Chapter 4
Field Investigative Methods

4-1. General

a. Adequate conceptualization of a hydrogeologic system often requires the acquisition of new field data. This chapter provides an overview of different methods which can be employed to gain a better understanding of subsurface conditions pertaining to the occurrence and flow of groundwater. Key references are provided to allow for a more detailed understanding of concepts and applications. Hazardous, toxic, and/or radioactive waste (HTRW) investigations often require special consideration beyond the scope of this text.

b. Initially, information that can be obtained in the process of, and as a product of, the construction of a well is described. The construction and development of wells can provide a wealth of information on subsurface conditions. Geologic logging during drilling of a borehole enables the delineation of high-conductivity and low-conductivity strata. Borehole geophysical methods can provide information on the lithology, porosity, moisture content, permeability, and specific yield of water-bearing rocks; additionally, borehole geophysical methods can also help define the source movement and chemical characteristics of groundwater. Completed wells offer information on hydraulic head and water quality. Finally, wells provide a conduit through which stress can be placed upon an aquifer by the extraction or injection of water. Aquifer properties, such as transmissivity and storage coefficient, can then be estimated by the aquifer response to these stresses.

c. An overview of surface geophysical methods is then presented. Surface geophysical methods allow for the nonintrusive gathering of information on subsurface stratigraphy and hydrogeologic conditions. Surface geophysical methods include seismic refraction and reflection, electrical resistivity, gravitational methods, electromagnetic methods, and ground-penetrating radar. A section on cone penetrometers is then included. Cone penetrometers often provide a cost-effective method for gathering significant data on subsurface stratigraphy. Finally, overviews on the use of geochemistry, and the response of water levels to loading events to gain information on subsurface conditions are included.

d. An additional method for acquiring new hydrologic data is studying the interaction between surface water and groundwater. For example, the effects of surface water fluctuations on groundwater levels can be used to estimate the aquifer transmissivity and storage coefficient. Analytical methods for quantifying interaction of surface water and groundwater are presented in Chapter 6.

4-2. Wells

a. Well drilling methods.

(1) General. The overriding objectives in pumping well design and construction are as follows: the attainment of the highest yield possible with minimum drawdown in pumping wells, good water quality, minimizing environmental effects, ensuring borehole integrity, minimizing siltation, and reasonable short- and long-term costs. Various well drilling methods have been developed in response to the range of geologic conditions encountered, and the variety of borehole depths and diameters that are required. The most common methods employed in drilling deep wells are direct and reverse circulation mud rotary, direct and reverse circulation air-rotary with casing drive, hollow stem auger drilling, and the cable tool method. The terms direct and reverse refer to the direction in which the drilling fluid (mud or air) is circulated. In direct drilling, the drilling fluid is circulated down the string of drill tools out the bit and up the annulus between the tool string and the borehole wall. In reverse, as the name implies, the direction of circulation is reverse that of direct drilling. An in-depth description of drilling methods can be found in Driscoll (1986).

(2) Mud rotary. The rotary methods provide a rapid means for drilling in a wide range of geologic conditions. In direct mud rotary, a hollow rotating bit is used, through which a mixture of clay and water, known as drilling mud, is forced out under pressurized conditions. This drilling mud serves the dual purpose of transporting cuttings to the surface along with sealing the borehole wall, thus allowing the hydrostatic

pressure of the drilling mud to hold the borehole open. Advantages in using the direct mud rotary method include its rapid drilling rate, and the non-requirement for placing casing during drilling operations in unconsolidated material. Disadvantages include mud disposal, the need to remove mud lining from the boring walls during well development, and difficulty in identifying when the water table is encountered.

(3) Air rotary. In air-rotary drilling, air, rather then drilling mud, is used to remove cuttings and cool the bit. Air rotary drilling can be done open-hole (semi- and consolidated formations) or in conjunction with simultaneously driving the casing (unconsolidated formation). Air for drilling is supplied either by an on-board or auxiliary air compressor. Air is circulated at volumes up to 57 m^3/min at pressure up to 2,400 kpa; however, in unconsolidated formations pressure above 1,000 kpa is unnecessary and can cause excessive borehole erosion and borehole instability. The air should be filtered to remove compressor oil and other contaminants prior to use in drilling. When drilling in unconsolidated formations, air rotary drilling is typically done in conjunction with driving the casing to stabilize the borehole. The advantages of air rotary drilling are its rapid drilling (penetration) rate, lack of drilling mud and associated clean-up, and the accuracy with which the water table can be located when drilling at low pressures (i.e., < 700 kpa). Disadvantages include higher cost, access for larger equipment, and noise.

(4) Hollow stem auger. Hollow stem auger drilling is a rotary drilling method that does not require circulation of a fluid medium. Rather, the borehole is advanced and cuttings removed by a cutter head followed by a continuous flight or helix of auger ramps which can be likened to a wood screw. Modern hollow stem auger drills can install wells to depths greater than 80 m in unconsolidated formation (hollow stem augers are not for use in semi- or consolidated formations). When drilling, a cutting head is attached to the first auger flight, and as the auger is rotated downward, additional auger flights are attached, one at a time, to the upper end of the previous auger flight. As the augers are advanced downward, the cuttings move upward along the continuous flighting. The hollow stem or core of the auger allows drill rods and samplers to be inserted through the center of the augers. The hollow stem of the augers also acts to temporarily case the borehole, so that the well screen and casing may be inserted down through the center of the augers once the desired depth is reached, minimizing the risk of possible collapse of the borehole that might occur if it is necessary to withdraw the augers completely before installing the well casing and screen. The hollow-stem auger drilling technique is not without problems. These are more completely described in Aller et al. (1989), but generally include:

(a) Heaving: Sand and gravel heaving into the hollow stem may be difficult to control, and may necessitate adding water to the borehole.

(b) Smearing of silts and clays along the borehole wall: In geologic settings characterized by alternating sequences of sands, silts, and clays, the action of the augers during drilling may cause smearing of clays and silts into the sand zones, potentially resulting in a considerable decrease in aquifer hydraulic conductivity along the wall of the borehole. The smearing of clays and silts along the borehole wall may, depending on the site-specific properties of the geologic materials, significantly reduce well yield or produce unrepresentative groundwater samples even after the well has been developed.

(c) Management of drill cuttings: Control of contaminated drill cuttings is difficult with the auger method, especially when drilling below the water table.

(5) Cable tool method.

(a) The cable tool method is one of the oldest and most versatile drilling techniques. Penetration into the subsurface is achieved by lifting and dropping a string of tools suspended from a cable, with the weight of the falling tools providing the driving force. The string of tools generally consists of four sections: the swivel socket, the drilling jars, the drill stem, and the drill bit. The swivel socket rotates the bit, allowing it to strike a different area of the hole bottom with each stroke. The drilling jars consist of two loosely interconnected rods. Their purpose is to enable a reverse hammering effect to free the bit and stem, should they become lodged in the borehole. The drill stem keeps the drill bit driving straight, while also providing additional weight. The bit crushes and mixes any materials in the drilling path. The debris is removed by the addition of water (when above the water table) into the borehole to produce a slurry that can then be pumped out. Cable tool drilling is usually limited to borehole diameters less than 75 cm (30 in.) and drilling depths less than 600 m (2,000 ft).

(b) The advantages of this type of drilling are low cost and ability to drill into a variety of mediums in many conditions. Additionally, this method provides for an accurate logging of formation changes. It is sensitive to any medium changes, allowing the driller to adjust sample increments. This method also uses less water than other drilling methods, which is convenient when drilling in desolate arid regions. The major disadvantages are a slow drilling progress, the limitation in borehole sizes and depths, and the need to drive casing coincident with drilling when drilling in unconsolidated materials.

b. Well design and completion.

(1) General. Well design should address the following factors: the depth of the well screen or screens; diameter of screen and casing; type of material (e.g. mild steel, stainless steel, etc.); the type of well screen (mill slot, shutter slot, continuous slot, etc.); gradation of the filter pack (formation stabilizer) surrounding the well screen; and the type and composition of annular seals (e.g. conventional neat cement versus high-solids bentonite grout). Well completion involves setting and positioning casing and well screens, placing filter pack, sealing the annular space, and constructing well-head features at the ground surface. While each of these design elements is dependent upon site-specific conditions such as the purpose of the well and available funding, there are some general guidelines that need to be incorporated into every design. Figure 4-1 illustrates basic well components. Driscoll (1986) presents a more complete discussion of well design and completion procedures.

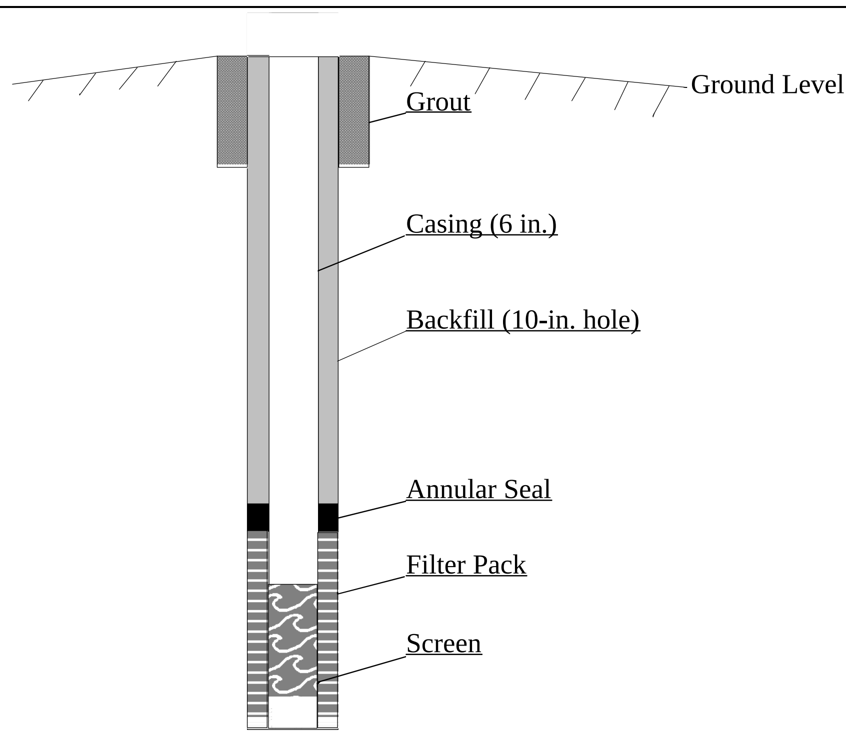

Figure 4-1. Basic well components

(2) Casing. Casing should be of sufficient strength to withstand not only the depth of installation, but also a certain amount of abuse during handling and installation. Casing should be of sufficient diameter to accept a pump at least one size larger than currently required in order to account for potential lowering of the water table.

(3) Filter pack. The filter pack commonly consists of a graded sand which is artificially placed around the well screen to stabilize the aquifer, minimize sediment entering the well, permit the use of a large screen slot size, and provide an annular zone of high permeability. The filter pack is a key element in the hydraulic efficiency of the well. The filter pack needs to provide a smooth gradation transition from the formation. Essentially, the gradation of the filter pack is based upon the uniformity coefficient (a measure of how well it is sorted) and the D_{70} (70 percent passing sieve size) of the formation. These parameters are obtained from sieve analyses of formation samples obtained during exploratory drilling. Depending upon the uniformity coefficient, the D_{70} of the formation is multiplied by a factor from 3 to 9. The resulting value is the new D_{70} for the filter pack. Utilizing the new D_{70}, the filter pack gradational curve is constructed such that it roughly parallels the formation gradational curve.

(4) Well screen. Well screen design encompasses a balance between required strength and desired hydraulic efficiency. Hydraulic efficiency is basically a function of the amount of open area in a well screen; the greater the open area, the greater the area available for groundwater flow and thus greater hydraulic efficiency. Generally, one strives to maximize hydraulic efficiency at a prescribed strength. A key element of well screen design is the size of the openings, referred to as slot size. The slot size is a function of the filter pack gradation. The slot size is typically selected to retain 80-90 percent of the filter pack. Well screens are placed at the depths of interest to: hydrologically isolate formations, prevent sand movement into the well, and minimize hydraulic resistance to water entering the well. Screens are available in a variety of materials, diameters, and slot sizes depending on the hydrologic and water quality parameters of the aquifer, the desired well yield, and aquifer thickness.

(5) Annular seals. In choosing an annular sealant, the following factors should be considered: borehole stability (e.g., an unstable or caving borehole needs an easily placed, quick-setting sealant such as high-solids bentonite grout); the method with which the well was drilled; and the type of well casing (e.g., the heat of hydration from thick cement seals can deform/melt PVC casing).

(6) Placement of cement or grout. Wells are cemented, or grouted, in the annular space surrounding the casing to prevent entrance of water of unsatisfactory quality, to protect the casing from corrosion, and to stabilize caving rock formations. It is important that the grout be introduced at the bottom of the space to be grouted by use of a tremie pipe to ensure the zone is properly sealed.

c. Well development. Wells are developed by removing the finer material from the natural formations surrounding the screening. A new well is developed to increase its specific capacity and prevent silting. Development procedures are varied and include pumping, surging, hydraulic jetting, and addition of chemicals. The basic purpose of all these methods is to agitate the finer material surrounding the well so that it can be carried into the well and pumped out. Pumping involves discharging water from a well in successive steps until clear water is produced. Surging utilizes a block which is moved in an up-and-down motion with increasingly faster strokes. Compressed air can also be utilized to create rapid changes in water levels within the well casing. Hydraulic jetting utilizes a high-velocity stream of water which is rotated across the full extent of the screened area removing finer-grained material from the gravel packing by turbulent flow. Chemical additives, such as hydrochloric acid, can be employed in open hole wells in limestone or dolomite formations to remove finer particles and widen fractures.

d. Well efficiency. The objective in well design is to avoid excessive energy costs by constructing a well that will yield the required water with the least drawdown. Well efficiency can be defined as the ratio of the drawdown in an aquifer at the radius of the well borehole (just outside the filter pack in the aquifer) to the drawdown inside the well. The difference between aquifer and well drawdowns is attributed to head losses as water moves from an aquifer into a well and up the well bore. These well losses can be reduced by reducing the entrance velocity of the water, which is accomplished by installing the maximum amount of screen and pumping at the lowest acceptable rate. Other factors involved in reducing well loss include proper development techniques and proper filter pack design.

4-3. Monitoring Wells

a. The primary objectives of a monitoring well are to provide an access point for measuring groundwater levels and to permit the procurement of groundwater samples that accurately represent in situ groundwater conditions at the specific point of sampling. To achieve these objectives, it is necessary to fulfill the following criteria:

(1) Construct the well with minimum disturbance to the formation.

(2) Construct the well with materials that are compatible with the anticipated chemical and geochemical environment.

(3) Properly complete the well in the desired zone.

(4) Adequately seal the well with materials that will not interfere with the collection of representative water samples.

(5) Sufficiently develop the well to remove any additives associated with drilling and provide unobstructed flow through the well (Aller et al. 1989).

b. In addition to appropriate construction details, the monitoring well must be designed in concert with the overall goals of the monitoring program. Key factors that must be considered include the following:

(1) Intended purpose of the well.

(2) Placement of the well to achieve accurate water levels and/or representative water quality samples.

(3) Adequate well diameter to accommodate appropriate tools for well development, aquifer testing equipment, and water quality sampling devices.

(4) Surface protection to assure no alteration of the structure or impairment of the data collected from the well (Aller et al. 1989).

c. In essence, one should strive to construct a well that is transparent to the aquifer in which it is constructed. Aller et al. (1989) and American Society for Testing and Materials (ASTM) (1993) provide in-depth guidelines for the design and installation of groundwater monitoring wells.

4-4. Geologic Logging

Logs of rock and soil encountered during drilling can provide the most direct and accurate means for the delineation of high-conductivity and low-conductivity strata. The character, thickness, and succession of the underlying formations provide important data as to existing aquifers, aquitards, and aquicludes and the interaction between surface water and the subsurface. All geologic logs should follow procedures listed in Engineer Manual (EM) 1110-1-4000 (1994).

4-5. Measuring Water Levels

a. Data uses. Accurate measurements of groundwater levels are essential for conceptualization of site hydrogeology. Information which can be provided by water level measurements includes the following:

(1) Rate and direction of groundwater movement.

(2) Status or change in groundwater storage.

(3) Change in water level due to groundwater withdrawal.

(4) Amount, source, area of recharge, and estimate of discharge.

(5) Hydraulic characteristics of an aquifer.

(6) Identify areas where the water table is near the land surface.

(7) Delineate reaches of losing or gaining streams or canals.

b. Data sources. Water level data can be acquired from a number of sources, including existing wells, piezometers, and from surface water/ groundwater interfaces such as lakes, streams, and springs. Observation wells can be installed at necessary locations where other resources do not exist.

c. Data requirements. In addition to water level elevation, the following information should be recorded with each measurement:

(1) Local well name and owner.

(2) Date drilled.

(3) Well use.

(4) Location by legal description, such as latitude and longitude coordinates.

(5) Approximate location relative to local landmarks.

(6) Elevation of land surface and measuring point.

(7) Well depth, size and type of casing, location and type of perforations.

d. Methodology. There are essentially three main techniques to measuring water levels in non-flowing wells, the graduated steel tape (wetted-tape method), the electrical measuring line, and air lines. All three have their advantages and disadvantages for measuring under certain conditions.

(1) Graduated steel tape method. This method is widely considered to be the most accurate method for measuring water levels in non-flowing wells. Tapes in lengths of 50, 100, and 300 m, and 100, 200, 500, and 1,000 ft are among the most common. They are available as either black or chromium-plated, with black being preferred by most. Tapes up to 150 m (500 ft) in length are usually hand-crank-operated, while longer tapes are often motor-driven. A lead weight is generally attached to the end to aid in plumbness and added feel. A lead weight is less likely to foul any pumps due to its soft nature. The attachment should be made so that should the weight become lodged in the well, it will break off allowing retrieval of the tape. To acquire a measurement, the lower end of the tape is marked with carpenter's chalk. The amount submerged into the water will enable a reading to be taken by viewing the wetted portion. Corrections for thermal expansion of tapes greater than 300 m (1,000 ft) in length should be applied in extreme temperatures. Two measurements should be taken, with an agreement of less than 0.6 cm (0.25 in.). If water is dripping down the well, or if the water surface is disturbed, it may be impossible to get an accurate reading. If oil is present on top of the water in depths greater than a foot, then the thickness of the oil layer must be known to compensate for the lower density; thus, a higher water level measurement. The oil level can be determined by using a water detector paste that will show both the water and the oil levels.

(2) Electrical method. Electrical measuring devices generally consist of two electrodes that complete a circuit when immersed in water. These electrodes are attached to a power supply by a conductive cable. There are various other types of electrode/cable combinations, with the two-conductor cable and special probe being the most common. The cable is generally 150 m (500 ft) long and uses a hand-cranked reel. The advantage to the electrode method is the ability to take multiple measurements without having to fully remove the cable from the well. It also is more accurate than the steel tape when measuring in a pumping well where the water may be splashing or dripping down the well. These conditions will usually foul a steel tape measurement. They are also safer when used in pumping wells because they detect the water immediately, lessening the chance of lowering the probe into pump impellers. The disadvantages are that they are more bulky than the steel tape, and less accurate under ideal conditions. The measurements should be within 1 cm (0.04 ft) for less than 60-m (200-ft) depths, and about 3 cm (0.1 ft) for 150-m (500-ft) depths. Measurements have been within 15 cm (0.5 ft) for depths as great as 600 m (2,000 ft). Adapters can be added to sensing probes to detect oil. After multiple uses, the length of the cable should be checked because stretching may occur during use.

(3) Air line. Air pressure lines consist of an airtight tube that when submerged into the water is purged by compressed air. The pressure required to purge the tube is related by the depth of the tube in the water. Multiplying the pressure in psi by 2.31 ft/psi will give the depth. In metric, multiplying the pressure in Pascals by 4,850 m/Pascal will give the depth. That distance can then be subtracted from the total length of the tube in the well and the depth to water will be determined. This technique works well where the surface of the water is being disturbed. The durability of air lines has historically been a problem, as they become clogged with mineral deposits or may form leaks, both leading to false measurements. The accuracy of this technique relies mostly on the accuracy of the gauge being used. Other measuring techniques should be employed periodically.

e. Recording devices. Automated devices for recording changes in water levels may be mechanical, electronic, or electromechanical. Electromechanical devices usually consist of a float that measures the actual vertical changes in water levels. Mechanical or electronic devices consist of submerged probes that measure changes in pressure from varying water depths. Rapid changes in depth are measured with greater accuracy with pressure sensing devices since they are able to detect the changes more rapidly than a float. Floats lose most of their accuracy from cable friction along the well walls. The recording device itself is generally a simple mechanism that is able to chart the water level versus time. Due to the delicate nature of the recording device, some sort of housing should be provided to protect it from weather and vandalism.

f. Measurement frequency. The basic factors determining measurement frequency are the types of fluctuations expected, the potential use of the data, and the available personnel. Fluctuations occur due to many factors, including: pumping, recharge (from any number of sources, manmade and natural), and evapotranspiration. Use of the data will determine the desired frequency of measurements, with restraints from equipment and personnel. Automatic recorders are best for high-frequency measurements. Human error may cause discrepancies in frequent measurements causing the data to skew results. Weekly and monthly measurements may miss pumping and recharge events completely. Under certain pretenses, infrequent measurements (semi-annual) may suffice.

g. Effect of changes in barometric pressure on water levels in confined aquifers. Changes in atmospheric pressure can have a significant effect on water levels in wells penetrating a confined aquifer. In confined aquifers, well measurements should be corrected to a constant barometric pressure (Section 4-12).

4-6. Pumping Tests

a. General. Pumping tests (or aquifer tests) are in situ methods that can be used to determine hydraulic parameters such as transmissivity, hydraulic conductivity, storage coefficient, specific capacity, and well efficiency. Hydrogeologic values derived from pumping tests are averaged over the spatial zone of influence of the test. The basic steps involved in performing a pumping test are: (1) background measurements; (2) pumping test measurements; and (3) recovery measurements. Depending on data needs and well and geological conditions, two general types of pumping tests can be performed : constant-rate pumping tests, and step-drawdown pumping tests. Data measured during a pumping test include: flow rates, time, and water levels. Atmospheric pressure measurements can be additionally made when performing tests in confined aquifers. Several analytical methods for data interpretation are available. Appendix D presents an overview of general methods available. Recommended references for a more in-depth discussion of pumping tests and accompanying analytical methods are: Dawson and Istok (1991), Kruseman and De Ridder (1983), Driscoll (1986), and Walton (1987).

b. Flow to pumping wells.

(1) General. The study of well hydraulics is a complicated blend of mathematics, fluid mechanics, and soil physics. It is as much an art as a science. The following sections present wells from a somewhat idealized perspective, oftentimes greatly simplifying the true system. Through this idealization, the resulting equations simplify to solutions that are exact or easily approximated to near exact solutions. General assumptions for all cases are: (a) that the aquifer is isotropic, homogeneous, and of infinite areal extent;

(b) the well fully penetrates the aquifer; (c) the flow is horizontal everywhere within the aquifer; (d) the well diameter is so small that storage within the well is negligible, and; (e) water pumped from the well is discharged immediately with decline of piezometric head. The general governing equation for all idealized cases is Laplace's equation in cylindrical coordinates. Detailed derivations of these equations are performed in Freeze and Cherry (1979).

(2) Specific capacity. The specific capacity of a well is the yield per unit drawdown, and is determined by dividing the pumping rate at any time by the drawdown at the same time. The specific capacity of a well depends both on the hydraulic characteristics of the aquifer and on the construction, pumping rate, and other features of the well. Values of specific capacity, available for many supply wells for which aquifer-test data are not available, are widely used by hydrologists to estimate transmissivity.

(3) Cone of depression. The movement of water from an aquifer into a well results in a cone of depression (also known as zone of influence). Because water must converge on the well from all directions, and because the area through which the flow occurs decreases toward the well, the hydraulic gradient must get steeper toward the well. The size of a cone of depression is dependent primarily on the well pumping rate, elapsed time since start of pumping, aquifer type, aquifer transmissivity, and aquifer storativity (Figure 4-2). Withdrawals from an unconfined aquifer result in drainage of water from rocks through which the water table declines as the cone of depression forms. Because the storage coefficient of an unconfined aquifer closely approximates the specific yield of the aquifer material, the cone of depression expands slowly. On the other hand, a lowering of the water table results in a decrease in aquifer transmissivity which will cause an increase in drawdown both in the well and in the aquifer. Withdrawal from a confined aquifer causes a drawdown in artesian pressure and a corresponding expansion of water and compression of the mineral skeleton of the aquifer. The very small storage coefficient of a confined aquifer results in the rapid expansion of the cone of depression.

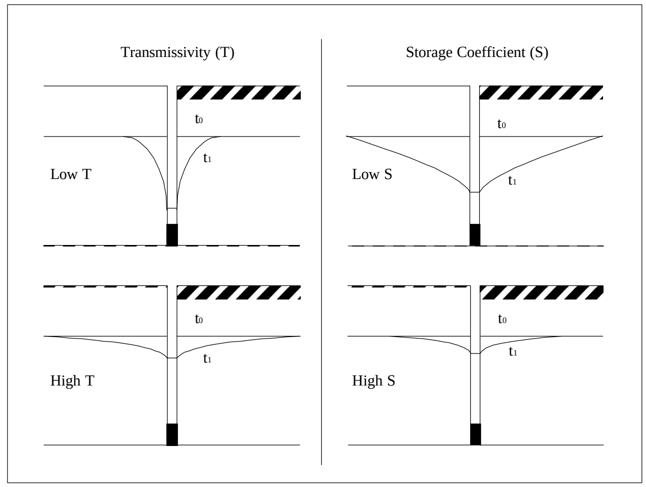

Figure 4-2. Influence of transmissivity and storage coefficients on cone of depression for similar aquifers at a constant pumping rate

c. Types of pumping tests.

(1) Constant-rate test. A constant-rate pumping test consists of pumping a well at a constant rate for a set period of time (usually 24 or 72 hr), and monitoring the response in at least one observation well. The number and location of observation wells is dependent upon the type of aquifer and the objectives of the study. Values of storage coefficient, transmissivity, hydraulic conductivity (if aquifer thickness is known), and specific capacity can be obtained.

(2) Step-drawdown test. During a step-drawdown test, the pumping rate is increased at regular intervals for short time periods. The typical step-drawdown test lasts between 6 and 12 hr, and consists of three or four pumping rates. Because step-drawdown pumping tests are typically much shorter than constant-rate pumping tests, transmissivity and storativity values are not as accurate for these tests. The primary value of the step-drawdown test is in determining the reduction of specific capacity of the well with increasing yields.

(3) Recovery test. A recovery test consists of measuring the rebound of water levels towards preexisting conditions immediately following pumping. The rate of recovery is a valuable source of data

which can be used for comparison and verification of initial pumping test results.

d. Pumping test design.

(1) General. Before implementing a constant-rate or step-drawdown pumping test, the well should be developed adequately to reduce the influence of well construction on aquifer response. Aquifer data from a pumping test should be derived from both the pumping well and appropriately placed observation wells. Small diameter pumping wells are preferable because of their quicker response to changes in hydraulic head. The accuracy of data taken from a pumping well is often less reliable because of turbulence created by the pump. Furthermore, drawdown data from an observation well are required for the accurate calculation of the storage coefficient of the aquifer. Thus, at least one observation well should be used when practicable. Design of a field pumping test (also called an aquifer test) is as much art as it is science, and requires judgement tempered by experience. Assumptions must be made concerning the type of aquifer and its characteristics, and a suitable test developed based on those assumptions. The following procedure may be followed as a guide to design an aquifer pumping test.

(2) Development of conceptual geologic model. To design a pumping test, it is necessary to have some knowledge (or make assumptions) of the subsurface stratigraphy. Items of concern include the type, thicknesses, and dip of strata, as well as the ease with which this strata can be drilled. If no borings have been drilled in the project area, it will be necessary to start with a geologic literature search of USGS and state agency documents (see Section 3-2).

(3) Development of conceptual hydrologic model. Items of concern include type and depth of the aquifer(s), as well as the hydraulic conductivity, transmissivity, storativity or specific yield, and yield and specific capacity of pumping wells. Water quality may also be a concern, particularly if a discharge permit is required for disposal of the pumped water. If no wells have been drilled in the project area, it will be necessary to glean this information from U.S. Geological Survey (USGS) or state agency reports, or to make assumptions that seem reasonable based on the conceptual geologic model. Nearby property owners may have wells and can be of some help, as can local water well drillers.

(4) Define the test objectives. While it may at first seem that the objectives are simply to “learn about the aquifer,” on further examination the question becomes “What exactly do you want to learn about the aquifer?” Is this test being conducted as part of a water budget study where the concern is defining transmissivity and storativity; or is the test part of a water supply study where the concern is specific capacity and safe well yield; is the test part of a groundwater contaminant transport study where the ultimate question is the velocity of the groundwater? Is there any concern between the possible interconnection of two or more separated aquifers, such as a near-surface water table aquifer and a deeper artesian aquifer? A careful definition of the test objectives is essential to ensure a successful test.

(5) Determining the well pumping rate (Q). It is usually desirable to pump at the maximum practical rate so as to stress the aquifer as much as practical for the duration of the test. This translates into more drawdown at the pump well and observation wells, and therefore more data available for the final analysis. The maximum rate will be limited by the efficiency of the well construction and the specific capacity of the well, and should be a rate such that the well will not be dewatered below the pump intake screen during the duration of the test. If a new well is to be drilled for this pump test, then it will be necessary to initially assume a pumping rate based on the conceptual hydrologic model previously mentioned.

(6) Determining the test duration (t). Practical constraints usually limit the time available for the test, and at a maximum it is useless to run the test beyond the point at which a steady-state condition is reached (i.e., no more drawdown) or the point at which the pumping well intake screen begins to dewater. Pumping tests last anywhere from 6 hr to 2 weeks, depending on the objectives and the aquifer characteristics, but most probably fall between 1 and 3 days for the pumping phase of the test, followed by an equal amount of time to monitor the recovery.

(7) Determining the observation well locations. Observation wells should be located in areas of influence of the pumping test. However, wells placed too close to the pumping well will be influenced by the vertical flows in the immediate vicinity of the pump well and may yield erroneous data. A good rule of thumb is to place the observation wells a distance no less than (1.5)(*b*) from the pumping well, where *b* is the aquifer thickness. However, this rule has often been violated with no apparent ill effects, especially for low pumping rates. To determine the maximum radial distance (*r*) at which observation wells can be placed from the pumping well, assume a minimal drawdown (*s*) that you believe to be significant, and solve the appropriate discharging well analytical equations in reverse. To check for aquifer anisotropy, locate wells at equal distances from the pumping well but in differing azimuthal directions. To allow for distance drawdown solutions and to allow for calculation of the cone of influence of the pumping well, locate wells at differing radial distances from the pumping well. Project budgets will usually provide a practical constraint for the number of observation wells, so well locations must be optimized to fit the test objectives, and compromises often must be made. In the event that an observation well(s) cannot be optimally located, then the observation well(s) should be replaced with a cluster of depth-staggered piezometers. A piezometer cluster would have at least one piezometer at (0.25)(*b*) and another at (0.75)(*b*). Using depth-staggered piezometers allows the collection of draw-down data which can be readily corrected for partial penetration and delayed yield.

(8) Drill the pumping well. Since the conceptual models developed earlier are not absolutes, it is often necessary to reevaluate and refine these models as actual field data are obtained. The first well drilled should be the pumping well, and it should be thoroughly logged as drilled to evaluate the actual site stratigraphy. A performance test should be conducted on this well as soon as possible after completion, and prior to drilling the observation wells. Down-hole tests may be conducted on the open hole prior to constructing the well to obtain hydrologic data on particular zones. These tests may consist of either pump-in (pressure tests) or pump-out (variable head) tests, and can be analyzed by methods as explained in U.S. Department of Interior (1977). These tests will yield data to refine the earlier estimates of specific capacity, well yield, transmissivity, hydraulic conductivity, and aquifer thickness.

(9) Refine the conceptual geologic and hydrologic models. Use the data obtained from the first well drilled to reevaluate the pumping rate, test duration, and observation well locations. Make changes to the field layout as needed. From a practical standpoint, this may have to be accomplished in a motel room at night after working all day in the field with the drilling crew.

(10) Drill the first observation well and perform a mini-pumping test. It would be most conservative to drill the closest observation well first, since this well will predictably have the greatest drawdown of all the planned observation wells. Use the refined conceptual models to predict drawdown in the single observation well after a short period of pumping (1 to 4 hr recommended). Measure drawdown in both the pumping well and the observation well, and compare the measured and predicted values. Further refine the conceptual models as necessary and drill the remaining observation wells.

e. Single well tests. It is also possible to obtain useful data from production wells when data from observation wells are not available. The procedure for this determination is similar to the Jacob method. Values of drawdown are recorded directly from the pumping well. However, because of well loss in the pumping well, the estimates of storativity and transmissivity derived from the straight-line intercept with the line of zero drawdown are a rough approximation.

f. Well interference. Well interference occurs when the cones of depression from adjoining wells intersect. Well interference reduces the available drawdown, and the maximum yield of a well.

g. Aquifer boundaries. Aquifer boundaries can be of two types: recharge and impermeable. A recharge boundary is a boundary which serves as a potential or actual source of recharge to the aquifer, and has the effect of decreasing the response of an aquifer to withdrawals. Examples of recharge boundaries include zones of contact between the aquifer and rivers, lakes, and mountain-front recharge areas. An impermeable boundary is a zone of contact across which minimal flow occurs. Impermeable boundaries have the effect of increasing the response of the aquifer to withdrawals. One of the assumptions of analytical methods used to analyze pump test data is that the aquifer to which they are applied is infinite in extent. This assumption is commonly met for practical purposes in aquifers that are aerially extensive to a degree where pumping will not have an appreciable effect on recharge and discharge, and most water is derived from groundwater storage. In situations where lateral boundaries have an appreciable influence on aquifer response, the hydraulic effect can be assumed, for analytical convenience, to be due to the presence of other pumping wells, called image wells. A recharge boundary has the same effect on drawdowns as a recharging image well, and an impermeable boundary has the same effect on drawdowns as a discharging image well.

4-7. Slug Tests

Slug tests are applicable to a wide range of geologic settings as well as small-diameter piezometers or observation wells, and in areas of low permeability where it would be difficult to conduct a pumping test. A slug test is performed by injecting or withdrawing a known volume of water or air from a well and measuring the aquifer's response by the rate at which the water level returns to equilibrium. Hydraulic conductivity values derived relate primarily to the horizontal conductivity. Slug tests have a much smaller zone of infiltration than pumping tests, and thus are only reliable at a much smaller scale. A general overview of slug tests can be found in Fetter (1994). Recommended references for in-depth discussions of slug tests and accompanying analytical methods are: Bouwer and Rice (1976); Bouwer (1989); Hvorslev (1951); Cooper, Bredehoeft, and Papadopulos (1967); and Papadopulos, Bredehoeft, and Cooper (1973).

4-8. Borehole Geophysics

a. General.

(1) Subsurface geophysical logging involves the lowering of a sensing device within a borehole for the determination of physical parameters of the adjacent rock and fluids contained in that rock. This is accomplished by the propagation or detection of electrical currents, radiation, thermal flow, or sound waves through the surrounding subsurface. Geophysical well logs can be interpreted to determine the lithology, geometry, resistivity, formation factor, bulk density, porosity, permeability, moisture content, and specific yield of water-bearing rocks, and to define the source, movement, and chemical and physical characteristics of groundwater. Borehole geophysical logs provide a continuous record of various natural or induced properties of subsurface strata and of the pore fluids contained within those strata. Borehole geophysics also provide information about the fluid standing within the borehole and well construction. These data, when interpreted in a conjunctive manner, can provide accurate and detailed information about subsurface conditions.

(2) A general overview of borehole geophysical methods is presented in this section. For a more in-depth discussion, the following references are recommended: EM 1110-1-1802, Keys and MacCary (1971), and Taylor, Hess, and Wheatcraft (1990).

b. Planning a well logging program. The objective of any well logging program should be to acquire data on a real-time basis and to develop the background data to be able to monitor changes in the borehole environment over time. Borehole geophysical logs require calibration in the geologic environment in which they will be run. This is because logs have non-unique response, and there are no published or standard correction factors for many geologic media common to groundwater studies, such as all igneous rocks, metamorphic rocks, and certain sedimentary rocks such as conglomerates. Calibrating for a geologic environment in which little or no data is available will require that core samples be obtained and tested for physical properties such as density, porosity, and saturation. Logging company contracts typically contain a clause which states that they are not responsible for the quality of the data. This principle is part of the larger concept of a quality assurance/ quality control (QA/QC) program. At a minimum, a logging QA/QC program should consider the following:

(1) Calibration. When was the tool last calibrated and how? Tools should be calibrated at standard pits on a regular basis. These pits are located at the University of Houston and at the U.S. Geological Survey Denver Field Center. Calibration also means the use of field standards to check the tool at the beginning and end of each day.

(2) Core analysis. Preferred, necessary in new area.

(3) Water analyses. Essential, also includes mud analyses.

(4) Well construction details. Essential if logging inside existing well.

(5) Local hydrogeology. Essential for understanding logs and anticipating problems and/or anomalies.

(6) Logging procedures. Essential, requires onsite presence. An example is logging speed. Some logs should run at speeds as low as 7.5 m/min (25 ft/min).

(7) Data processing. All logs need some correction. Depth is commonly ±5 m (15 ft), scales off up to ±20 units. Additionally, borehole effects need to be corrected for. In order to perform this type of error analysis, the data (log) must be digitized so corrections can be made and the data replotted.

(8) Drilling. Carry out drilling operations in a manner that produces the most uniform hole and least disturbance to the formation.

The final principle to keep in mind is that logs should always be interpreted collectively, on the basis of a thorough understanding of the principles and limitations of each type of log, and a basic understanding of the hydrogeology of the study area. Table 4-1 summarizes the application of various types of logs. Figure 4-3 presents an example of the conjunctive use of borehole geophysical logs.

c. Types of logs.

(1) Caliper log.

(a) Principle. A caliper log is a record of the average borehole diameter. It is one of the first logs

Table 4-1
Applications of various borehole geophysical methods

Parameter	Borehole Geophysical Method
Stratigraphy and porosity	Natural gamma log Gamma-gamma log Acoustic log Neutron log Spontaneous potential log
Stratigraphy	Caliper log Resistance log
Moisture content	Neutron log
Location of zones of saturation	Spontaneous potential log Temperature log Neutron log Gamma-gamma log
Physical and chemical characteristics of fluids	Resistivity log Spontaneous potential log Temperature log Fluid conductivity log
Dispersion, dilution, and movement of waste	Fluid conductivity log Temperature log Gamma-gamma log

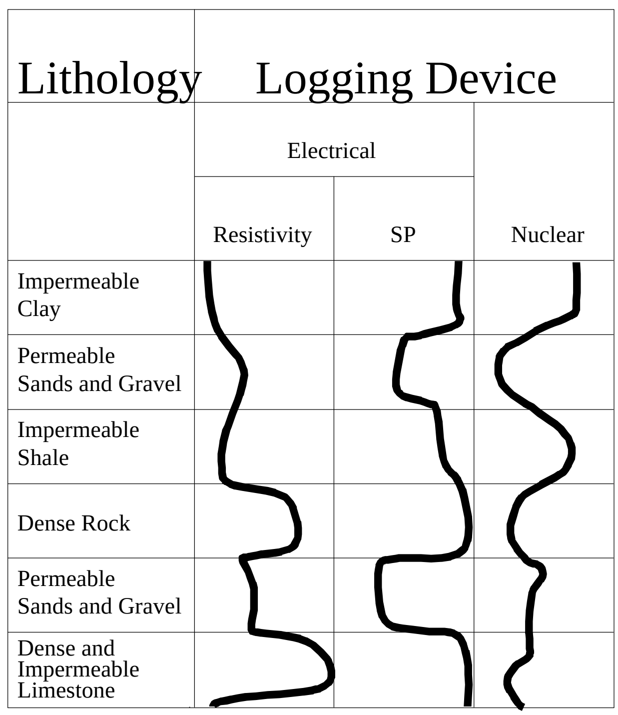

Figure 4-3. Conjunctive use of borehole geophysical logs

which should be run, and one of the most useful and simplest tools. The caliper log is necessary for the selection of the size of other tools and for any borehole corrections to other logs. Most caliper tools consist of a body or sonde with from one to four "arms" that follow the borehole wall.

(b) Application. Caliper logs are utilized for identification of lithologic horizons, location of fractures or other openings in the borehole wall, guidance in well design and construction, and most importantly, for the borehole correction needed for other logs such as single point resistance and gamma-gamma.

(2) Fluid conductivity and temperature logs.

(a) Principle. Fluid-conductivity logs provide a measurement of the conductivity of the fluid within the borehole, which may or may not be related to the fluid(s) in the formation. Generally, the conductivity is derived from measuring the potential drop between two closely spaced electrodes.

(b) Application. Fluid-conductivity measurements are needed for the correction of other logs which are sensitive to changes in the electrochemical nature of the borehole fluid(s) such as spontaneous potential and most resistance logs. It is good practice to make a temperature log simultaneously with the fluid-conductivity log. This allows the most accurate conversion to specific conductance, which is needed to calculate equivalent salinity, by avoiding the disturbance of the fluid column that may be induced by running a separate thermal probe prior to the fluid-conductivity probe. Fluid conductivity and temperature logs should be run at the beginning of the logging process.

(3) Spontaneous potential log.

(a) Principle. The spontaneous potential (SP) tool measures the natural electric potential between borehole fluid and the formation. The SP log must be run in an uncased borehole filled with a conductive fluid. Two sources of potential are recognized. The first, and least significant, is the streaming potential caused by dissolved electrolytes such as NaCl, moving through a porous media. This phenomenon occurs where filtrate is lost to the formation or where the borehole is gaining or losing fluid. The second, and most significant, is the electrochemical reaction that occurs at the interface between dissimilar materials. Currents tend to flow from the borehole into permeable beds until sufficient cross-sectional area of a resistant bed is encountered to carry the current.

(b) Application. The SP log can be used for lithologic identification or correlation. As previously discussed, the direction of the deflection of the SP log is an indication of either sand or shale. It is only a qualitative indicator and should never be used alone. Thus, SP should not be used for calculating water quality during hydrogeologic investigations.

(4) Resistance logging.

(a) Principle. Resistance logging provides a calculation of the resistance, in ohms, of the geologic materials between an electrode placed within the borehole and an electrode placed at the surface or between two electrodes placed within the borehole. The resistance log must be run in an uncased borehole filled with a conductive fluid. A potential difference in volts or millivolts is measured between the two electrodes and the resistance is calculated by Ohm's Law when the current I is held constant:

$$E = I\,r \tag{4-1}$$

where

E = potential [volts]

I = current [amperes]

r = resistance [ohms]

(b) Application. The most common type of resistance logging is the single point or point resistance method. Because the radius of investigation is small, the single point resistance log is strongly affected by the conductivity of the borehole fluid and variation of borehole diameter. Single point resistance logging is very useful because any increase in formation resistance produces a corresponding increase in the resistance recorded on the log and thus deflections on a single point log can be attributed to changes in lithology (although the response is nonlinear). Single point systems do not experience the log reversal at thin beds that multielectrode systems do. These properties make the single point log one of the better logs for lithology or stratigraphic correlation.

(5) Resistivity logging.

(a) Principle. Though their names are similar, resistivity logging is different from resistance logging. Resistivity includes the dimensions of the material being measured and is an electrical property inherent to the geologic material. The relationship between resistance and resistivity is analogous to that of weight and density. Resistivity is defined by:

$$R = r \times S / L \tag{4-2}$$

where

R = resistivity [ohm-meters]

r = resistance [ohms]

S = cross-sectional area [L^2]

L = length [L]

The resistivity of sediments depends on the physical properties of those sediments and the fluid(s) they contain. Most sediments are composed of particles of very high electrical resistance. All resistivity logs must be run in an uncased borehole filled with a conductive fluid. When saturated, the water filling the pore spaces is relatively conductive compared to the sediments. Thus, the resistivity of sediments below the water table is a function of the salinity of the water filling pore spaces and how those pore spaces are interconnected. Resistivity logging devices measure the electrical resistivity of a known (assumed) volume of geologic material using either direct or induced electrical currents. Below the water table the resistance of a formation depends on the composition of the water within it, and on the length and shape of interconnected pores.

(b) Application. Resistivity logs are generally used to estimate the physical and chemical characteristics of fluids, formation resistivity and porosity, and mud resistivity. Normal logs are the most commonly used resistivity tools in groundwater investigations. Normal logs measure the apparent resistivity of a volume of geologic material surrounding the electrodes. The records produced by normal devices are affected by bed thickness as well as bed resistivity. As bed thickness decreases, the resistivity peak decreases in amplitude.

(6) Natural-gamma logs.

(a) Principle. Some of the most useful logging methods involve the measurement of either natural radioactivity of the geologic media and the fluids within it, or the attenuation of induced radiation. Nuclear methods can be used in either open or cased boreholes provided there are not multiple casing strings and seals. Natural-gamma logs are records of the amount of natural-gamma radiation emitted by geologic materials. The chief uses of natural-gamma logs are the identification of lithology and stratigraphic correlation. Potassium, of which about 0.012 percent is K_{40}, is abundant in feldspars and micas which decompose readily to clay. Clays also concentrate the heavy radioelements through the processes of ion exchange and adsorption. In general, the natural-gamma activity of clay-rich sediments is much higher than that of quartz sands and carbonates. The radius of investigation of a natural-gamma probe is a function of the probe, borehole fluid, borehole diameter, size and number of casing strings and seals, density of the geologic materials, and photon energy.

(b) Application. The most important application in groundwater studies of the natural-gamma log is the identification of clay- or shale-bearing sediments. Clays tend to reduce the effective porosity and hydraulic conductivity of aquifers, and the natural-gamma log can be used to empirically determine the shale or clay content in some sediments. The natural-gamma log does not have a unique response to lithology. The response is generally consistent for a given locality.

(7) Gamma-gamma logs.

(a) Principle. Gamma-gamma logs are records of the intensity of gamma radiation from a source in the probe after the radiation has been backscattered and attenuated within the borehole and surrounding geologic materials. The gamma-gamma probe contains a source of gamma radiation, generally cobalt-60 or cesium-137, shielded from a sodium iodide detector. Gamma radiation from the source penetrates and is scattered and absorbed by the fluid, casing, grout, and geologic materials surrounding the probe. Gamma radiation is absorbed and/or scattered by all material through which it travels. The radius of investigation of gamma-gamma probes is reported to be about 15 cm (6 in.). The bulk density of the geologic material, fluids, or casing and seals will affect the radius of investigation. The distance between the source and detector will also significantly alter the volume of material investigated.

(b) Application. The main uses of gamma-gamma logs are for the identification of lithology, and the measurement of bulk density and subsequent determination of porosity. They may also be used to locate cavities and grout outside of casing. Gamma-gamma density is widely used for determination of total porosity by:

$$\text{Porosity} = \frac{\text{Grain density} - \text{Bulk density (from log)}}{\text{Grain density} - \text{Fluid density}} \qquad (4\text{-}3)$$

Grain density can be derived from laboratory analyses of cores (or, for quartz sands, a value of 2.65 g/cc can be used). The fluid density for groundwater studies is assumed to be 1 g/cc; however, if the fluid is saline or contains levels of contaminants high enough to alter fluid density, then laboratory analysis of density is necessary. In an unconfined aquifer or a partially dewatered confined aquifer, it should be possible to derive specific yield from gamma-gamma logs. Specific yield should be proportional to the difference between the bulk density of saturated and drained sediments, assuming porosity and grain density do not change. Bulk density may be read directly from a calibrated and corrected log or derived from charts providing correction factors. Errors in bulk density obtained by gamma-gamma methods are on the order of ± 2 percent. Errors in the porosity calculated from log-derived bulk densities depend upon the accuracy of grain and fluid densities used. In addition to determining porosity, gamma-gamma may be used to locate casing, collars, or the position of grout outside the casing. Gamma-gamma logs can also indicate water level and significant changes in fluid density (fresh water-brine interface). A license must be obtained to use a gamma-gamma log.

(8) Neutron logs.

(a) Principle. The various types of neutron logs are potentially the most useful techniques in borehole geophysics as applied to groundwater studies. This is due to the fact that the measured response is due to hydrogen and thus, generally, water. Neutron logs also have advantages over other nuclear logs in that they can be run in liquid-filled or dry holes, cased or uncased holes, and have a relatively large volume of influence. In neutron logging, neutrons are artificially introduced into the borehole environment, and the effect of the environment on the neutrons is measured. Assuming that the vast majority of hydrogen occurs in the form H_2O, materials with higher porosity (and thus higher water content) will slow and capture more neutrons, resulting in fewer neutrons reaching the detector. The converse is true for materials of low porosity. This assumption does not hold when hydrocarbons, chemically or physically bound water, and/or other hydrogenous materials are present. Neutron logs are affected by changes in borehole conditions to a lesser degree than other geophysical logs that measure the properties of geologic materials. The most marked extraneous effect on neutron logs is caused by changes in borehole diameter.

The volume of influence, which is defined by the radius of investigation, is an important factor in the analysis of neutron logs. The radius of investigation is a function both of the source-detector spacing, the petrology of the material, and the water content within the volume of influence. The radius of investigation of neutron tools has been reported to be from 15 cm (6 in.) for high-porosity saturated materials to 60 cm (2 ft) in low-porosity materials. These estimates may be conservative, as recent laboratory work with semi-infinite models suggests that the radius of investigation in saturated sands was greater than 50 cm (20 in.).

(b) Application. Neutron logs are used chiefly for the measurement of moisture content in the unsaturated zone and total porosity (water filled) in the saturated zone. In most geologic media the hydrogen content is directly proportional to the interstitial-water content; however, hydrocarbons, chemically or physically bound water, or any hydrogenous material can give anomalous values. For example, gypsum has a high percentage of water associated with the crystal structure which can result in it appearing to be a material of high porosity. This has been used to distinguish between anhydrite (high neutron count rate) and gypsum (low neutron count rate). Although a neutron log cannot be used to measure porosity above the water table, it is very useful for measuring changes of water content in the unsaturated zone. A license is required to use a neutron log.

(9) Acoustic logs.

(a) Principle. Acoustic logging utilizes a transducer to transmit an acoustic wave through the borehole fluid and into the surrounding rocks. The four most common types of acoustic logs are: acoustic velocity, acoustic wave form, cement bond, and acoustic televiewer. Acoustic logs can provide data on porosity, lithology, cementation, and fractures. Acoustic logging is appropriate only for consolidated (cemented) material. Acoustic-velocity logs, also called sonic logs or travel-time logs, are a record of the travel time of an acoustic wave from one or more transmitters to receivers in a probe. The velocity of the acoustic signal is related to the mineralogy and porosity of the formation. The radius of investigation of an acoustic-velocity probe is reported to be approximately three times its wavelength; the wavelength is equal to the velocity divided by the frequency. At a frequency of 20 kHz, this radius ranges from less than 30 cm (1 ft) in unconsolidated materials to about 120 cm (4 ft) in hard rocks.

(b) Application. Acoustic-velocity logs are useful for providing information about lithology and porosity when used in consolidated materials penetrated by uncased, fluid-filled boreholes. Transit times decrease with greater depth and with increases in cementation. Acoustic velocities may vary with confining pressure for several hundred feet below the ground surface, most notably in slightly consolidated materials. Secondary porosity will not be detected by an acoustic-velocity log because the acoustic wave will take the fastest path through the formation. Intervals of secondary porosity can be identified by cross-plotting data from an acoustic-velocity log and a neutron log or a gamma-gamma log.

4-9. Surface Geophysics

a. General. Surface geophysical methods generally do not provide the vertical resolution of borehole geophysical methods. However, surface geophysical methods provide valuable information on site geology on a greater spatial scale. Thus, conceptual model development often requires the conjunctive use of surface and borehole geophysical methods. Additionally, surface geophysical methods allow for the nonintrusive gathering of information on subsurface stratigraphy and hydrogeologic conditions. This section presents an overview of: seismic refraction and reflection, electrical resistivity, gravitational methods, electromagnetic methods, and ground-penetrating radar. Recommended references are included when a more in-depth understanding of concepts and principles is desired.

b. Seismic geophysical methods.

(1) The seismic exploration method deals with the measurement of the transmission, refraction, reflection, and attenuation of artificially generated seismic waves traveling through subsurface materials. The refraction and reflection methods are the most widely used seismic methods for hydrogeologic site characterizations. Both of these methods make use of the fact that seismic waves travel through different materials, such as soil, weathered rock, intact rock, etc., with differing velocities. Measurements are made by generating a seismic disturbance at or just below the ground surface and measuring the time required for the disturbance to travel through the ground and to one or more seismic sensors, called geophones, which are firmly implanted into the ground surface. With a suitable geometric arrangement of the seismic source and geophones, and theory to determine the probable travel paths, considerable information can be gained on the geometry and stratigraphy of the underlying soil and rock materials. In some cases, particularly in unconsolidated sediments, the depth to the water table may be computed.

(2) This section provides a brief overview of the seismic refraction and reflection methods, along with applications in hydrologic site characterization studies. Also, the strengths and weaknesses of each method will be assessed. For a more in-depth discussion, the following references are recommended: EM 1110-1-1802; Telford et al. (1990); and Zohdy, Eaton, and Mabey (1974).

c. Types of seismic geophysical methods.

(1) Seismic refraction.

(a) Principle. Seismic refraction technology is based on the fact that elastic waves travel through differing earth materials at different velocities. The denser the material, the higher the wave velocity. When seismic waves are propagated through a geologic boundary of two layers with separate densities, a refracting of propagation direction occurs. Through the propagation of a set of elastic waves, usually through small explosions, and the recording of the time travel at differing distances on a seismograph, the layer depths and their acoustic velocities can be estimated. Seismic refraction methods are only effective in formations with definite boundaries between strata and where density increases with each successive lower layer.

(b) Application. The acoustic velocity of a medium saturated with water is greatly increased in comparison with velocities in the vadose zone. Thus, the refraction method is applicable in determining the depth to the water table in unconsolidated sediments. The velocities associated with those of saturated unconsolidated materials, although indicative of saturation, are by no means unique. For example, a dry, weathered rock layer can exhibit the same velocity ranges as those normally associated with saturated, unconsolidated materials. The refraction method is also applicable in determining the depth and extent of a rock aquifer as well as the thickness of overlying unconsolidated materials. Common hydrologic problems that relate to this situation are that of mapping buried channels or determining the thickness of unconsolidated materials, whether saturated or not, in a bedrock valley.

One of the major limitations of the seismic refraction method is that each successive velocity layer must have a velocity greater than the one above it. If a low-velocity layer is between layers with greater velocities, the low-velocity stratum will not be detected and erroneous depths to deeper interfaces will be computed. However, in most hydrologic cases an increase in velocity as a function of depth can be expected (such as the case when there is a water table in sediments which are underlain by bedrock). Another limitation of the method is its inability to detect thin intermediate velocity layers. An example of this situation is a relatively thin saturated zone at the bottom of a thick sand layer which overlies a high-velocity bedrock surface. In this case, the refracted arrivals from the bedrock arrive prior to those from the top of the saturated sand and, as a consequence, the saturated layer will not be detected.

(2) Seismic reflection.

(a) Principle. The basic principle of seismic reflection is that seismic waves are reflected at interfaces between geologic units with different seismic velocities. Seismic velocities depend upon the elastic constants of a porous medium. The time required for an acoustic signal to travel from the source to the reflecting stratigraphic boundary and back to a defined point on the surface is measured by a geophone (Figure 4-4). The geophone detects the reflected signals from the various reflecting horizons and transmits this information to a seismograph where the times of arrival are recorded. By measuring the time the energy takes to propagate from the source to a reflecting horizon and back to the surface and by also knowing the velocity of the material along the path of travel, the depth to the reflecting horizons can be computed. By recording the output of each geophone in a seismic line, a visual representation of the local pattern of ground motion called a seismogram is obtained (Figure 4-5). By displaying the seismogram for each geophone side by side, a vertical profile of the subsurface may be obtained.

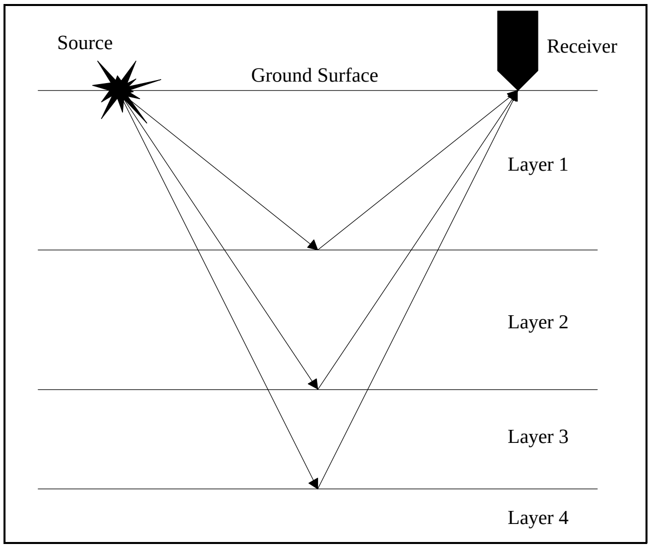

Figure 4-4. Reflected energy from three layers

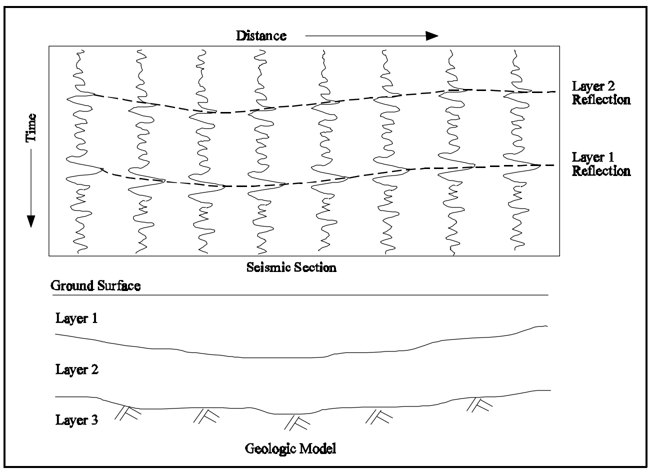

Figure 4-5. Illustration of seismic section for a hypothetical geologic model

(b) Application. One important advantage the reflection method has over the refraction method is that succeeding layers do not have to increase with velocity. The reflection method is more accurate, has better resolution, and can determine the depths to more layers than the refraction method. It also uses shorter geophone lines and uses smaller energy sources. Seismic reflection methods are capable of producing detailed information on subsurface structure. However, interpretation of seismic reflection data requires analysis by a trained geophysicist using powerful computer techniques; moreover, the collection of data requires expensive field equipment and large field teams (Smith and Wheatcraft 1991).

d. Additional surface geophysical methods.

(1) Surface electrical resistivity.

(a) Principle. Resistivity of a material is defined as the ability of that material to impede the flow of electric current through the material. In a surface resistivity survey, a direct current or low-frequency alternating current is sent through the ground between metal stakes or electrodes. The accompanying drop in electric potential is measured at a point between the current electrodes. Electrical resistivity displays a wider range of values than any other physical property in rocks (Zohdy, Eaton, and Mabey1974). Resistivity depends primarily on the amount, distribution, and salinity of water in the rock being studied. Saturated rocks have lower resistivities than unsaturated and dry rocks. Electrical resistivity methods are most useful in determining depth to rock and evaluating stratified formations where a denser stratum overlies a less dense stratum. Clays and conductive materials also reduce the rock's resistivity. An in-depth discussion of surface electrical resistivity can be found in EM 1110-1-1802.

(b) Application. Electrical resistivity methods have a variety of applications. Although the field techniques are relatively time-consuming, it is often the chosen method because surface resistivity surveying is one of the less costly geophysical techniques. Resistivity surveying is commonly used in groundwater studies for determining the water table depth, locating freshwater aquifers, mapping confining clay layers, and mapping saltwater intrusion and contaminant plumes. Other applications of electrical resistivity include: determination of depth to bedrock, cavern location in karst regions, permafrost mapping, and geothermal exploration.

(2) Gravitational methods.

(a) Principle. Gravitational methods are based on measurement of small variations in the gravitational field at ground surface. If subsurface rocks of differing density are present in the study area, the resulting irregularity in mass distribution will be reflected in a corresponding change in gravity intensity on the surface. Geophysical gravity surveys involve measurement of the magnitude and spatial variation of the earth's gravity field using a gravity meter. If the earth were perfectly spherical and radially uniform, the acceleration of gravity would be constant over the earth; however, this is not the case. Measurement, definition, and geological interpretation of the departures from radial uniformity are the objectives of gravity surveys; some of the departures are global or regional in scale, while some of the departures are local in nature. Local departures from radial uniformity in the subsurface are referred to as anomalies and give rise to local gravity variations or gravity anomalies. The concept of a gravity anomaly is illustrated in Figure 4-6, where the terms total or measured gravity, regional gravity trend, residual gravity, and gravity anomaly are defined.

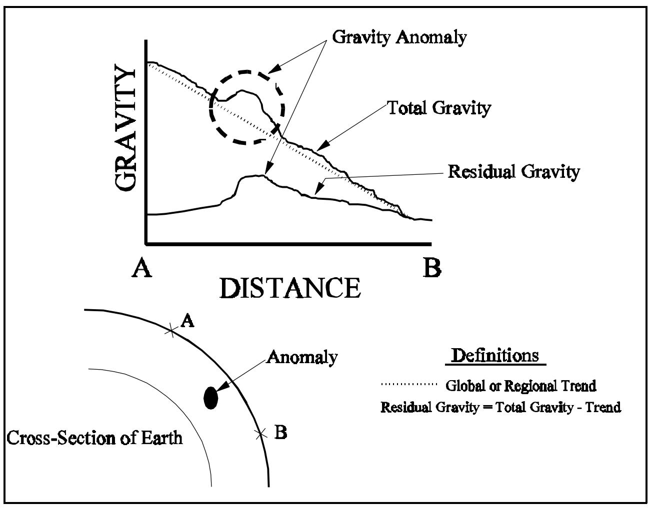

Figure 4-6. Concept of gravity anomaly and definition of residual gravity anomaly

(b) Application. For hydrogeologic investigations, gravity surveys have two primary applications. The first of these applications contributes to the definition of local- to regional-scale geology and is a standard or classical use of gravity surveys. Gravity surveys can be used to map “bedrock” topography, detect and map buried river channels (Figure 4-7), detect and map large fracture zones, and detect truncations or “pinchouts” of major aquifers or aquitards. The second application area for gravity surveys in hydrogeologic investigations involves the determination of fundamental hydrogeologic parameters or properties. Gravity surveys can be used for monitoring gravity changes associated with groundwater level changes; if the bulk porosity is known, the elevation change can be determined from the gravity change, or if the elevation change is known from a monitor well, a representative bulk porosity can be determined from the gravity change. An emerging application area for gravity surveys is to monitor gravity changes associated with a pumping well. Theoretically, if gravity surveys are conducted before and during well pumping, the shape of the drawdown curve can be determined, flow heterogeneity can be mapped, and estimates of bulk hydraulic conductivity can be determined from the gravity data. Telford et al. (1990) and Carmichael and Henry (1977) discuss standard gravity survey procedures in detail, and Butler (1980) discusses procedures for microgravity surveys.

(3) Electromagnetic methods.

(a) Principle. The electromagnetic (EM) method involves the propagation of time-varying, low-frequency electromagnetic fields in and over the earth. The electromagnetic method provides a means of measuring the electrical conductivity of subsurface soil, rock, and groundwater. Electrical conductivity is a function of the type of soil and rock, its porosity, its permeability, and the fluids which fill the pore space. In most cases the conductivity (specific conductance) of the pore fluids will dominate the measurement. Accordingly, the electromagnetic method is applicable both to assessment of natural hydrogeologic conditions and to mapping of many types of contaminant plumes. Additionally, trench boundaries, buried wastes and drums, as well as metallic utility lines can be located with electromagnetic techniques.

Natural variations in subsurface conductivity may be caused by changes in soil moisture content, groundwater specific conductance, depth of soil cover over rock, and thickness of soil and rock layers. Changes in basic soil or rock types, and structural features such as fractures or voids may also produce changes in conductivity. Localized deposits of natural organics, clay, sand, gravel, or salt-rich zones will also affect subsurface conductivity.

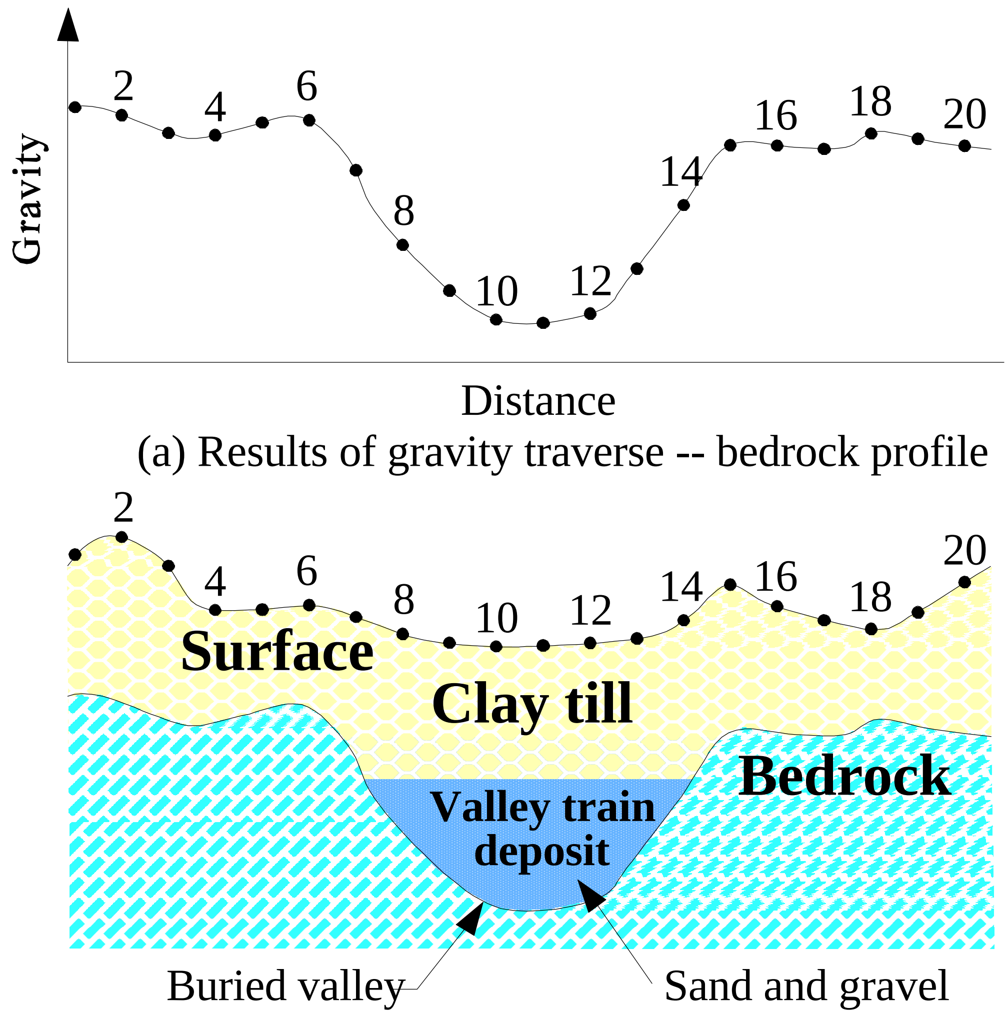

Figure 4-7. Illustration of Gravity Anomaly above a Buried Channel

(b) Application. There are two basic techniques available for electromagnetic surveying. Profiling is accomplished by making fixed-depth electromagnetic measurements along a transverse line to detect lateral variations. Sounding is accomplished by making conductivity measurements to various depths at a given location to detect vertical variations.

Electromagnetic systems are susceptible to signal interference from a variety of sources, originating both above the ground and below. Electromagnetic noise may be caused by nearby power lines, powerful radio transmitters, and atmospheric conditions. In addition to other forms of electromagnetic noise, instrument responses from subsurface or surface metal may make it difficult to obtain a valid measurement. Unique interpretation of subsurface conditions generally cannot be obtained from electromagnetic sounding data alone; it must be supported by drilling data or other geologic information.

(4) Ground-penetrating radar theory.

(a) Principle. Ground-penetrating radar (GPR) utilizes high frequencies of electromagnetic waves which are propagated in a straight line into the ground to depths which vary from a few feet to tens of feet, depending on the electrical conductivity of the terrain. The use of GPR is similar to the seismic reflection technique because both methods record the time required for a wave to travel to an interface between two formations and then reflect to the surface. In general, electromagnetic methods lack the resolution and depth penetration of resistivity surveys, but have the advantage of being rapid and less expensive.

In geologic materials, the presence of water is one of the most important factors determining electrical properties. In addition, ions dissolved in the water give rise to an electrical conduction mechanism which is a major factor in most soils and rock. Basically the conductivity is roughly proportional to the total dissolved solid content; hence, the more ions dissolved in the solution, the higher the conductivity. The electrical conductivity of a soil is much harder to predict. It is very dependent on the pore-water conductivity. In addition, it is dependent on the surface conduction mechanisms present in the soil matrix. Surface conduction addresses the charge transport associated with charges moving on the surface of the mineral grains. Generally surface conduction is very small in clean, coarse-grained material such as quartz sand; however, it is a major factor in fine-grained soils such as clays. As a result, clays are very important in GPR investigations because they have a strong impact on electrical conductivity of the medium. As electromagnetic waves propagate downward into the ground, reflections are generated by changes in the electrical impedance in the ground.

(b) Application. Before starting a GPR survey, one must determine if the site conditions and desired target are suitable. Of primary concern is the target depth; GPR has a very definite and often limited depth of investigation based on the site geology. Clay and saturated soils attenuate the GPR signal, thereby severely limiting the depth of penetration. The target size should also be qualified as accurately as possible. In order for GPR to work, the target must present a contrast in electrical properties to the host environment in order that the electromagnetic signal be modified, reflected, or scattered. The host material must be qualified in two ways. First, the electrical properties of the host must be defined. Second, the degree and spatial scale of heterogeneity in the electrical properties of the host must be estimated. If the host material exhibits variations in properties which are similar to the contrast and scale of the target, the target may not be recognizable from the responses generated by the host environment. Lastly, the area where the survey is to be performed should be free of the presence of extensive metal structures and of radio frequency electromagnetic sources or transmitters.

4-10. Cone Penetrometer Testing

a. General. Cone penetrometer testing (CPT) has been utilized in the geotechnical field for at least 65 years. Benefits of using the CPT system include lower costs, faster data acquisition, less invasive disturbance to the subsurface, and no acquisition-derived wastes. A CPT apparatus is typically truck-mounted, similar to a drilling machine. A basic CPT system consists of four basic components; the truck, hydraulic thrust system, data acquisition and reduction system (computers), and the sensor assembly, i.e. the cone. (Figure 4-8). The truck not only transports the CPT unit, but also supplies the power to drive the CPT system. In addition, the truck also provides the mass necessary to counteract the hydraulic thrust. Truck sizes vary anywhere from 4,400 to 28,500 kg, with 17,500 kg being most common.

b. Hydraulic thrust system. The hydraulic thrust system provides the force to push the sounding rod(s)/cone assembly into the ground. The depth of penetration is a function of several factors; truck weight, soil density and cementation skin friction on rods, and deviation (from vertical) of rods. Depending upon the interaction of these factors, CPT has been done at depths up to 100 m (300 ft), with depths of 25 to 30 m (80 to 100 ft) routine. This makes CPT a truly practical alternative to drilling.

c. Data acquisition system. The data acquisition and reduction system receives the signals from the sensor in the cone assembly and processes them,

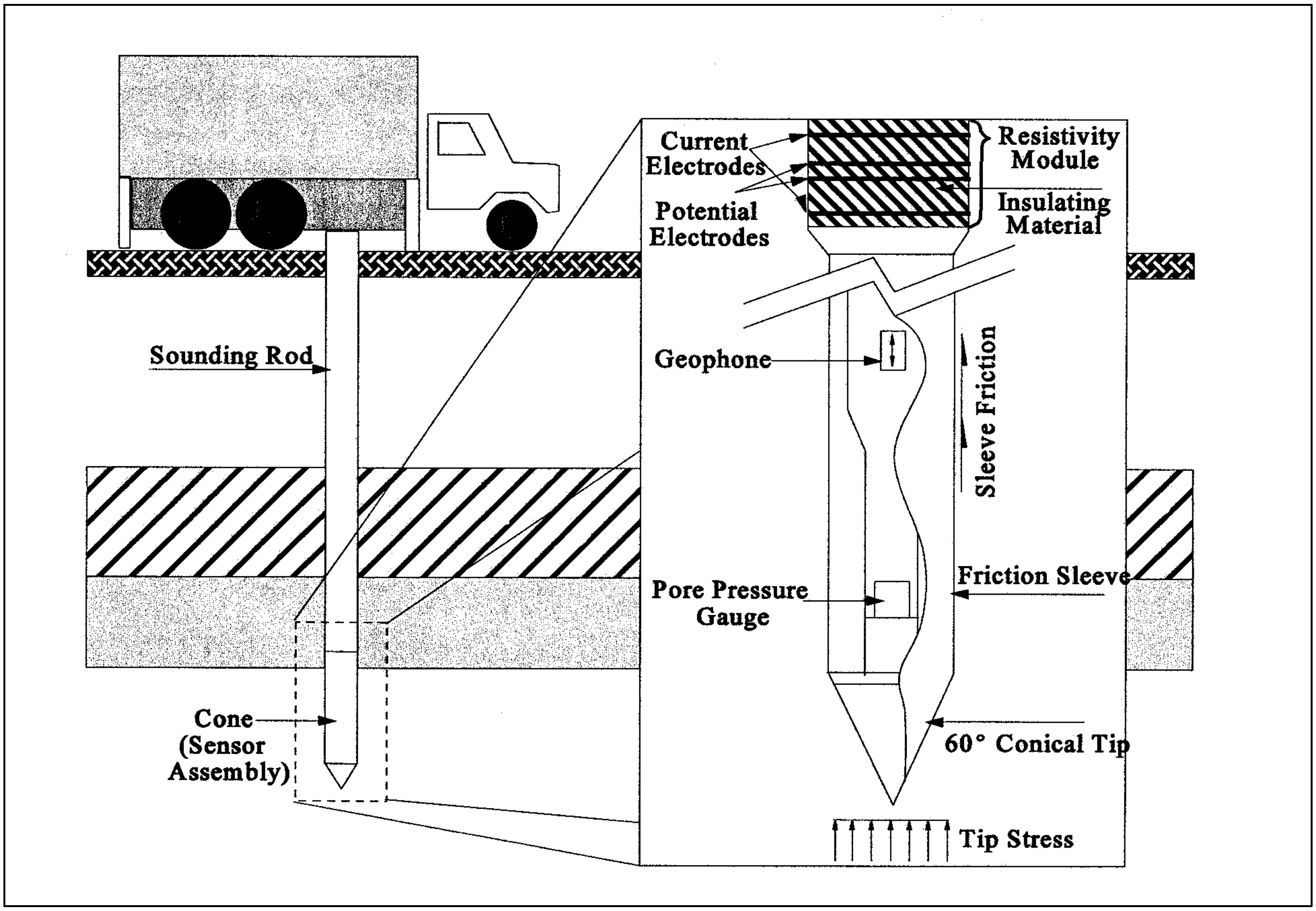

Figure 4-8. Components of cone penetrometer testing system

providing both digital and hard copy of raw data and basic interpretation. Interpretations are in the form of soil behavior types, which are based upon a database relating the ratio of skin friction to the tip resistance to soil type. In addition, the data acquisition and reduction system performs system monitoring to ensure the sensors are functioning properly. The type of data that can be acquired and processed is limited only by the selection of sensors. Currently, there are proven sensors for soil type (stratigraphy), pore pressure (water content/water table), soil electrical resistance, seismic velocity, radiation (gamma), laser-induced florescence, temperature, pH, and soil gas and groundwater sampling. The CPT system does not produce samples for direct observation. Thus, it is preferable for the CPT to be used in conjunction with lithologic data obtained from standard drilling methods.

d. Sensor assembly. The cone assembly houses all the sensor elements. The sensors within the cone are connected to the data acquisition and reduction system by a multi-lead electrical cable which runs through the center of the sounding rods. When sampling soil, groundwater, or soil gas, the cone containing the sensor elements fig4-8is replaced with a "dummy." The dummy has a tip which is pushed ahead of the sounding rods, exposing the annulus of the rods to the environment, allowing the insertion/use of various soil, water, and gas samplers.

e. Limitations. Limitations of the CPT method include:

(1) Smaller trucks require an anchoring system which is sometimes difficult to get.

(2) Large trucks with reaction mass pose access problems.

(3) Rocks/debris in the near surface can interfere with data acquisition.

f. Site characterization and analysis penetrometer system (SCAPS). SCAPS is a resource to be used by all Corps districts and laboratories for the investigation of HTRW sites. An in-depth explanation of SCAPS capability, along with points of contact, can be found in ETL 1110-1-171.

4-11. Isotope Hydrology

a. General. Isotopes are atoms of the same element that have different masses; they have the same number of protons and electrons, but a different number of neutrons (Figure 4-9). The 92 natural elements give rise to more than 1,000 stable and radioactive isotopes. These are often called environmental isotopes. Environmental isotopes are commonly categorized into two general groups: stable isotopes and unstable isotopes. Stable isotopes are not involved in radioactive decay. Most stable isotopes do not react chemically in the subsurface environment and are of particular use in determining the source of groundwater. Unstable isotopes are undergoing decay. Unstable isotopes are of particular use in determining the age of water. The relative abundance of isotopes of hydrogen, oxygen, and carbon in the hydrologic cycle is presented as Table 4-2. An in-depth discussion on the use of environmental isotopes can be found in Fritz and Fontes (1980).

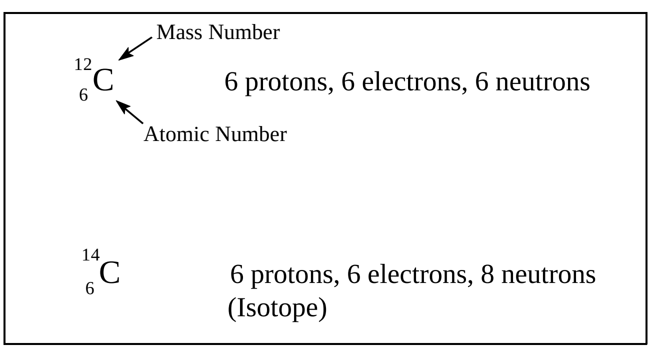

Figure 4-9. Example of carbon isotope ^{14}C

Table 4-2
Relative Abundance of Isotopes of Hydrogen, Oxygen, and Carbon in the Hydrologic Cycle (Freeze and Cherry 1979)

Atom	Relative Abundance (%)	Type
^{1}H	99.984	
^{2}H (deuterium)	0.016	Stable isotope
^{3}H (tritium)	$0\text{-}10^{-15}$	Radioactive isotope (½ life 12.3 yr)
^{16}O	99.76	
^{17}O (oxygen-17)	0.04	Stable isotope
^{18}O (oxygen-18)	0.20	Stable isotope
^{14}C (radiocarbon)	<0.001	Radioactive isotope (½ life 5,730 yr)

b. Stable isotopes.

(1) General. Stable isotopes can serve as natural tracers that move at the average velocity of groundwater, and are of particular use in determining the recharge areas, degrees of mixing between waters of different origin, and hydrograph separation. The most common stable isotopes used in hydrologic analysis are ^{18}O and ^{2}H (also known as deuterium or D).

(2) Isotopic fractionation. In lighter elements, such as hydrogen (H), and oxygen (O), the differences in mass produced by isotopes is significant to the total mass of the atom. These differences in mass cause isotopic fractionation in nature. Isotopic fractionation is any process that causes the isotopic ratios in particular phases or regions to differ from one other. For example, the ratio of $^{16}O/^{18}O$ in rain is different from the ratio in the oceans. This ratio is represented by δ:

$$\delta^{18}O = \frac{(^{18}O/^{16}O)_{sample} - (^{18}O/^{16}O)_{standard}}{(^{18}O/^{16}O)_{standard}} \times 1{,}000 \qquad (4\text{-}4)$$

Similarly, the isotopic fractionation ratio of ^2H (deuterium-D) is represented by δD. For a specific area, the relationship between $\delta^{18}O$ and δD in rainfall is approximately linear and can be plotted on a meteoric water line, an empirically derived relationship for continental precipitation.

(3) Use of stable isotopes as natural tracers. Isotopic fractionation of $\delta^{18}O$ and δD during phase changes enriches one isotope relative to another. Water that has been subject to evaporation is enriched in ^2H (D) relative to ^{18}O because of its lower atomic weight. Fractionation is temperature-dependent. For example, winter precipitation is depleted in ^{18}O and ^2H compared with summer precipitation. Additionally, precipitation at the beginning of a storm is often higher in ^{18}O and ^2H than at the end of the storm, as the heavier isotopes are selectively removed from the vapor phase. These processes provide water masses with unique signatures that can be used as natural tracers in groundwater studies. Hence, the source areas of different waters, and the mixing patterns between waters can be assessed.

(4) Use of stable isotopes for hydrograph separation. Stable isotopes have also been used in hydrograph separation (Sklash 1990). Rivers have two principal sources of water: surface runoff, and groundwater. In rivers where runoff is the major source of water, large seasonal variations in $\delta^{18}O$ and δD are measured. In rivers where groundwater (baseflow) is the major source, these variations in $\delta^{18}O$ and δD are much less significant due to a much longer retention period and aquifer mixing.

c. Unstable isotopes.

(1) General. Unstable isotopes are of particular use in determining the age of water. Radioactive decay is the conversion of atomic mass to energy in the form of gamma rays, alpha particles, etc., over time:

$$-\frac{dM}{dt} = kM \qquad (4\text{-}5)$$

where

M = mass of unstable isotope

k = decay constant

The half-life ($t_{½}$) of an isotope is defined as the time period in which half of the initial amount of unstable isotopes have decayed and can be calculated by the following formula:

$$t_{1/2} = \frac{\ln 2}{k} \qquad (4\text{-}6)$$

The two most commonly used unstable isotopes in groundwater hydrology are ^3H (tritium) and ^{14}C (radiocarbon). ^{36}Cl (radiochloride) is also used for the dating of very old groundwater.

(2) ^3H (tritium). Tritium has a half-life of 12.3 years. Small amounts are produced naturally in the atmosphere. Between 1952 and 1969 nuclear testing in the atmosphere raised the tritium content in rainfall from 5-10 TU (tritium units) in the 1940's to 100-1,000 (or more) TU in the 1960's. The peak of tritium levels occurred in 1963 (Figure 4-10). Currently (in 1996) the tritium content in rainwater is approximately 10-30 TU. Tritium in groundwater is not significantly affected by chemical processes. Common uses of tritium analysis include:

(a) Distinguishing between water that entered into the aquifer prior to 1952 (pre-bomb), and water that was in contact with the atmosphere after 1953.

(b) Estimating recharge rates by locating the depth of the tritium peak which occurred in 1963 (Robertson and Cherry 1989).

(c) Estimating groundwater flow velocity.

Because of hydrodynamic dispersion, mixing of aquifer waters, and the variable tritium source, age estimates are best viewed as one more input in the formulation of a hydrogeologic conceptual model,

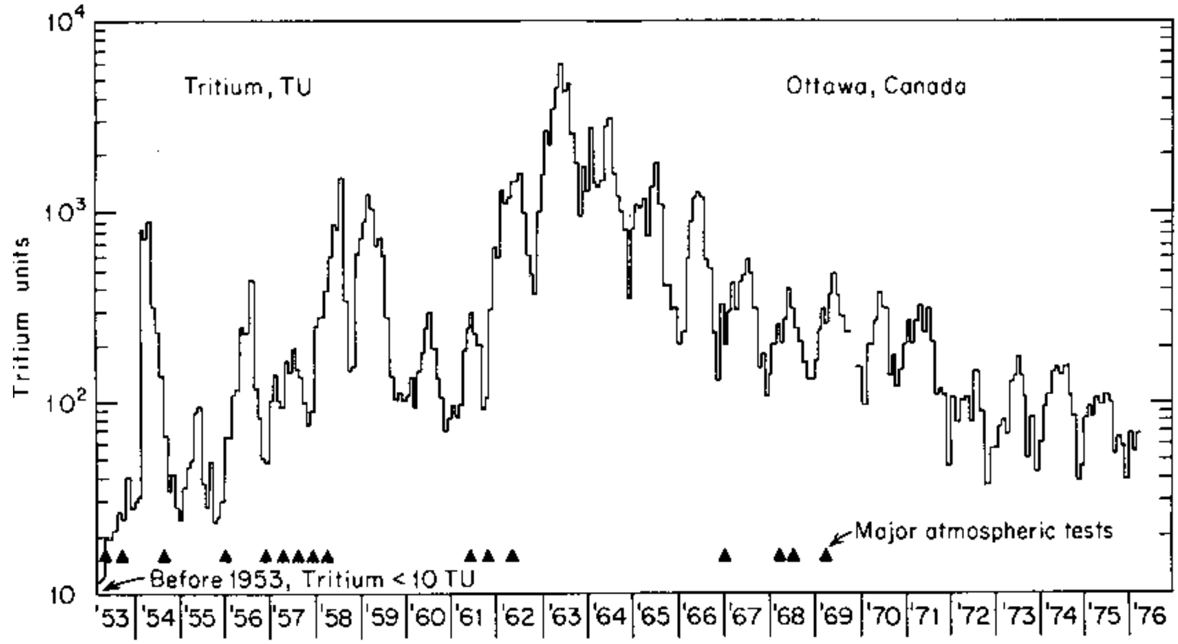

Figure 4-10. Variations of tritium (TU) in precipitation at Ottawa, Canada ("Groundwater," by Freeze/Cherry, © 1979. Reprinted by permission of Prentice-Hall, Inc., Upper Saddle River, NJ.)

rather than an exact determination of residence time (Smith and Wheatcraft 1992). Table 4-3 provides an estimate of groundwater residence time as of 1987 (Davis and Murphy 1987).

Table 4-3
1987 Relationship Between Tritium Concentration and Groundwater Age (Davis and Murphy 1987)

Concentration, TU	Interpretation (1987)
< 0.2	Water is older than 50 yr
0.2 - 2.0	Water is older than 30 yr
2 - 10	Water is likely at least 20 yr old
10 - 100	Water is less than 35 yr old, may be modern
> 100	Probably related to peak fall-out period of 1960-1965

(3) ^{14}C (radiocarbon). ^{14}C has a half-life of 5,730 years. Like tritium, small amounts of ^{14}C are also produced naturally in the atmosphere; and like tritium, much higher concentrations of ^{14}C were introduced into rainfall by atmospheric nuclear testing. Because of its longer half-life, ^{14}C can be a useful tool for dating groundwater as old as 30,000 years (Davis and Murphy 1987). Hydrogeologic settings with residence times of this magnitude include large-scale regional flow systems, and systems in thick low-permeability sediments. The measurement of ^{14}C along several points in a regional flow system allows for an interpretation of age differences, areas of recharge, and flow velocities. Complications which can occur when using radiocarbon analysis include:

(a) Dissolution of carbonate minerals or oxidation of organic matter may add "dead" (no detectable ^{14}C) carbon to water, giving an erroneously old age. A number of correction techniques exist. Phillips et al. (1989) review six methods and apply age dating as a tool on modeling groundwater flow in the San Juan Basin.

(b) Mixing of aquifer waters. A low ^{14}C content can be indicative of either old water, or a mixture of young water and "dead" water. Therefore, low ^{14}C measurements can be interpreted for age of ground-water only in flow scenarios where mixing is insignificant.

(4) ^{36}Cl (chloride-36). ^{36}Cl has a half-life of 300,000 years. ^{36}Cl is produced by cosmic ray interaction with the atmosphere. ^{36}Cl has been used to date very old groundwater up to 1 million years old (Phillips et al. 1986). Disadvantages are that abundance is very small, and the analytical techniques required are complex and expensive.

d. Approximate cost (1988) of isotopic analysis. Hendry (1988) made the following cost estimates for isotopic analysis:

Isotope	Cost
^{2}H	$40
^{18}O	$30
^{3}H	$45-$100[1]
^{14}C	$70-$215[1]

[1] Range of costs reflects degree of accuracy required.

Collecting samples of ^{18}O, ^{2}H, and ^{3}H is simple. ^{14}C is not as simple, but is relatively easy, requiring only the precipitation of the dissolved inorganic carbon.

e. Example of the use of isotopes in groundwater studies.

(1) Setting. The year is 1996. A disposal site is located above the water table in a shallow phreatic aquifer (Figure 4-11). This aquifer is underlain by a clay layer which appears to confine an underlying aquifer. The lower aquifer is used for domestic water supplies. Water-level measurements show that water is moving laterally from site A to site B in both aquifers. Hydraulic gradients also indicate that there is the potential for downward flow from the phreatic aquifer to the underlying aquifer.

(2) Question. Will the clay layer, which appears to separate the two aquifers between sites A and B, prevent flow from the upper aquifer to the lower one?

(3) Solution. The “non-isotopically inclined hydrogeologist” might answer: “How many test holes need to be drilled to make sure the clay layer is continuous?” and “What tests can we perform to determine the vertical hydraulic conductivity of the confining layer?” This can be at a considerable cost. However, the “isotopically aware hydrogeologist” would consider the following approach:

Use isotopic analysis to determine if such a connection exists.

(4) Hypothetical results:

(a) Tritium (^{3}H) concentrations more than 5.0 TU were encountered in the piezometers above and below the clay layer.

(b) Analysis: Post-bomb (1953) water has entered both the phreatic and underlying aquifer and the clay layer is not an effective barrier to water movement. Thus, any contaminants that might migrate from the waste site could enter the lower aquifer and contaminate local water supplies.

(c) Tritium (^{3}H) concentrations in piezometers in the deep aquifer were measured at less than 0.1 TU.

(d) Analysis: The age of the water is greater than 50 years, although this provides little information as to the degree to which the clay layer acts as a barrier.

(e) ^{14}C analyses were conducted in the deep piezometers at sites A and B, and results indicated age dates on the order of tens of thousands of years.

(f) Analysis: The clay layer is continuous and acts as a barrier to separate the phreatic aquifer from the deeper aquifer.

4-12. Response of Groundwater Levels to Loading Events

a. General. It is possible to estimate values of hydraulic properties of aquifers from the frequency response of the water-level fluctuations. Short-term fluctuations in confined aquifers can be caused by changes in atmospheric pressure of the atmosphere, earth tides, seismic events, and external loads such as passing trains. In many cases, there may be more than one mechanism operating simultaneously, with atmospheric pressure changes and earth tidal fluctuations being the two common natural events. These fluctuations offer evidence that confined aquifers are not rigid bodies, but are elastically

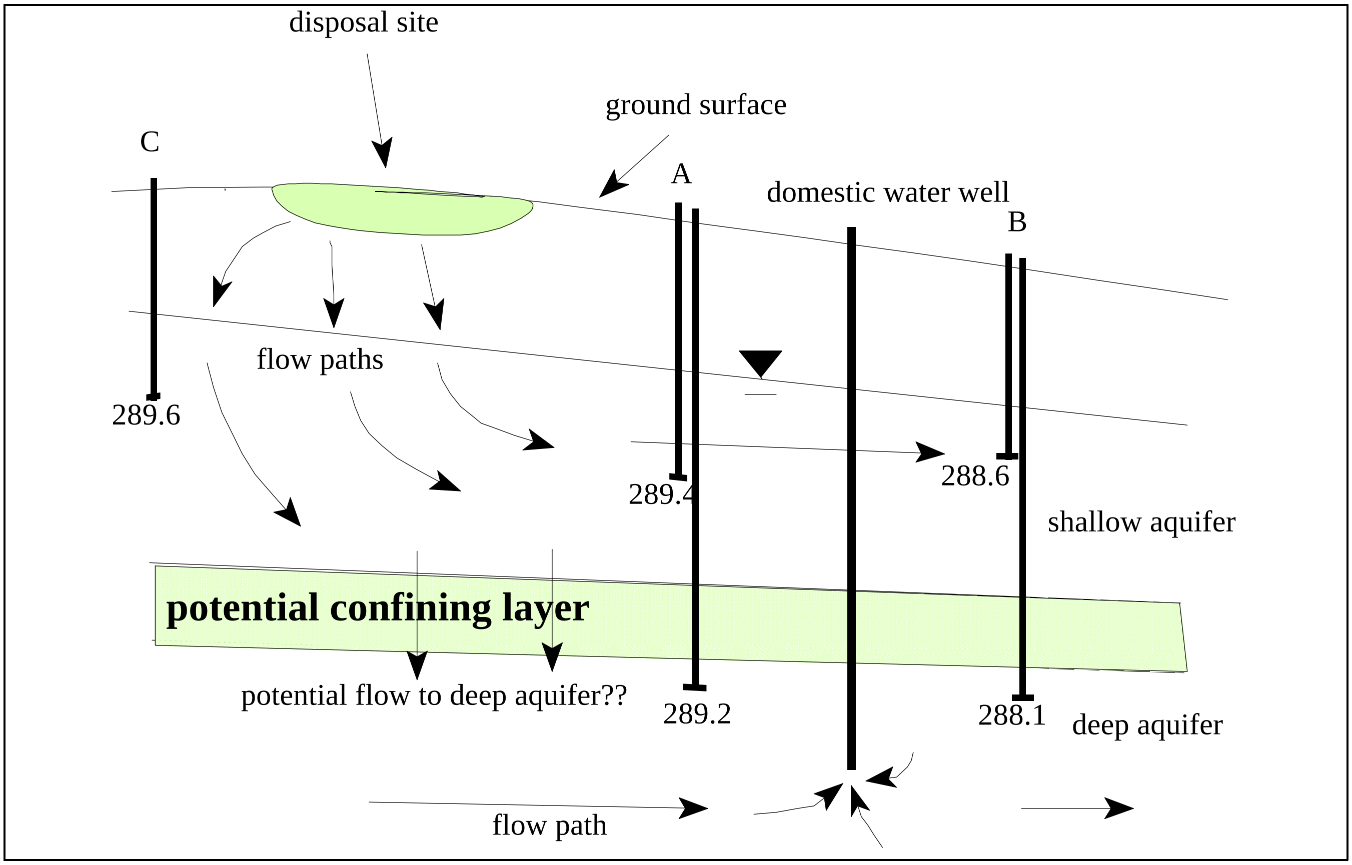

Figure 4-11. Hypothetical proposed disposal site

compressible. Earth tides can lead to water-level changes of 1 or 2 cm; atmospheric pressure changes may cause fluctuations of several tens of centimeters, depending upon the elastic properties of the aquifer and the magnitude of change in atmospheric pressure. Hydraulic properties, such as storage coefficient (storativity) and porosity, can be calculated from the response of measured water levels to these natural loading events. These types of water-level changes are damped in unconfined aquifers.

b. Effects of changes in atmospheric pressure on water levels.

(1) General. Although variations in barometric pressure have no significant effect on the water table levels in unconfined aquifers, the variations do cause well water levels for confined aquifers to fluctuate greatly. This is explained by recognizing that aquifers are elastic bodies. In a confined aquifer, an increase in atmospheric pressure is transmitted directly to the water surface of the piezometer, tending to displace water from the piezometer into the aquifer. On the other hand, the increased atmospheric pressure also increases the load on the confined aquifer, which tends to displace water from the aquifer into the piezometer. Part of this increased atmospheric load is born by the mineral skeleton of the aquifer, however, and the net result of an increase in barometric pressure is to decrease the water level in the piezometer. Conversely, decreases in atmospheric pressure produce increases in piezometer water levels. For an unconfined aquifer, atmospheric pressure changes are transmitted directly to the water table, both in the aquifer and a well; hence, no fluctuation results. Thus, when measuring water levels in confined aquifers, the effect of atmospheric pressure should be considered.

(2) Barometric efficiency. In confined aquifers, when atmospheric pressure changes are expressed in terms of columns of water, the ratio of water level change to pressure change expresses the barometric

efficiency of an aquifer. In Figure 4-12, the upper curve indicates observed water levels. The lower curve shows atmospheric pressure (inverted) in feet of water and multiplied by 0.75. A close correspondence of major fluctuations exists in the two curves. Thus, Figure 4-12 illustrates a measured barometric efficiency of approximately 0.75 for an aquifer. Typical barometric efficiencies in confined aquifers range from 0.20 to 0.75. The units of measurement (SI or metric) for water levels and atmospheric pressure used in Figure 4-12 are not important, but they must be consistent with each other.

(a) To convert the values on the right y-axis of Figure 4-12 into values we are familiar with from the evening news weather report, the units must be changed from feet of water to inches of mercury, considering the factor of barometric efficiency:

(ft of water) (12in./ft) (1 in. Hg/13.6 in. water) (1/barometric efficiency) = in. Hg

In metric units, (Hg, inches)(2.54) = (Hg, centimeteters)

(b) Barometric efficiency can be defined mathematically by:

$$B = \frac{\Delta h \gamma_w}{\Delta p_a} \tag{4-7}$$

where

B = barometric efficiency of an aquifer

Δh = change in measured water level

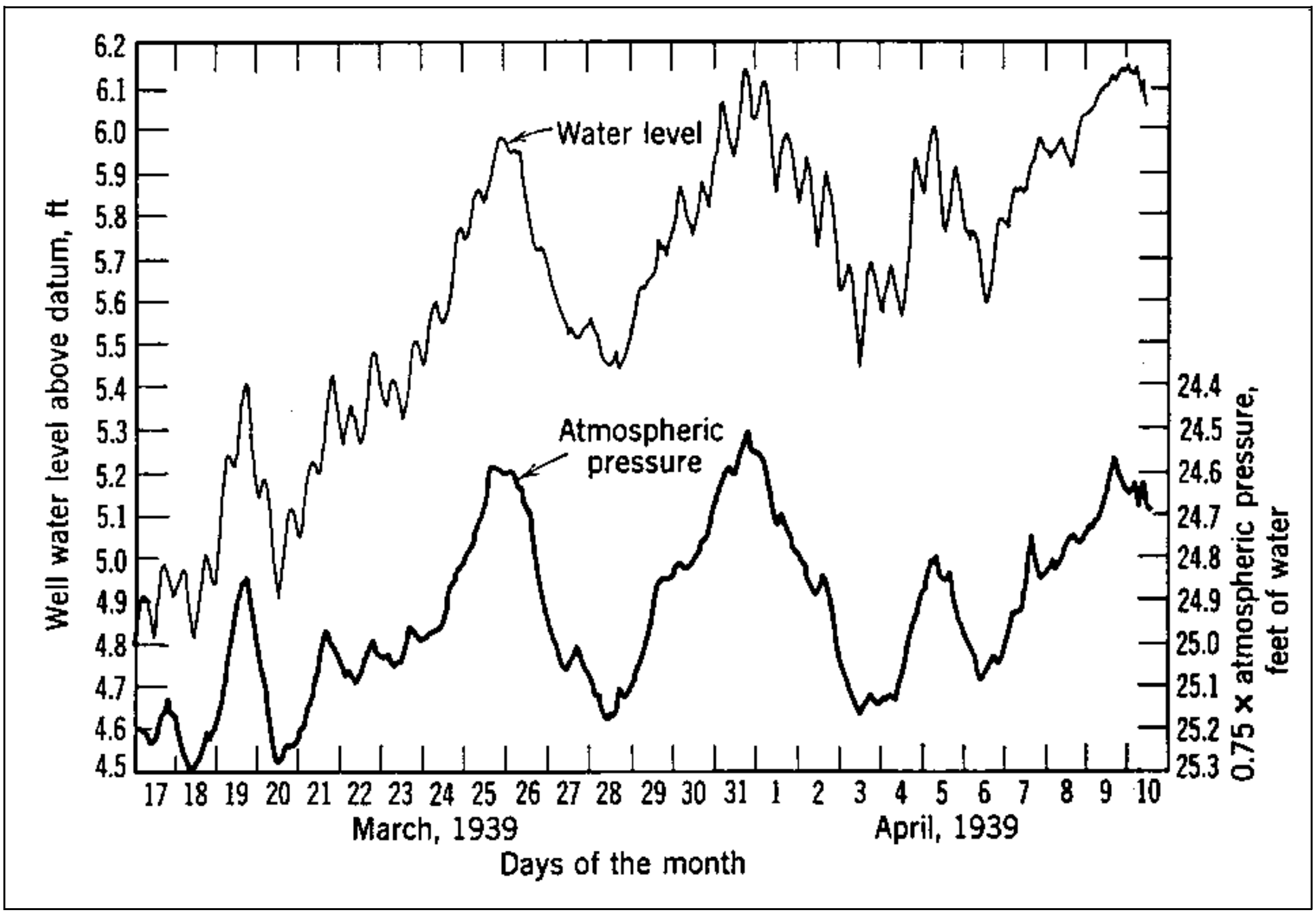

Figure 4-12. Response of water level in a well penetrating a confined aquifer to atmospheric pressure changes. (Robinson, ©1939, reprinted by permission of the American Geophysical Union)

γ_w = specific weight of water

Δp_a = change in atmospheric pressure

(c) In confined aquifers, well measurements can be corrected to a constant atmospheric pressure by:

- Deriving barometric efficiency.
- Correcting changes in water levels for corresponding changes in atmospheric pressure.

(d) Jacob (1940) derived an expression for relating the barometric efficiency of an aquifer to aquifer properties:

$$B = \frac{nE_s}{nE_s + E_w} \qquad (4\text{-}8)$$

where

B = barometric efficiency of an aquifer

n = porosity

E_w = bulk modulus of compressibility for water

E_s = modulus of elasticity of the aquifer solids

(e) Thus, barometric efficiency is directly proportional to the rigidity of an aquifer. Barometric efficiency approaches one for rigid aquifers, and is small for flexible unconsolidated aquifers. A barometric efficiency of one suggests that the well is a perfect barometer, in which all changes in stress on the aquifer are borne by the mineral skeleton. The right side of Equation 4-8, and therefore barometric efficiency, is constant for a given aquifer.

(3) Relationship between barometric efficiency and storage coefficient. The compressibility of an aquifer can be expressed as:

$$\beta = \frac{n}{E_w} + \frac{1}{E_s} \qquad (4\text{-}9)$$

where

β = aquifer compressibility

n = porosity

E_w = bulk modulus of compressibility for water

E_s = modulus of elasticity of the aquifer solids

(a) The storage coefficient of a confined aquifer can be defined as:

$$S = \beta\gamma_w b \qquad (4\text{-}10)$$

where

S = storage coefficient

β = aquifer compressibility

γ_w = specific weight of water

b = aquifer thickness

(b) By combining Equations 4-8, 4-9, and 4-10, a relationship between barometric efficiency and aquifer storage coefficient can be derived:

$$S = \frac{n\gamma_w b}{E_w B} \qquad (4\text{-}11)$$

where

S = storage coefficient of the confined aquifer

n = porosity

γ_w = specific weight of water [1,000 kg/m^3]

b = aquifer thickness [m]

E_w = bulk modulus of compression of water [2.07×10^9 N/m^2]

B = barometric efficiency of the aquifer

(4) Example problems.

(a) If the confined aquifer in Figure 4-12 is 40 m thick and has a porosity of 0.2, what is its estimated storage coefficient?

$$S = \frac{n\gamma_w b}{E_w B}$$

S = (0.2)(1,000)(30)(9.8)/(2.07 × 10^9)(0.75) = 3.8 × 10^{-5}

Note: the value of 9.8 (gravity) in the above equation is required to convert from units of Newtons to units of kilograms.

(b) As illustrated in Figure 4-13, well A and well B are screened beneath a confining layer. Well A was measured on 3/1/90 to be 301.0 ft above mean sea level (msl); well B was measured on 3/3/90 to be 300.75 m above msl. The barometric efficiency of the aquifer is 0.50. When well A was measured, the barometric pressure was 756 cm (of water column). When well B was measured, the barometric pressure was 806 cm (of water column). What is the gradient between the two wells?

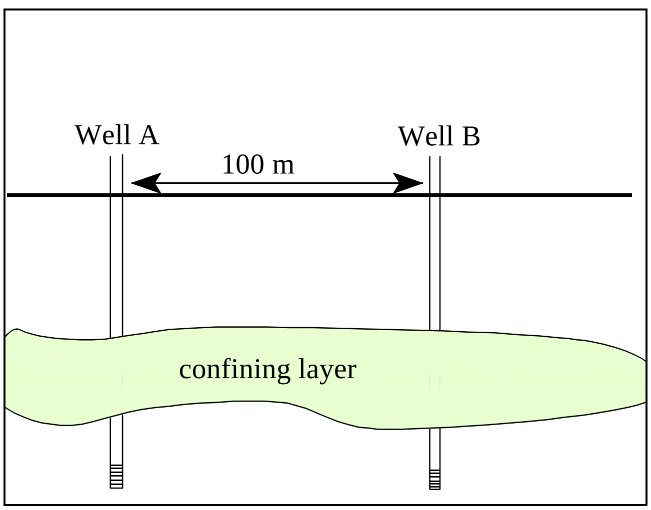

Figure 4-13. Hypothetical well locations

The change in barometric pressure = 50 cm of water column.

The barometric efficiency = 0.5.

Therefore, the change in water levels = 0.25 m; therefore, the gradient = 0.

c. Earth tides.

(1) General. Water level changes in response to tidal fluctuations can occur in confined aquifers as a response to gravity, or in confined aquifers which outcrop to the ocean. In the latter case, changes in pressure heads due to tides are transmitted directly to the water in the aquifer at the outcrop. In confined aquifers not adjacent to the ocean, the effect of gravitational forces on water levels is a function of the rigidity of the aquifer. As discussed in the previous section, atmospheric pressure acts not only on the rock matrix and its contained water, but also on the water level in an open observation well. Gravitational forces act only on the rock matrix and its contained water. Earth tides are predominantly the result of the gravitational pull of the moon; and to a lesser extent, the result of the gravitational pull of the sun. Earth tides cause small (1-2 cm) water-level fluctuations in wells located in confined aquifers.

(2) Tidal efficiency. The tidal efficiency of an aquifer is defined as the ratio between change in head in a confined aquifer and change in tidal force:

$$T_e = \frac{\Delta h \gamma_w}{\Delta F_t} \tag{4-12}$$

where

T_e = tidal efficiency of an aquifer

Δh = change in measured water level [ft]

γ_w = specific weight of water

ΔF_t = change in tidal force

The tidal efficiency is inversely proportional to the rigidity of an aquifer. Tidal efficiency approaches zero for rigid aquifers, and approaches one for flexible unconsolidated aquifers. A tidal efficiency of one suggests that the well is perfectly flexible, in which all changes in stress on the aquifer are born by the pore water. The relationship between barometric efficiency *B* and tidal efficiency T_e is:

$$B + T_e = 1 \qquad (4\text{-}13)$$

4-13. Conclusion

Investigation of the subsurface is a dynamic and inexact science; but is essential to the success of a groundwater study. Aquifer characterization is dependent upon the quality and quantity of data gathered and the interpretation of that data to obtain a good understanding of the hydrogeologic setting. Often, site characterization studies focus on pumping tests and borehole geophysics, and neglect other valuable and cost-effective investigative methods such as cone penetrometers, surface geophysics, and isotopic analyses. Due to time and financial constraints, it is important for the study manager to be familiar with all potential sources of data, and plan the site investigation in the most efficient manner to meet study objectives.