PDHonline Course C249 (3 PDH)

Groundwater Investigations

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2020

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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.

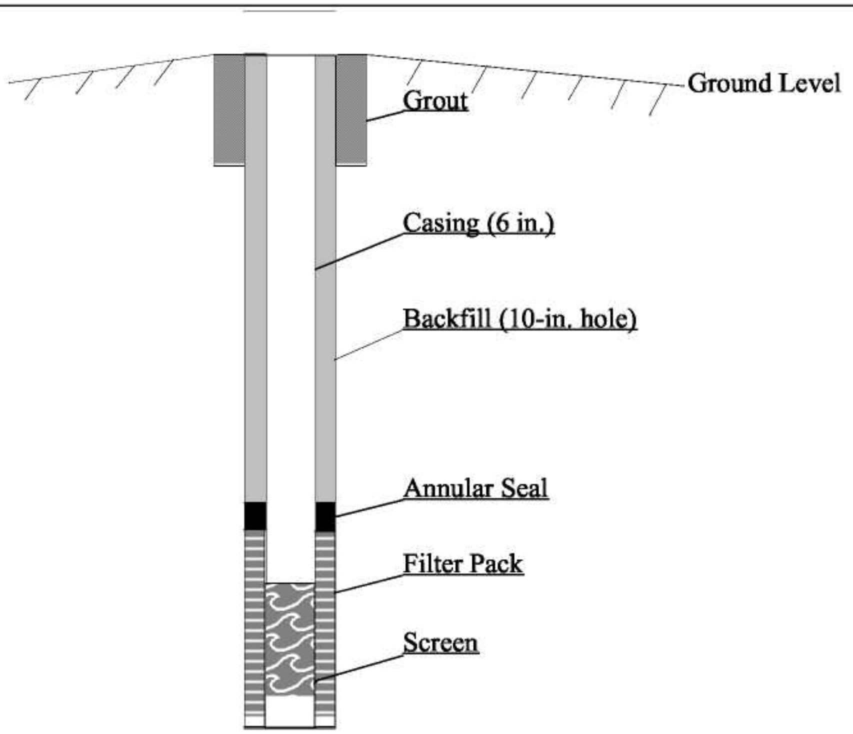

Figure 4-1. Basic well components

(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.

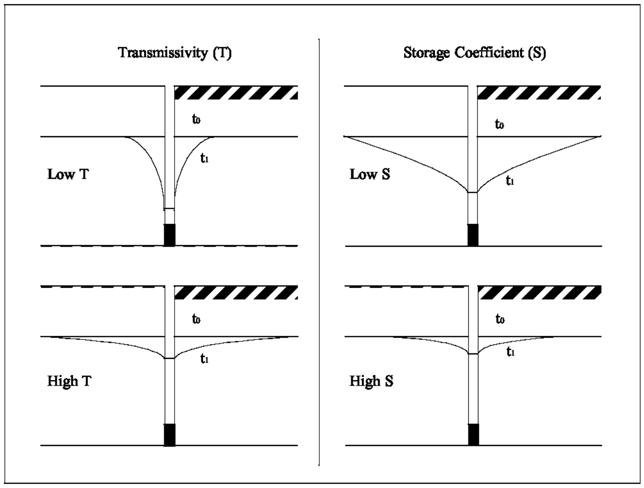

Figure 4-2. Influence of transmissivity and storage coefficients on cone of depression for similar aquifers at a constant pumping rate

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: