted Strickland
Director : Chris Korleski

TECHNICAL GUIDANCE MANUAL FOR GROUND WATER INVESTIGATIONS

CHAPTER 16

Application of Geophysical Methods For Site Characterization

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PREFACE

This document is part of a series of chapters incorporated in Ohio EPA's *Technical Guidance Manual for Hydrogeologic Investigations and Ground Water Monitoring* (TGM), which was originally published in 1995. DDAGW now maintains this technical guidance as a series of chapters rather than as an individual manual. These chapters can be obtained at http://www.epa.state.oh.us/ddagw/tgmweb.aspx.

The TGM identifies technical considerations for performing hydrogeologic investigations and ground water monitoring at potential or known ground water pollution sources. The purpose of the guidance is to enhance consistency within the Agency and inform the regulated community of the Agency's technical recommendations and the basis for them. In Ohio, the authority over pollution sources is shared among various Ohio EPA divisions, including the Emergency and Remedial Response (DERR), Hazardous Waste Management (DHWM), Solid and Infectious Waste (DSIWM), and Surface Water (DSW), as well as other state and local agencies. DDAGW provides technical support to these divisions.

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. 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. The procedures used 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.

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ACKNOWLEDGMENTS

This guidance was developed by Ohio EPA's Division of Drinking and Ground Waters (DDAGW). The following are acknowledged for the preparation of this document.

Dan Tjoelker was a primary author for the 1995 geophysics section of Chapter 11 section and **Lisa Koenig** was responsible for updating the section to stand on its own as Chapter 16.

Jeff Patzke served as editor and project coordinator.

TECHNICAL CHANGES FROM THE FEBRUARY 1995 TGM

The Ohio EPA Technical Guidance Manual for Hydrogeologic Investigations and Ground Water Monitoring (TGM) was finalized in 1995. The geophysical techniques were part of Chapter 11 (Supplementary Methods). Some of the tables in this chapter can also be found in Chapter 3 (Characterization of Site Hydrogeology).

No significant technical changes were made to the document. The chapter was revised to include undated references, including references to specific ASTM Standards and internet links to United States Environmental Protection Agency (U.S. EPA and United States Geological Survey (USGS).

INTRODUCTION

Geophysics provides an efficient and cost-effective means of collecting geologic and hydrogeologic information. Various techniques can be used to help determine the hydrostratigraphic framework, depth to bedrock, extent of ground water contaminant plumes, nonaqueous phase liquids (NAPLs), location of voids, faults or factures, location of abandoned wells, and the presence of buried material, such as steel drums, tanks, or pipelines. Geophysical investigations are most effective when used in conjunction with a drilling or boring program and should not be a substitute for such a program. Typically, one may apply multiple methods to refine the conceptual models. Use of multiple methods also hedges against one method failing to provide useful data. 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. An understanding of the method's theory, field procedures, and interpretation along with an understanding of the site geology is necessary to successfully complete a survey. Personnel not having specialized training or experience should be cautious about using geophysical methods and should solicit assistance from a qualified practitioner (ASTM D6429). Appropriate proof of qualification and experience of all personnel involved should accompany any report.

Additional information on geophysical methods can be found at the following U.S EPA and United States Geological Survey (USGS) web sites.

- http://www.epa.gov/superfund/programs/dfa/geometh.htm
- http://water.usgs.gov/ogw/bgas/
- http://water.usgs.gov/ogw/bgas/methods.html

SURFACE GEOPHYSICAL METHODS

Surface geophysical methods are generally non-intrusive and can be employed quickly to collect subsurface data. When performed properly and utilized early in the site characterization process, the methods can provide valuable information for placing monitoring wells and borings. They can be used later in the investigation to confirm and improve site characterization. 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 , and surface spontaneous potential (SP). These methods and their applications are summarized in Tables 16.1, 11.6, and 16.3. 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. Additional information can be found in U.S. EPA (1997). ASTM D6429-99 (2006) provides information for the selection of surface geophysical methods.

GROUND PENETRATING RADAR

The ground penetrating radar (GPR) method involves the use of a transmitter to emit high frequency electromagnetic waves into the subsurface. The transmitter is either moved slowly across the ground surface or moved at fixed station intervals. 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. Under optimum conditions, GPR data can resolve changes in soil horizons, bedrock fractures, water-insoluble contaminants, geological features, man-made buried objects, voids, and hydrogeologic features such as water table depths and wetting fronts (Benson et al., 1982). This method is generally less applicable for the delineation of contaminant plumes. ASTM D6432-99 (2005) provides guidance on the use of ground penetrating radar for site characterization.

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, 2006). 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.

The frequency of the transmitting antenna can be low, medium, or high (Benson et al., 1982). 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.

The quality of the data can be degraded by a variety of factors such as uneven ground surface, system noise; overhead reflections from power lines trees, etc.: and external electromagnetic noise from radio transmitters. These should be considered before any GPR study is undertaken and accounted for during data interpretation.

Table 16.1 Typical applications of surface geophysical methods (Benson et al, 1982).

APPLICATION	RADAR	EM	RES	SEISMIC	MD	MAG
NATURAL CONDITIONS						
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
SUB-SURFACE CONTAMINATION LEACHATES/PLUMES						
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
LOCATION AND BOUNDARIES OF BURIED WASTES						
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*
UTILITIES						
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
SAFETY						
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 16.2 Surface geophysical methods for locating and mapping of buried wastes and utilities (Benson, 2006).[a]

METHOD	BULK WASTES WITHOUT METALS	BULK WASTES WITH METALS	55 GALLON DRUMS	PIPES AND TANKS
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)

[a] Applications and comments should only be used as guidelines. In some applications, an alternate method may provide better results.

Table 16.3 Surface geophysical methods for evaluation of natural hydrogeologic conditions (Benson, 2006).[a]

METHOD	GENERAL APPLICATION	DEPTH APPLICATION	MAJOR LIMITATIONS
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.

[a] Applications and comments should be used as guidelines. In some applications, alternative methods may provide better results.

ELECTROMAGNETICS

Electromagnetics (EM) measures the electrical conductivity of soil, rocks, and fluid that fills pores. 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.

With EM, 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, 2001). Changes in the phase, amplitude, and orientation of the primary field can be measured either with a ***frequency-*** or a ***time-domain system*** (Benson, 2006). The frequency-domain system measures changes in magnitude of the currents induced. The frequency domain can be single or multiple. Multiple frequency EM is relatively new, but may provide better characterization of the subsurface. With time-domain, 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. The depth of penetration of the transmitted field is a function of the frequency of operation. Lower frequencies penetrate deeper, while higher frequencies are attenuated more rapidly. The frequency dependent penetration depth provides an opportunity to interpret multifrequency EM data to evaluate the depth and size of targets (U.S. EPA, 2000). ASTM Standard D6820 and D6639 provide guidance on the use of time-dominated and frequency-dominated, respectively.

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, 2006).

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, 2006).

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 16.1). Only ranges can be provided because conductivity can vary drastically within material types.

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.

Typical EM noise or interference includes: power lines, atmospheric conditions, steel drums, fences, vehicles, railroad tracks, and buried utilities/pipes. These should be considered before any study is undertaken, and accounted for during data interpretation.

DIRECT CURRENT (DC) RESISTIVITY

The resistivity method involves the measurement of the ability of soil, rock and ground water to resist the flow of an electrical current. It is a function of the soil and rock matrix, percentage of fluid saturation and the conductivity of the pore fluids. 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 voltage. Several electrode configurations are used. The three most common arrays are Wenner, Schlumberger, and the dipole-dipole. These are described in Fetter (2001) and Sheriff (1989). Apparent resistivity is calculated based on the electrode separation, current applied, and measured voltage.

Figure 16.1 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, 2001). Contaminant plumes that display high total dissolved solids (TDS) concentrations cause lower resistivity measurements.

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 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 in homogeneities 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.

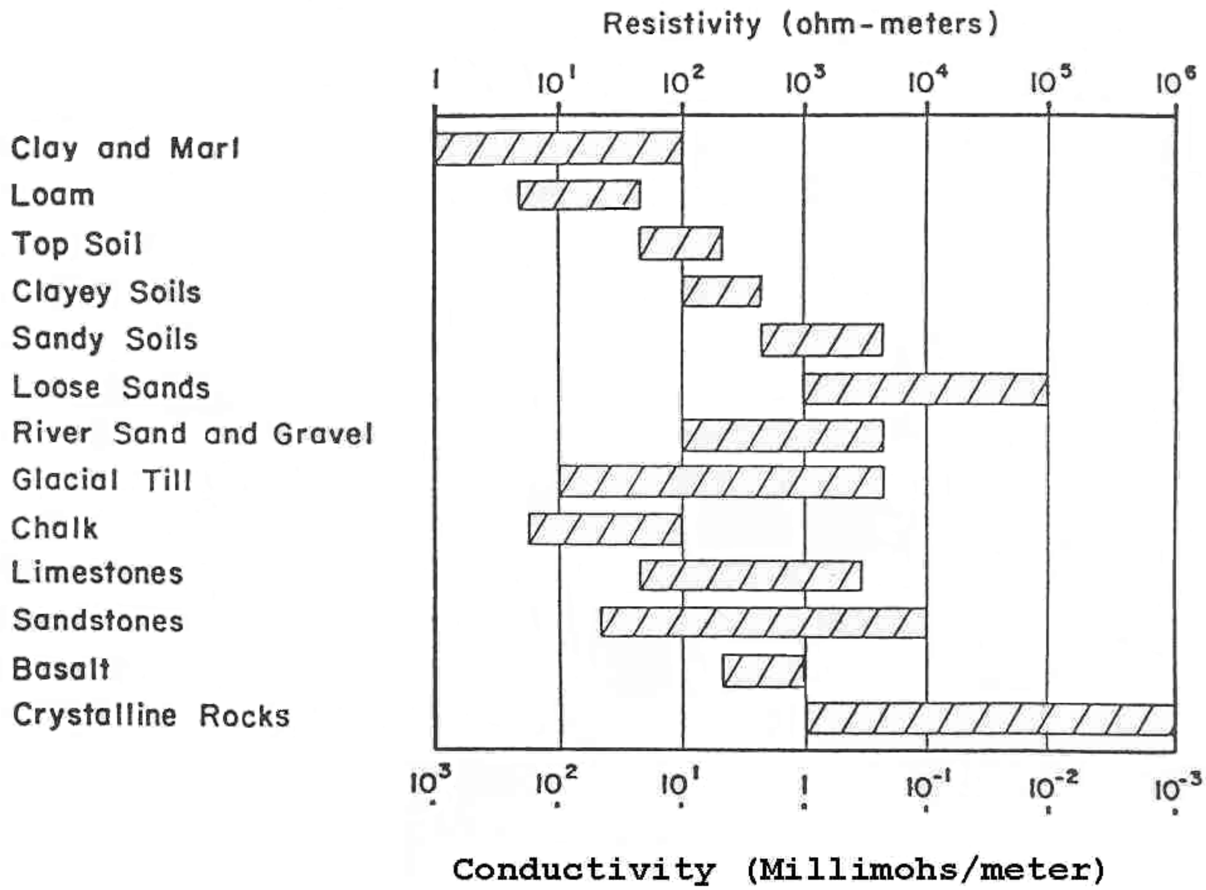

Figure 16.1 Range of electrical conductivities and resisitivities in natural soil and rock (Source: Benson et al., 1982.)

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.

Additional information on DC resistivity can be found in ASTM D6431-99 (2005).

Continuous resistivity profiling is a relatively new technique to assess the subsurface conditions under a water feature (e.g., river or lake). Contact USGS, Geophysical Technology Transfer Unit for additional information.

SPONTANEOUS POTENTIAL (SP)

Spontaneous Potential measures natural voltage. It can be used as a surface or subsurface (borehole) technique. In surface techniques, non-polarizing probes containing a metal salt (copper sulfate) are used to connect the instrumentation to the surface of the earth. One electrode is fixed as the reference electrode, and the second roves. Lateral resolution is a function of station spacing.

The primary application of surface SP is assessing seepage from dams and embankments. Surface SP can also be used to investigate subsurface water movement and landslides, location of faults, drainage structures, shafts, tunnels and sinkholes, and coal mine fires. It is also possible that SP can be used to map geochemical variations associated with contaminant plumes.

Depths of investigation are generally limited to 100 feet. Measurements are susceptible to interference from natural earth currents, soil conditions, topography, stray earth currents, cathodic protection currents, and cultural features. Corwin (1990) provides an overview of the method (ASTM D6429).

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, 2006). Seismic methods have limited applications for determining buried wastes and cannot be used to locate contaminant plumes (see Tables 16.1- 16.3). Types of seismic methods include refraction and reflection. Additional information on seismic refraction and reflection can be found in ASTM standards D7128 and D6439, respectively. In addition, *continuous seismic profiling* is a relatively new technique to assess the subsurface conditions under a water feature (e.g., river or lake). Contact USGS, Geophysical Technology Transfer Unit for additional information.

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.

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 16.4 summarizes additional properties that affect relative velocities in geologic materials.

Table 16.4 Properties that affect relative velocities in geologic material (based on Benson et al, 1982).

HIGHER VELOCITY	***LOWER VELOCITY***
high density rock	low density rock
older rock	younger rock
igneous	sedimentary
solid rock	cracked
unweathered	fractured
consolidated	weathered
saturated sediments	unconsolidated
wet soil	unsaturated sediments
	dry soil

Once waves are introduced at the surface, the primary wave travels in the form of a direct wave and a refracted wave. 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). 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.

To determine geologic conditions using refraction surveys, three fundamental assumptions should 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, 2006).

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, 2006).

Additional information on seismic reflection can be found in ASTM D7128-05.

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.). Additional information on magnetic surveys can be found in ASTM D7046-04.

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 ($1/depth^6$). 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

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 16.1-16.3).

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, 2006). 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, 2006). 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, 2006).

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, 2006). 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, 2006).

GRAVIMETRY

Gravity instruments measure minute changes in the earth's gravity due to changes in density of subsurface materials. The gravity method is useful in delineating buried valleys, bedrock topography, and geologic structural voids, and locating bulk buried waste. 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.

Benson (2006) 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[1]. 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 should 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.

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 of methods 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.

The geophysical logging system consists of probes, cable and drawworks, power and processing modules, and data recording units (figure 16.2). State-of-the-art logging systems are controlled by a computer and can collect multiple logs with one pass of the probe. 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, 2006). 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 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

[1]The earth's normal gravity is 980 gals.

response and result in inaccurate interpretations. Table 16.5 summarizes the characteristics and use of commonly utilized downhole logging instruments, while Table 16.6 summarizes the common applications. ASTM D5753-05 provides additional references and general guidance on planning and conducting borehole geophysical logging. Information in the standard includes: general logging procedures, documentation, calibration, and factors that can affect the quality of logging.

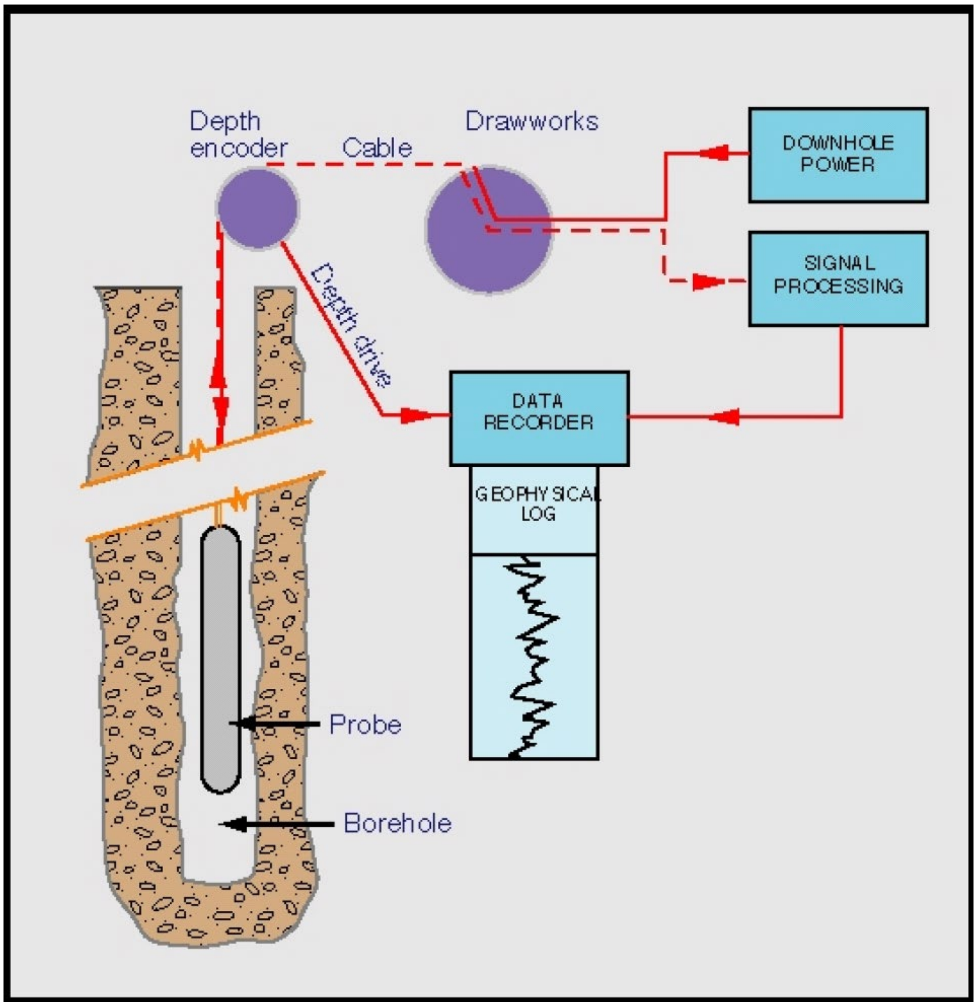

Figure 16.2. Geophysical logging (http://ny.water.usgs.gov/projects/bgag/schematic.html) USGS Web site http://water.usgs.gov/ogw/bgas/methods.html

NUCLEAR LOGS

Nuclear logging tools are used to evaluate stratigraphy, ground water conditions, and subsurface contaminant distribution. Types include: (1) tools that measure the natural radioactivity of a formation, and (2) tools that emit radiation and measure the corresponding response of the formation. The first type measures gamma radiation emissions from naturally occurring uranium, thorium, and radioactive potassium present within clay minerals, and it is useful in distinguishing clay-rich strata from sand-rich strata. The second type exposes the boring walls to a relatively strong radiation source (gamma rays or neutrons), and measures the formation response, which depends on its density (or porosity), water content, and the presence or absence of hydrocarbons.

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, 2006). 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).

Natural gamma measurement is conducted by first lowering the detector to the bottom of a hole, allowing it to equilibrate to the subsurface temperature, then reeling the detector up the hole at a steady rate of between five and 10 feet per minute. The gamma log measures the total gamma radiation emitted by a particular stratum in counts per second as the detector is raised in the column. Interpretation of the gamma log depends on the absolute value of the gamma counts and on the rate of change as the detector passes from one material to the next. Statistical variations in gamma emissions, significant at low counting rates, are smoothed out by integration over a short time interval. If logged too quickly, the smoothing effect leads to erroneous results by shifting the peaks in the direction of logging (U.S. EPA, 2000). ASTM D6274 provides guidance on the use of this method.

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 utilizes a radiation source and a detector. The neutron interactions with the subsurface material and measures the amount of hydrogen present. This 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. ASTM D6727 provides an overview of this method, general procedure, calibration and standardization, log quality and interpretation, and additional references.

Table 16.5 Downhole geophysics, characteristics and use (Benson et al., 1991).

DOWNHOLE LOG	PARAMETER MEASURED (OR CALCULATED)	CASING UNCASED/PVC/STEEL	SATURATED	UNSATURATED	RADIUS OF MEASUREMENT	AFFECT OF HOLE DIAMETER, AND MUD
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 senior typically 2-3 feet	N/A

Table 16.6 Summary of log application (Keys and MacCary, 1971).

REQUIRED INFORMATION ON THE PROPERTIES OF ROCKS, FLUID, WELLS, OR THE GROUND WATER SYSTEM	*WIDELY AVAILABLE LOGGING TECHNIQUES THAT MIGHT BE UTILIZED*
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. 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, 2006). 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. ASTM D6726 provides a more detailed overview of this method, general procedure, calibration and standardization, log quality and interpretation, and additional references.

Resistivity

The resistivity log provides measurements of the apparent resistivity of the material surrounding a borehole (Benson, 2006). 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. ASTM D6726 provides a more detailed overview of this method, general procedure, calibration and standardization, log quality and interpretation, and additional references.

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, 2006). 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, 2006). Though quantitative results are not provided, the SP may be useful in determining lithology, oxidation-reduction conditions, and fluid flow (Benson, 2006). 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 teleview. 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 ***televiewer*** 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, 2006).

DOCUMENTATION

If surface or downhole geophysical methods are utilized, it is important that the entire process be documented. Some of the features that should be presented are:

- Objective of the study, including description of the targets of interest.
- Description of chosen technique(s) and the rationale for their selection.
- Description of site location and the cultural and geologic/hydrogeologic setting (regional and site-specific, if available).
- Description of survey set-up, instrumentation, calibration, and data collection.
- Procedures for quality assurance and quality control.
- Summary of the collected data (including raw and corrected). Raw data and data files used for computer modeling should be kept on file and made available, if requested.
- Summary of data reduction.
- Interpretation of the data, including any correlations made from existing data.
- Site map.
- Any maps, graphs, traverses, profiles associates with the geophysical method. These should be labeled and contain details appropriate to the particular geophysical technique.
- Documentation of all problems encountered, and steps taken, if any, to solve them.

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