Siting, Drilling, and Construction of Water Supply Wells

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Science and Technology

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Contents

1

Basic Concepts

SOURCES OF GROUNDWATER

Groundwater is water that may have recently entered the soil as a result of rainfall or snow melt, or it may be an ancient source found in geologic formations well below the surface. This water is a portion of the hydrologic cycle (see Figure 1-1) where water falls to the earth and seeps into the soil and flows downward by gravity until it contacts a layer of impervious strata. Groundwater typically flows down gradient, taking the path of least resistance. Therefore, if high permeability underground conduits or channels are present, the water will tend to flow along these pathways. These formations may yield substantial quantities of water.

A body of rock that is sufficiently permeable to conduct groundwater to yield economically significant quantities of water to wells and springs is called an *aquifer*. Water that is located near the land surface, exposed to atmospheric pressure, and has no overlying confinement is called *the water table* or *surficial aquifer*. The surface of a water table aquifer tends to follow the surface of the ground, although some conditions cause exceptions. Aquifers will recharge creeks, lakes, or rivers whose bottoms are deeper than the top of the water table, and aquifers may be recharged by those same water bodies where the surface of the aquifer is beneath the creek, lake, or river bottom.

A spring forms when groundwater flows naturally from an aquifer to the surface, such as near a creek, lake, or river. Water flowing from a spring may have traveled hundreds of miles (kilometers) from where it seeped into the ground, or it could be from a surface water source only a few yards away.

Water table aquifers that are located up to four ft (1.5 m) below the surface may be subject to evaporation. Because there is little resistance to migration of water into water table aquifers, they are also more susceptible to contamination than deeper aquifers, a major consideration in locating wellfields. Below the water table aquifer may be other aquifers. These aquifers will be separated by a layer of material such as dolomite, clay, or other material that prevents or limits the exchange of water

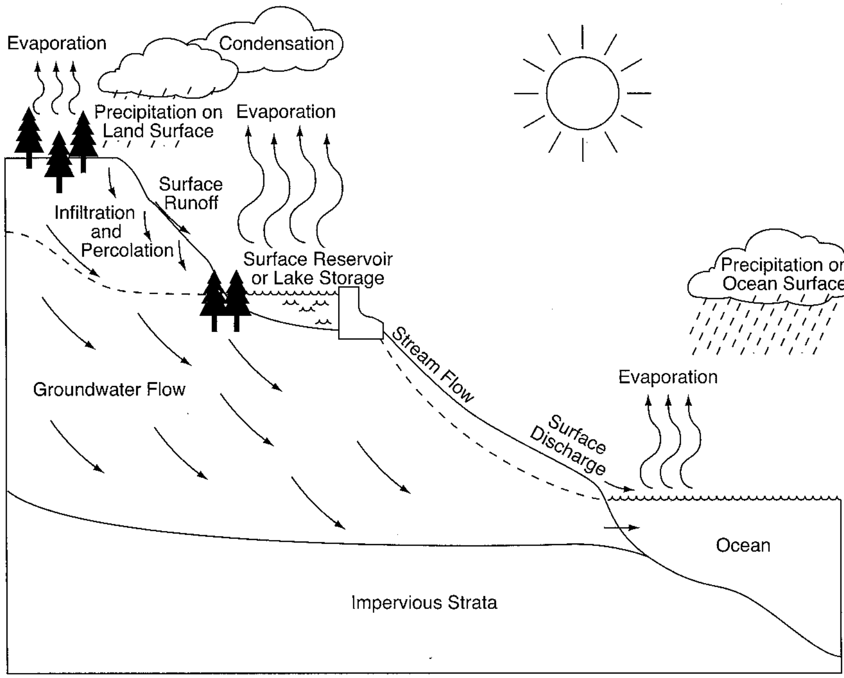


Figure 1-1 Hydrologic cycle

between the aquifer layers. Such limiting formations are called *confining units* or *aquitards*.

Aquifers that are located further beneath the surface and have low permeability formations above them are called *confined aquifers*. These aquifers may be under pressure and are termed *artesian aquifers* if their water surface rises above the bottom of the overlying confining bed when exposed to atmospheric pressure. The term *flowing artesian aquifers* refers to those aquifers where the water surface rises above the overlying confining unit and flows at land surface. An example is the Floridan aquifer in southeast Florida that will "flow" 30 ft (10 m) above the ground surface. Some confined aquifers are buried river valleys or the beds of an ancient lake. Examples exist in the Midwest, where such buried rivers are highly permeable and may yield large quantities of water.

The flow velocity and flow direction of groundwater depends on the elevation of the recharge source, the permeability of soil and rock layers, and the relative pressure of the groundwater. The movement of water through an aquifer is generally quite slow; however, the long-term movement of water through the rock may dissolve the formation. Eventually, this allows large cavities to interconnect and form underground rivers or caverns that can be tapped as a public water supply

Table 1-1 Porosity of rock formations

Strata	Porosity (%)	Specific Yield (%)	Specific Retention (%)
Soil	55	40	15
Clay	50	2	48
Sand	25	22	3
Gravel	20	19	1
Limestone	20	18	2
Sandstone	11	6	5
Granite	0.1	0.09	0.01
Basalt	11	8	3

Source: AWWA, 2003

source. At the same time, this water retains the dissolved minerals that often need to be removed for water supply purposes.

When attempting to identify water supplies, one must evaluate the productivity and water quality of each aquifer because the quantity and quality of water in the aquifers may vary greatly. The quantity and quality of groundwater depends on factors such as confinement, depth, aquifer thickness, rainfall, and geological formation. For example, because their relatively high permeability provides significant productivity, sand, shell, and gravel aquifers are more suitable for public water system than clay, granite, or dolomite. Sandstone is porous and often yields water of good quality in sufficient quantity to supply public water systems. Limestone has moderate porosity but often contains cracks and cavities that can provide substantial quantities of water (AWWA, 2003). Table 1-1 shows the porosity of rock formations.

Throughout North America, groundwater can generally be found from a few feet to hundreds of feet (or meters) below the land surface. However, except along the coastlines, deeper waters tend to have poorer water quality as a result of minerals dissolving into the water over many years. Deep formations are likely to be more distant from recharge areas, so the water will be older and have been in contact with the rock for a longer period of time. A balance must be struck in such areas between the decreased water quality from deeper aquifers (which might require additional treatment) and the potential for more productivity in a given well. Deep wells also have higher construction costs but are less susceptible to contamination. Therefore, while some deep aquifers may be prolific, the quality of water obtained from a well may not be usable for drinking water without substantial treatment.

The United States Environmental Protection Agency (USEPA) has created designations for aquifers based on water quality. While it is technically possible to treat almost all water to obtain acceptable quality, treatment may not be economical or practical for waters with greater than 10,000 mg/L of total dissolved solids. Such waters are generally not potential "underground sources of drinking water." All other aquifers are regulated as they may at some point be used for drinking water purposes.

BENEFITS AND DISADVANTAGES OF GROUNDWATER USE

Groundwater can have significant advantages over more traditional surface water uses.

Advantages of groundwater use include the following:

- Water has less exposure to contamination (assuming not a water table aquifer).
- Water quality is stable.
- Water temperature is stable.
- Water quality changes are slow to occur.
- Evapotranspiration losses are insignificant.
- Less treatment is typically required.

However, groundwater sources suffer from the following disadvantages:

- Difficult to cleanup once contaminated.
- No early warning of contamination—unseen plumes of contaminants can migrate into a wellfield without warning unless sentinel wells are constructed.
- Conflicts with land use with competing urban industrial, commercial, agricultural, irrigation, and ecosystem users in the same area.
- Sustainable yields are difficult to estimate.
- Water levels are not obvious.
- Recharge has limitations.
- Supplies are often limited in basins.
- Control of aquifer recharge may be outside of users' jurisdiction.
- Saltwater intrusion can occur in coastal areas.

In addition, aquifers are not available everywhere, just as surficial sources may not be.

CONSIDERATIONS FOR SITING WELLS

Considerations for siting production wells include the following four issues: (1) site availability, (2) water supply, (3) water quality, and (4) wellhead protection limitations. Many small water systems have made cost the prime consideration in selecting sites for public water supply wells, but water quality may have a longer-term impact. Therefore, one must balance and consider both water quantity and

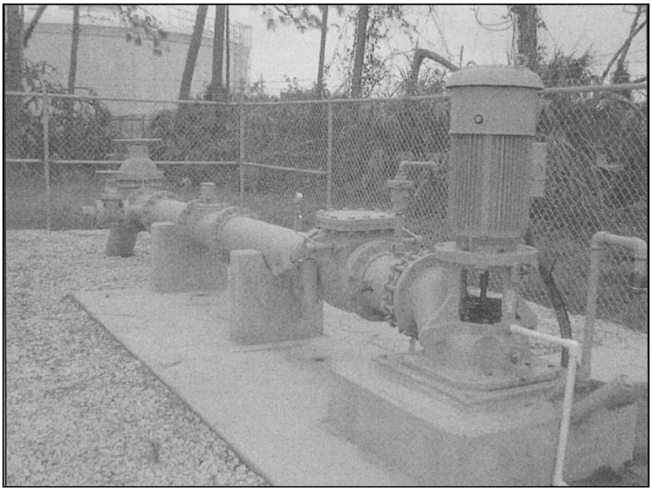


Figure 1-2 Typical well installation

quality. The water supply system must balance factors including well depth, geology of the area, characteristics of the rock formations, and dissolved minerals in the aquifer.

In most places, locating productive wells may be accomplished using local, expert knowledge of the geology of the region and the experience with existing wells. Figure 1-2 is an example of a well installation. Having noted the benefits of groundwater supplies, these principles can provide guidance in searching for well sites. There are several steps involved in identifying potential groundwater sources. The first is to locate the literature, prior investigations, local or regional water supply plans, and on-site activities of neighboring water purveyors with regard to groundwater use. If groundwater is available, others will likely know about it. Oil and gas drilling logs often identify formations that may be potential sources. Agricultural interests are often the first to tap groundwater supplies.

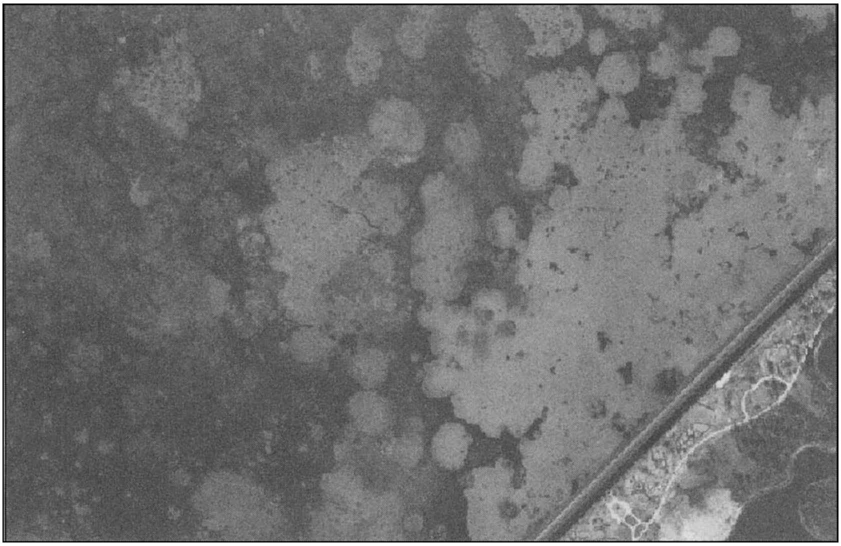
The United States Geological Survey (USGS) has extensively studied underground formations for the presence of suitable water throughout the United States. For studies within the United States, the literature search should begin with the USGS's *Summary Appraisals of the Nation's Ground Water Resources (1978–1982)*. Individual reports covering the region of interest can be obtained. Other published reports on groundwater resources are available from federal and state agencies that provide a summary of quantity and quality of available groundwater in various geographic regions, including major basin areas and state, county, and local regions.

Source: www.bcpa.net

Figure 1-3 Industrial aerial map

Source: www.bcpa.net

Figure 1-4 Residential aerial map



Source: www.bcpa.net

Figure 1-5 Undeveloped area aerial map

Regional water authorities or neighboring water purveyors may study potential groundwater basins for their sources. Most of this information is available in the public record and provides an excellent start in determining the potential for water supply availability and for the design of a wellfield. Local engineers, geologists, or hydrogeologists will also likely have a significant amount of information on water quality parameters and drilling conditions. However, such reports should not be relied on exclusively as even fairly site-specific reports are often general in nature, and many local details may be omitted.

The next step is to review the land use. Figures 1-3 through 1-5 show three aerial photographs downloaded from the Broward County property appraisers website. Such photographic images are routinely available online. Figure 1-3 is a heavily industrialized area. Land value in such areas may be very expensive. The availability of land to locate a well may be severely restricted as a result of surface activities, such as stormwater management related to buildings and parking areas. In addition, such areas contain businesses that use a variety of chemicals and processes that may potentially contaminate the groundwaters. Reviews of industrial pretreatment records for wastewater plants, hazardous materials licenses, and chemical inventories provided to environmental agencies may provide information on the chemicals that may possibly be accidentally discharged to groundwater. Potential pollution sources of this type must be avoided if at all possible. As a result, industrial sites are rarely acceptable as potential well locations without incurring significant expense for monitoring wells, monitoring industrial practices, wastewater pretreatment processes, and ongoing dialogue with the businesses. Most utilities typically avoid such sites.

Figure 1-4 is a residential site. Wells may be located in residential sites, but many of the same problems exist with residential sites as industrial sites. Residents rarely want wells located in their yards, nor the well access that is required. In addition, land costs are not inexpensive. Residential areas that utilize septic tanks may pollute groundwater with household chemicals, microbiological contaminants, salts, and nitrates. Residents also use a variety of pesticides, fertilizers, solvents, and other chemicals that, while in much smaller quantities than industrial complexes, may also contaminate the aquifer. It should be noted that monitoring programs rarely exist for residential development with regard to chemical contamination. As a result, care must be exercised in selecting well sites in residential areas—such sites should be pursued for deeper wells that are unlikely to be affected by surface activities.

Figure 1-5 shows a remote site that is well outside development. The land is unlikely to have been affected by industrial activity, but agricultural activity should be investigated. Agricultural use of land can also affect groundwater quality because of pesticide, herbicide, and waste runoff. Sites that are well outside development areas should be less expensive than sites in urban areas, but this cost differential must be weighed against the cost of transmission. Monitoring of remote sites should be included in any design as site visits will be less frequent. Ecosystem effects may be limiting factors if wetlands are located in the projected cone of depression. In addition, the site may not remain outside of expanding development forever, as Fort Lauderdale's Peele-Dixie wellfield, installed in 1926 shows (see next section).

Aerial photographs are useful but may not provide all the information needed to assess whether the land is a potential well site. Figures 1-6 through 1-8 are examples of surface features in undeveloped areas. Figure 1-6 is a waterfall in north Georgia. It routinely has copious amounts of water, and the area is relatively undeveloped (north of Atlanta, Ga.). However, once on the site, it is clear that the rock formations are granite, offering little capacity for groundwater sources. Also, the dammed lake in Figure 1-7 (also in north Georgia) appears to be a significant source of water to recharge the neighboring formation. However, a site visit demonstrates that the underlying rock is unlikely to have significant recharge potential unless direct accesses to the lake via fractures exists. Figure 1-8 is a familiar site in the desert of eastern Utah. There is little development within miles of this site, but the groundwater supply is far below the surface and provides little indication of its existence from the surface. In each case, aerial photographs are inappropriate for siting wells.

In addition to site visits to determine the potential for groundwater, the historical land use practices must be reviewed at the site. As land uses change,

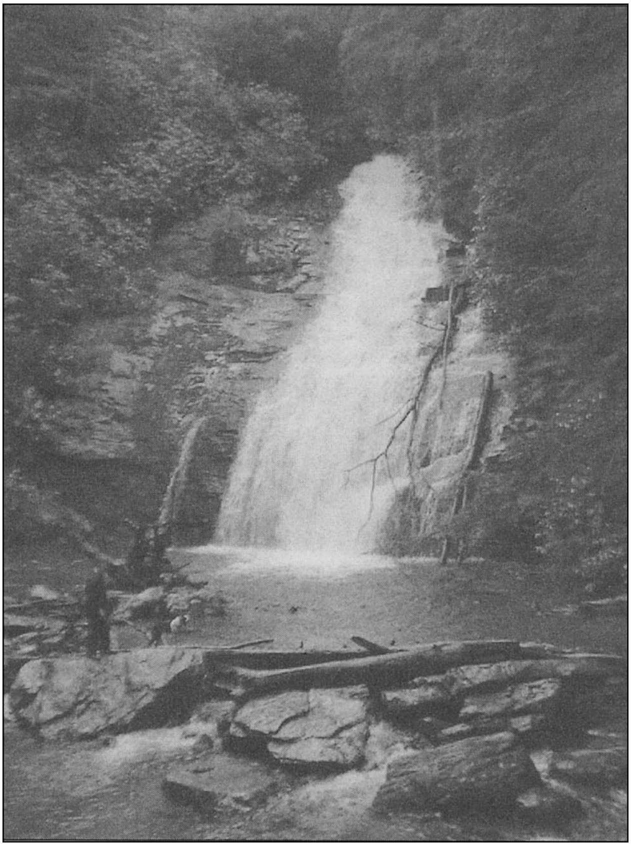


Figure 1-6 Helton Creek Falls, Blairsville, Ga.

aquifer quality may deteriorate with development, so potential development and effects of that development should be considered, which requires a good understanding of urban and industrial growth and zoning of the area associated with the groundwater supply. Wells and wellfields in developed areas should be located up-gradient of or down-gradient at an appropriate distance from potential threats to the water quality. More frequent testing for pollutants may be appropriate. Establishing early-warning monitoring (sentinel) wells at various depths may be required to maintain groundwater quality (AWWA, 2003). Property appraisers offices and local planning departments are good sources for evaluation of historical land uses.

The third step in identifying groundwater sources is to determine if the potential well site is sustainable. The term *sustainable* has a number of connotations,

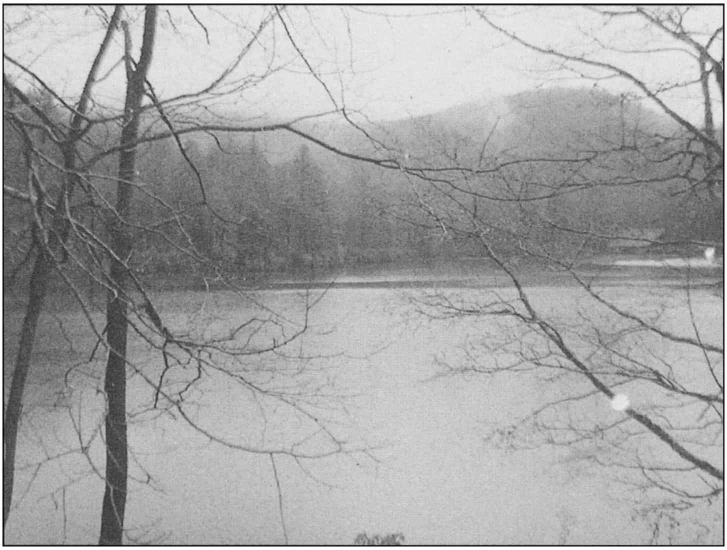


Figure 1-7 Lake Winfield Scott, Blairsville, Ga.

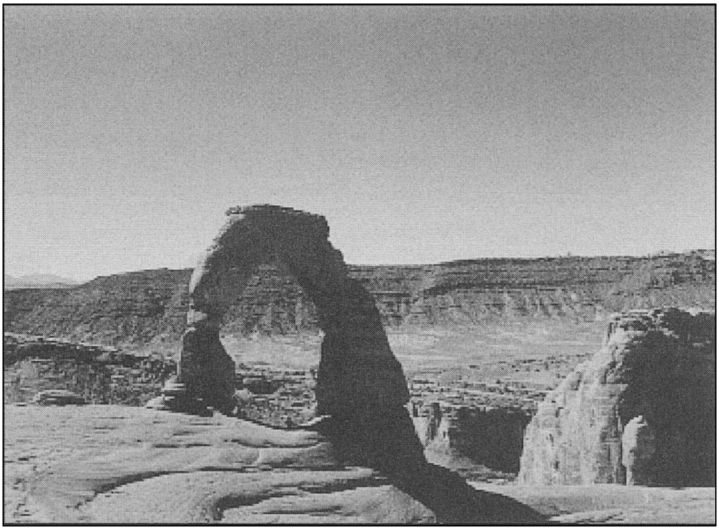


Figure 1-8 Delicate Arch, Arches National Park, Utah

but the focus for this book is on the ability to ensure long-term availability of the water supply. The issues involved in determining sustainability include

- Ongoing, consistent recharge of the aquifer,
- Variability in water levels,
- Water quality variability, and
- Competing users.

Ongoing recharge of the aquifer can be discerned through the use of well testing to monitor fluctuations in water levels with regard to rainfall. Locations beside lakes and streams that flow consistently throughout the year may provide good sites if no adverse environmental effects are experienced. Step-drawdown tests (discussed in chapter 4) also are needed to determine how significant the impact of the well may be to the aquifer locally and areally. Water rights access, a major factor in 18 western states, and water use or consumptive use permits in the southeast limit withdrawal amounts. Typically, development of new wellfields must demonstrate no infringement on existing water rights or competing water uses. Field investigations (as outlined in chapter 4) must be performed to confirm site-specific characteristics. Water quality considerations (chapter 2) are important when deciding whether a well site will provide water capable of potable use with reasonable treatment and delivery cost. Deterioration of water quality can have significant financial consequences because of higher treatment costs or the need to abandon the water supply wells. Therefore, some exploratory work should be done to provide needed details regarding water quality.

In conjunction with the evaluation, the following factors should be considered:

- The location of the well sites in areas where the demands are highest
- The cost to develop the water supply for the region
- The conveyance and treatment costs
- The potential revenue generation as it relates to construction and operating costs
- Environmental concerns, such as for endangered species and critical habitat
- Location of future growth

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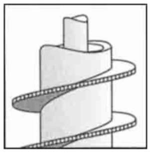


2

Regulations Regarding Well Location, Protection, and Water Quality

Until the 1960s, it was assumed that groundwater was not affected by surface activities. However, in the 1960s, the United States government found that nearly a quarter of the country's wellfields were affected by surface contaminants ranging from minerals to solvents and other hydrocarbons. This discovery provided documentation that water table aquifers can be easily contaminated by spills from surface activities. These problems led directly to the passage of the Safe Drinking Water Act (SDWA) in 1974. Improved methods of chemical analysis and more complete sampling of well water has revealed a large number of public water supply wells contaminated by careless use and disposal of synthetic chemicals (Bloetscher, et al., 2005). One example that has plagued water suppliers is leakage from underground fuel tanks that have contaminated hundreds of sites across the United States.

SAFE DRINKING WATER RULES

SDWA and its associated amendments are focused on protecting the public health from various contaminants in potable water supplies. Whether surface waters, groundwaters, or via operation and treatment, SDWA has basic requirements that must be met. SDWA authorized the United States Environmental Protection Agency (USEPA) to establish health-based national drinking water regulations by setting maximum permissible levels of a significant number of pollutants in drinking water (see Tables 2-1A and 2-1B). USEPA developed monitoring requirements to demonstrate compliance with the regulations. These monitoring requirements are permitted to change over time as improvements are made to treatment equipment, analytical techniques, and instruments.

During the ensuing decades, the efforts of the USEPA focused on metals and synthetic organic chemicals resulting from industrial contamination of surface water

Table 2-1A Primary drinking water standards

Contaminant	MCLG (mg/L)	MCL (mg/L)
Cryptosporidium	Zero	—
Giardia lambia	Zero	—
Legionella	Zero	—
Total coliforms	Zero	5%
Bromate	—	0.01
Chlorite	—	1
HAAs	—	0.06
THM total	Zero	1.1
Chloramines	—	4.0
Chlorine	—	4.0
Chlorine dioxide	—	4.0
Antimony	.005	0.005
Arsenic	Zero	0.01
Asbestos	7	7
Barium	2	2
Beryllium	0.004	0.004
Cadmium	0.005	0.005
Chromium	0.1	0.1
Copper	1.3	1.3
Cyanide	0.2	0.2
Fluoride	4	4.0
Lead	Zero	0.015
Mercury	0.002	0.002
Nitrate	10	10
Nitrite	1	1
Selenium	0.05	0.05
Thallium	0.0005	0.002
Gross alpha	Zero	15 piC/L
Beta emitters	Zero	4 mrem/yr
Radium 226/228	Zero	5piC/L
Uranium	Zero	.03

Table continued next page.

supplies. The USEPA reported that over 1,000 synthetic organic compounds (SOCs) have been found nationwide in drinking water samples. Although the potential risk for the majority of the population was minimal, it was noted that many of the contaminants detected were suspected carcinogens.

In the early 1980s, USEPA's focus turned to volatile organic compounds (VOCs), commonly used as solvents and found in groundwater systems throughout the US. While the majority of VOCs were present at very low levels, pollution had occurred in water supplies previously thought to be pristine. In the mid-1980s, USEPA's focus turned toward the legal use of pesticides because numerous pesticides had been

Table 2-1B Secondary drinking water standards (continued)

Contaminant	Secondary Standard
Aluminum	0.05 to 0.2 mg/L
Chloride	250 mg/L
Color	15 (color units)
Copper	1.0 mg/L
Corrosivity	Noncorrosive
Fluoride	2.0 mg/L
Foaming agents	0.5 mg/L
Iron	0.3 mg/L
Manganese	0.05 mg/L
Odor	3 threshold odor number
pH	6.5–8.5
Silver	0.10 mg/L
Sulfate	250 mg/L
Total dissolved solids	500 mg/L
Zinc	5 mg/L

Source: www.epa.gov
MCLG – Maximum Contaminant Limit Goal
MCL – Maximum Contaminant Limit
NOTE: Table does not include a myriad of organics, VOCs, and SOCs. Refer to USEPA website for these constituents (numbering nearly 100).

found in both surficial and groundwater supplies. Efforts are still underway to survey and assess the extent of pesticide contamination in water supplies.

Throughout the period, the USEPA continued to also focus on microbiological outbreaks and the use of disinfectant techniques. From 1972–1981, there were 335 reported outbreaks of waterborne disease involving 78,000 people. Viruses contributed to 11 waterborne outbreaks involving 5,000 cases. However, while these levels are historically low and continue to decline, concerns over *Giardia lamblia* and *Cryptosporidium* bacteriological contaminants and viruses persist.

As part of the 1986 amendments, SDWA required the USEPA to specify procedures compliance with the maximum contaminant levels (MCLs) and the use of the best available technology for those utilities that cannot comply. A priority list of contaminants that may have adverse impacts on the health of people and are known to, or are anticipated to, occur in public drinking supplies was also compiled as a requirement of the 1986 amendments. Possible sources of these contaminants include industrial and chemical production and use sites; landfills; septic tanks; and run-off areas. The 1986 SDWA Amendments gave USEPA the authority to allow states to acquire primacy, the responsibility for SDWA enforcement, upon compliance with specific federal criteria. In addition, a series of separate regulations were promulgated that affect utilities under the auspices of SDWA. These are discussed in the following sections.

Underground Injection Control Program Regulations

SDWA requires the USEPA to protect underground sources of drinking water. USEPA's permitting authority to govern underground injection programs results from rules promulgated in 1981 pursuant to SDWA under the *Federal Register* 40 CFR 144 and 146. These regulations were aimed at regulating disposal of waste via underground injection, especially the injection of hazardous materials. Hazardous wastes are commonly injected as part of oil refinery and industrial processes. Texas has hundreds of such wells. The regulations focus on design, construction, and operation of injection wells and monitoring the impact of the injectate.

Surface Water Treatment Rule

If the source water is surface water, the Surface Water Treatment Rule (SWTR), implemented in 1989, requires utilities to filter and disinfect their water to inactivate viruses and remove *Giardia lamblia* cysts. The concept of SWTR is for the removal of turbidity and suspended solids that interfere with the disinfection process. The indication of significant amounts of suspended solids require additional chlorine be used, which may also create conflicts with the Disinfection By-Products Rule portion of SDWA. Waters with considerable amounts of suspended solids are generally required to be filtered to reduce chlorine demands and remove potential pathogens.

Disinfection By-Products Rule

The Disinfection By-Products Rule regulates trihalomethanes and other carcinogenic organic compounds that can be produced from chlorine disinfection. These regulations apply to all drinking water. The major problem this rule poses is that to achieve the disinfection desired for raw water, the amount of chlorine by-products is significant, creating a conflict between violating fecal coliform and disinfection by-product standards.

Ground Water Rule

If the source water is groundwater, the Ground Water Rule may require that the water be disinfected on withdrawal unless the water meets the requirements for "natural disinfection" or if the system qualifies for a variance. This rule was passed in 1992, ostensibly to deal with unchlorinated well systems.

Wellhead Protection

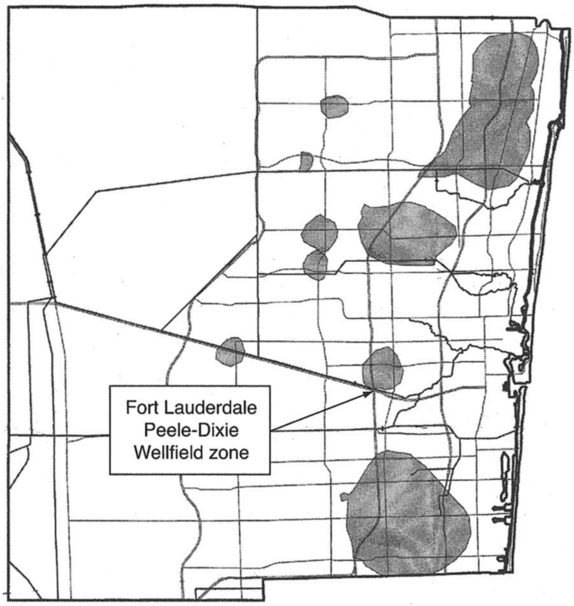
Wellhead or source water protection regulations were created to reduce the threat to water supplies from contaminants in runoff or as a result of surface activities. Watershed protection is a requirement of the SDWA Amendments of 1986 (Section 1428). Under Section 1428, each state must prepare a wellhead protection program and submit it to the USEPA for approval. The protection of public water supply wells from contamination through wellhead protection programs is considered an important component of comprehensive state groundwater protection programs. However, many states have promulgated minimal rules, while delegating specific implementation of the program to regional water management districts and/or counties.

While the best practice is to first locate wellfields where contamination is unlikely, one must also protect the wellfield from surficial impacts. This is hard to do without acquiring large amounts of property around the well. The issue becomes nearly impossible when the well needs to be located in a developed area. As a result, states and provinces have implemented regulations to protect underground sources of water. These actions include

- New requirements for installation and testing of underground storage tanks;
- Increased regulation for handling, using, and transporting toxic chemicals to reduce the possibility of spills;
- Greatly increased regulation of landfills and other waste disposal sites;
- Tighter control of the use of pesticides and agricultural chemicals;
- Sampling and monitoring of identified groundwater contamination locations; and
- Action to remove contamination (Bloetscher et al., 2005).

All of these actions will affect land use and local constituents. Delineation of a wellhead protection area is typically done through the use of numerical computer groundwater modeling of travel time of the pollutant (solute) transport. These numerical models, which are very complex, indicate large areas where many land uses are restricted or prohibited, conflicting with private property rights objectives. In some states, the conflicts with source water protection exist within private property rights laws that indicate that if the property is damaged more than ten percent, the regulating agency must compensate the land owner according to condemnation or "taking" rules. This could be a significant impediment to the implementation of wellhead protection programs in developed areas. Wellfield protection ordinances prohibit the use and/or storage of certain hazardous materials in zones around wells.

Figure 2-1 is an example of the wellhead protection zones in Broward County, Florida where some form of wellfield protection has been implemented. For example, Broward County's Chapter 27 wellhead protection rule outlines three regulated areas around wells. Zone 1 is within the 10-day travel period of a contaminant within the cone of influence. All new nonresidential activities are prohibited in these zones, and many existing ones have been terminated. However, hazardous material wellfield licenses are granted for activities that have been grandfathered into the property rights and are subject to all requirements for Zone 2 licenses.



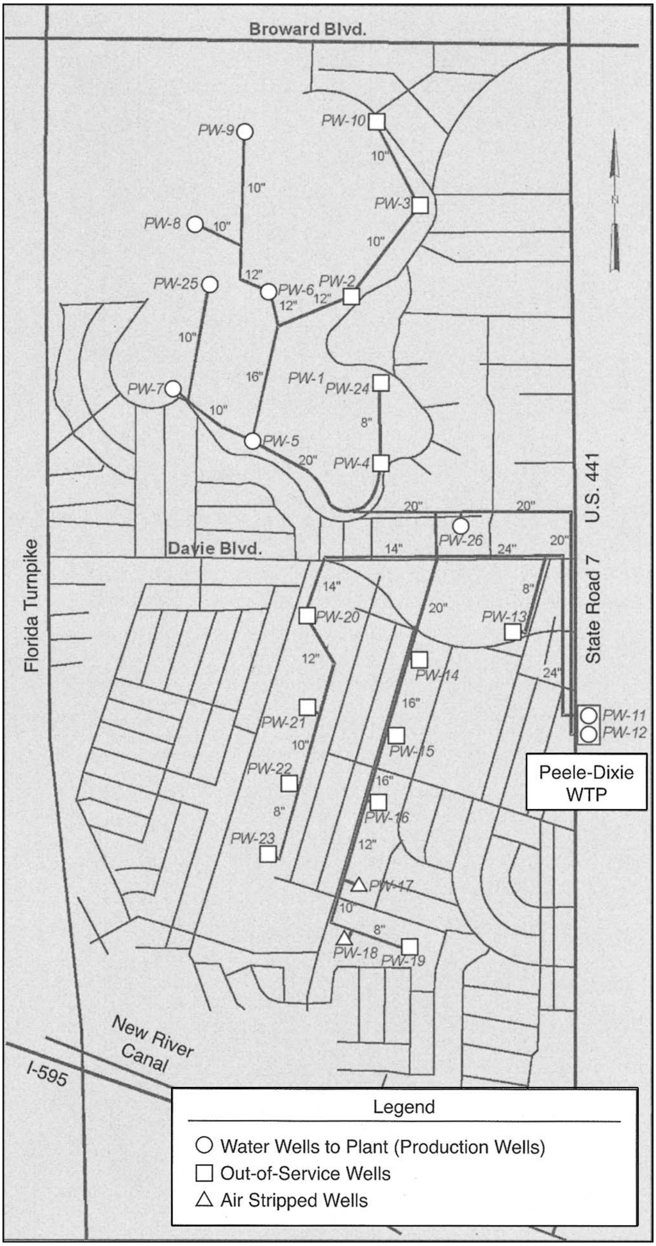
Source: Hazen and Sawyer, P.C., Boca Raton, Fla.

Figure 2-1 Broward County wellfield protection zones

Zone 2 encompasses areas between the 10- and 30-day travel times within the cone of influence. Hazardous materials are allowed in Zone 2 but are subject to 100 percent containment, daily inventory records, records of storage and use, emergency plans for spills, acquisition of emergency control devices to continue the use, monitoring of groundwater, reporting of spills, and certain other paperwork requirements.

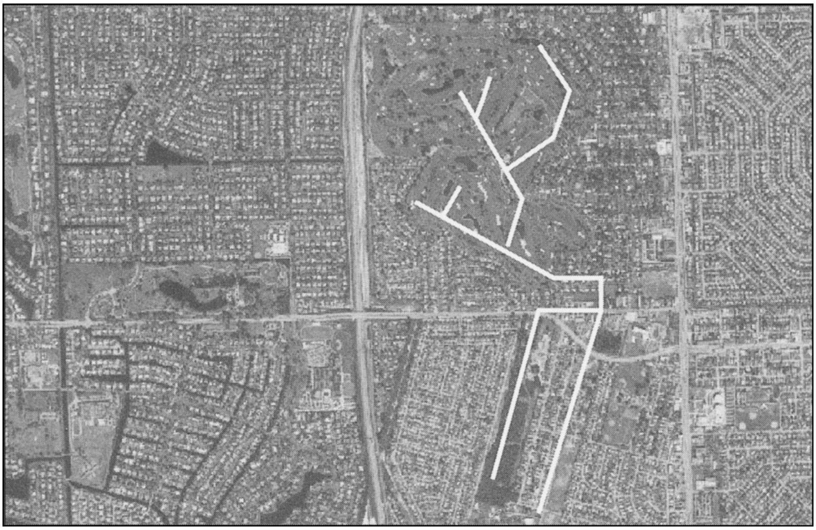
Zone 3 permits any use but requires a hazardous materials license above a certain specified (or threshold) quantity. Zone 3 does not require notification of the utility whose wellfield might be affected.

The following is an example of why wellhead protection is so important for water suppliers. Figure 2-2 shows the Fort Lauderdale Peele-Dixie wellfield. At the time of construction (1926), the city had a population of approximately 8,000 and had little competition for water. The first production wells were located approximately four miles inland away from any potential users or conflicts. This wellfield was located in an isolated area of the county and thought to be an ideal site for water supply. Figure 2-3 shows the area currently around this wellfield. The wellfield is located in a neighborhood, and a golf course has been built around the wells. Figure 2-4 shows a model developed to indicate the drawdowns of the well. Of concern is the fact that the wells draw water from the south, where there is a



Source: Hazen and Sawyer, P.C., Boca Raton, Fla.

Figure 2-2 Diagram of well locations for Fort Lauderdale's Peele-Dixie Wellfield (the northern half of the well are the original wells installed in 1926 that are now on the golf course of Fort Lauderdale Country Club)



Source: www.bcpa.net

Figure 2-3 2003 aerial map of vicinity of Fort Lauderdale's Peele-Dixie Wellfield. Compare to Figure 2-2.

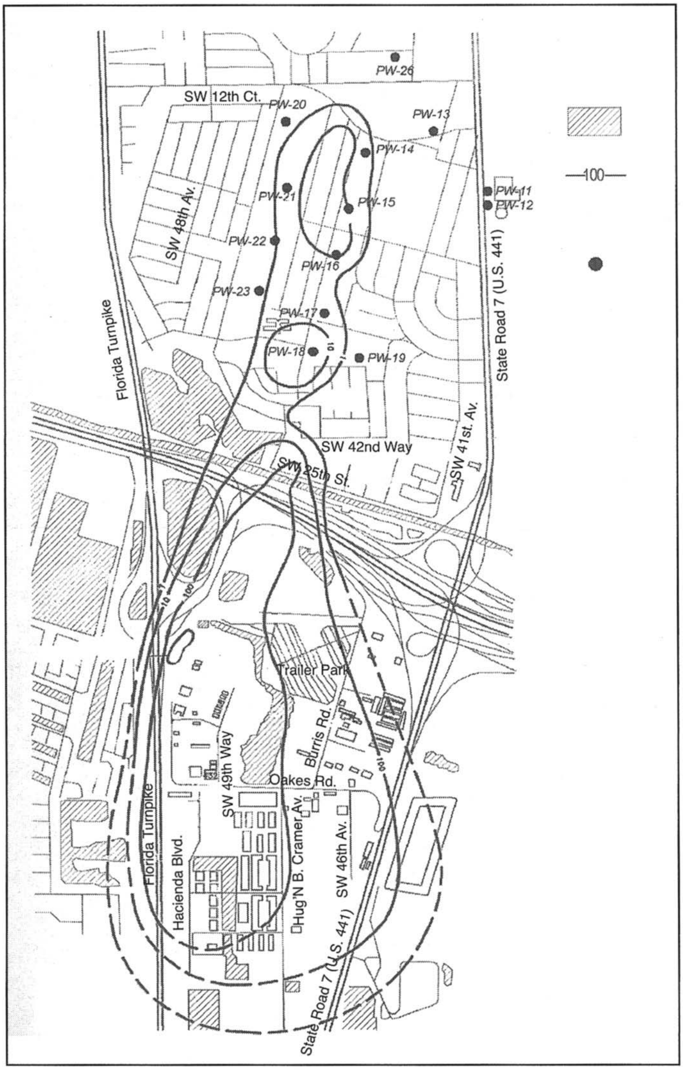
potential contamination site despite the fact that the aquifer is very productive and the wells have small zones of influence. If constructed today, the industrial site that may contaminate this wellfield would not be permitted because it is in the 30-day travel zone (see Figure 2-1).

In conjunction with wellhead protection efforts, water systems should identify any groundwater sources they are using that may be directly affected by surface water. The concern is that if there is minimal filtration occurring between the surface and the water withdrawn from wells, contaminants, especially microbiological constituents, may contaminate the water source. Water sources that meet this criterion are considered "groundwater under the direct influence of surface water." If an aquifer is determined to be groundwater under the direct influence of surface water and therefore vulnerable to contamination by disease-causing organisms found in surface water, the well water must be treated under the same requirements as a surface water system, meaning mandatory disinfection and filtration.

WATER QUALITY CONSIDERATIONS

Pathogens

Traditionally, the impurities that have affected the quality of a groundwater supply have included naturally occurring minerals in the form of dissolved inorganic salts.



Source: Hazen and Sawyer, P.C., Boca Raton, Fla.

Figure 2-4 Drawdown map of Fort Lauderdale's Peele-Dixie wellfield site (potential contamination source is located south of interchange)

High quantities of minerals mean low quality water. A significant relationship exists between mineral content and depth of groundwater; the mineral quality of groundwater generally declines with depth. In many sedimentary basins, where the older and deeper sediments were deposited by oceans, mineral content can change very abruptly. Poor-quality water can be drawn upward after production begins (*upconing*), even if a production well does not penetrate a saline zone. Similarly, operation of coastal production wells can induce saltwater intrusion into freshwater aquifers (Bloetscher et al., 2005).

Currently, many forms of contamination exist. Synthetic and naturally occurring organic compounds, solvents, petroleum products, refined minerals, and heavy metals must be considered when evaluating the development potential of a groundwater resource to meet SDWA requirements. Microbiological substances, especially in membrane treatment applications, are increasingly a concern. In many cases, construction, maintenance, and operation of facilities to remove these substances are more costly than finding a new water source.

There are over 100 microorganisms that are human pathogens (Feacham, et al., 1981), most of which are introduced into the body via ingestion, inhalation, dermal contact, or entry through wounds or body orifices (Hurst, 1996). Infected persons excrete large numbers of these pathogens, which often find their way into ground- and surface water systems via septic tanks or sewer systems. Each organism has a different dose–response relationship with vastly different threshold doses for infection. Typically, very high quantities of these organisms are required to cause bacterial infections, while with certain viruses, one organism may be sufficient to cause infection. Available studies indicate that bacteria are generally removed during wastewater treatment and disinfection, but depending on the treatment process employed, viruses may only experience a 50 percent removal (Yates, et al., 1987).

Microorganisms associated with waterborne disease can be broken into three groups: protozoans, bacteria, and viruses. Each has unique environmental fate and effect characteristics in groundwater. Protozoans and their cysts are common in surface waters and are much larger than either viruses or bacteria. The cyst stage is an encapsulation that protects protozoans from harsh environmental conditions. *Cryptosporidium* and *Giardia lamblia* are the two protozoans most studied because of their presence in drinking water (generally unfiltered surface water), and their recent link to waterborne illness outbreaks (Milwaukee, 1993).

Giardia lamblia is believed to be the most common protozoan pathogen present in surface waters. Its population appears to remain constant throughout the year in surface water impoundments (Rose and Carnahan, 1992). Neither *Cryptosporidium* nor *Giardia lamblia* appears to be a common problem for groundwater except in those groundwater systems under the influence of surface waters, where the surface–groundwater connection allows them to enter the aquifer and potentially contaminate wells. Agricultural operations, sludge and manure fields, and recently turned cropland where manure has been placed are potential sources of this contamination. While these are generally believed to be too large to move significant distances in groundwater systems, they are serious issues for surface waters and where groundwaters have direct connection to surface activities. Disinfection is generally not effective in destroying protozoans.

Bacteria are the most widely distributed life form on Earth (Chapelle, 1993). Chapelle notes that bacteria are extremely important to consider in groundwater projects as bacteria inhabit virtually every subsurface environment, producing methane gas and consuming rich organic soils. The key bacteria families responsible for waterborne diseases include gram-negative bacteria such as: *Legionella*, the *Pseudomonads*, *Klebsiella*, *Escherichia coli*, *Shigella*, *Enterobacter*, *Salmonella*, and *Vibrio cholerae*. Most of these pathogenic bacteria are approximately 0.4 to 14 μm long and 0.2 to 12 μm wide, which mean they are much smaller than protozoans, thus making it easier for them to move in the subsurface.

Bacteria have their own enzymes and most are mobile, allowing them to move in the subsurface. Bacteria reproduce by splitting into daughter cells, each of which continues to split, forming additional bacteria and eventually, a biomass. The respiration ability of bacteria permits them to survive in soils and aquifers. There are three respiration types:

1. Bacteria that use inorganic chemicals to serve as electron acceptors such as oxygen, ferric iron, and sulfates.
2. Bacteria that are aerobic—requiring oxygen.
3. Bacteria that are facultative anaerobes—capable of fermentation or using oxygen as electron receptors (Chapelle, 1993).

The respiration mechanism is important because it affects the ability of bacteria to colonize wells and the aquifer; it also affects the growth rate of bacteria indigenous to the aquifer as a result of the constituents introduced by surface activities.

Bacteria will commonly colonize wells because of the nutrients that are brought into the borehole by pumping. One example is *Pseudomonas aeroginosa*, one of the most common opportunistic bacterial pathogens. It has a colonization rate of 2.6 to 24 percent of the human population (USEPA website) and is the most common infection in hospitals. *Pseudomonas aeroginosa* is an extraordinarily versatile organism that will live in nearly any environment. *Pseudomonas aeroginosa* requires no specific vitamins, growth factors, or amino acids; it is a facultative anaerobe. However, the most important concern about this pathogen is its ability to create a slime matrix that encapsulates other bacteria and protects them from otherwise harsh aquifer conditions.

Commonly found bacteria in the subsurface include *Gallionella* and *Desulfovibro gallionella*. These are obligate aerobes that obtain energy by oxidizing dissolved ferrous iron to form ferric oxyhydroxides—meaning it will be a problem in wells constructed with steel materials (Chapelle, 1993). *Desulfovibro* is a sulfur-reducing bacterium that uses hydrogen or simple organic compounds as an energy source and sulfates as the terminal electron acceptor, which leads to hydrogen sulfide gas formation (Chapelle, 1993). Sloughing events may introduce significant quantities of these bacteria into the treatment plant. Other bacteria may also colonize the slime matrix (Bloetscher, et al., 1997). Bacteria are generally removed by filtration and destroyed by disinfection, although the *Pseudomonads* are resistant to chlorine.

Viruses are molecular entities that possess little or no enzymatic capabilities, no energy capability, and no mechanisms for synthesis. They are small—20 to 300 nm in size. They cannot reproduce; they require a host cell to multiply. All viruses are composed of nucleic acid and either RNA or DNA (but not both), which allows them to replicate in other cells, including bacteria—where they are called *bacteriophages* (Chapelle, 1993). Pathogenic viruses tend to be smaller than other viruses and can only be seen with an electron microscope. Most are 27 to 70 nm in size and are symmetrical in shape. Viruses are obligate parasites, always searching for the correct host cell that will allow the virus to multiply. Viruses cannot survive or infect without such a host organism or cell (Chapelle, 1993). The majority of viruses tend to be resistant to chloroform but may be inactivated to various degrees during wastewater treatment processes or by chlorine, bromine, ozone, ultraviolet light, or formaldehyde (Block, 1989). Viruses are conserved at –20°C (Block, 1989).

Human viruses found in natural waters are almost always associated with fecal material eliminated from the bodies of infected individuals. Therefore, virus concentrations in wastewater are high, and groundwater that may be influenced by treated wastewater or septic tanks may be contaminated. Major viruses of concern are: Hepatitis A, Coxsackie, Echo, Norwalk, rota- and reoviruses (Block, 1989). While vaccines may be available for some viruses, the wild strains never disappear from the environment (Bouwer, 1991).

Communities with poor hygiene and a high proportion of children have provided opportunities for a series of studies attempting to characterize the survival times of various pathogens. The studies confirm that in groundwater, filtration by straining is the most effective method for reducing bacterial presence in an aquifer (Powelson, et al., 1993), while virus depletion is affected by adsorption to soil particles (assuming there are no fractures or fissures in the rock that might cause viruses to move significantly further from the source water, making them harder to find).

Viruses and bacteria have been shown to live 28 to 90 days in groundwater and move 7 to 30 meters routinely (Asano, 1991; Teusch, et al., 1991). In tests for viral contamination under sludge land application sites, both Norwalk virus and hepatitis A viruses have been known to move in the groundwater environment (Gerba and Bitton, 1984). Vaughn et al. (1983) detected viruses originating in septic tanks that had passed through 3.6 m of unsaturated soil and 67 m of saturated soil (Powelson, et al., 1993). Schaub and Sorber (1977) recovered bacteriophage #2 in 47 percent of samples after 72 hr, after it had flowed through 18 m of unsaturated, silty soils (Powelson, et al., 1993). Janson, et al. (1989) recorded Echovirus 11 m deep, 14 m

Table 2-2 Factors affecting survival of enteric bacteria in soil

Factor	Comments
Moisture content	Survival time increases with moisture and high rainfall
Moisture holding capacity	Survival time less in sandy soils with lower moisture content
Temperature	Survival time longer at lower temperature
pH	Survival time shorter in acidic soils than alkaline soils
Sunlight	Survival time shorter in the presence of sunlight
Organic matter	Increase survival time and rate of regrowth with high amounts of organic matter
Microflora antagonism	Increased survival time in sterile soil

Adapted from Yates, et al., 1987

from a recharge basin for reclaimed water (Powelson, et al., 1993). In a Waldo, Fla. migrant camp, the survival of indigenous populations of total coliforms and fecal streptococcus in situ was over 70 days, and a link was shown between the same septic tanks and the presence of Echoviruses 22/23 (Feacham, et al., 1981).

Table 2-2 outlines the factors that can be expected to remove bacterial particles successfully over a short distance. Filtration is useful because the bacteria are relatively large and filter theory indicates that filtration will remove particles successfully up to 1/20th of the pore size (Gerba and Bitton, 1984). Therefore, smaller pores equal faster removal. Because of this correlation, the physical process of particle removal in saturated soils is fairly well understood and is probably adequate for predicting removal, except in fractured rock formations. Virus removal faces the same problem with rock fractures (Yates, et al., 1987). The shape of the bacteria also is a factor in removal via filtration (Gerba and Bitton, 1984).

Bacterial survival increases with increased moisture content, increased moisture retention capability of the rock, warmer temperatures, higher pH, and increased nutrient capacity (Teutsch, et al., 1991). It is not surprising that bacterial counts are highest in areas having wet, organic-rich soils (Teutsch, et al., 1991). Sorption can also play a role in bacterial survival. Clays are fine particles with negative charges that are very conducive to sorption (Gerba and Bitton, 1984). The repulsing factors resulting from these negative charges are reduced when sorption occurs. Cations in solution (Fe^{+2}, Cu^{+2}, and Zn^{+2}) play a role in removal of bacteria, while anions have little effect (Gerba and Bitton, 1984). Where soil is absent, the benefit of filtration is eliminated, but the benefits of rock filtration and reduced surface biomass matter may provide better indications of survival times (Bouwer, 1991).

While bacterial removal is preferentially accomplished in the soil via filtration, sorption, or biodegradation, virus removal is most efficiently accomplished via soil sorption although increases in temperature significantly affect viral survivability as

Table 2-3 Summary of maximum viral travel distances in groundwater

Organism	Maximum Movement Horizontal (m)	Maximum Movement Vertical (m)
Coliphage T4	1,600	—
Coliphage 174, T4	900	18
Coliphage f2	189	18.3
A. aerogenes Type 2 phage	680	—
Enterovirus	35	—
Polio vaccine	<40	—

Adapted from Gerba and Bitton, 1984

well (Gerba and Bitton, 1984). Inactivation of viruses also appears to be dependent on the efficiency of adsorption sites, temperature, and the initial number of viruses discharged. Other factors include soil conditions, pH, moisture content, aerobic or anaerobic conditions, particle size, clay content, organic content, cation-exchange capacity, virus type, and rainfall (Keswick, et al., 1982). Table 2-3 shows the maximum horizontal and vertical movement of a series of viruses.

True field studies are difficult to conduct because the use of actual viruses injected into the ground is not viewed favorably, and lab studies often cannot replicate the actual aquifer condition. What is known is that the survival of viruses and bacteria in the subsurface is determined in part by their retention on soil particles, which are generally dependent on temperature and rainfall. Table 2-4 outlines these factors.

Because viruses are sensitive to UV light, they are likely to be active longer in groundwater than in surface water because UV rays do not penetrate the aquifer system (Chapelle, 1993). Groundwater is assumed to be isothermal (constant temperature) (Yates, et al., 1985). However, viruses can survive for years in refrigerators at 41°C (39.2°F), and it appears for every 10°C increase, the virus die-off rate doubles (Gerba and Bitton, 1984). Above 30°C (86°F), temperature is the controlling factor for virus survival (Gerba and Bitton, 1984). Gerba and Bitton's (1984) multivariate study concluded that temperature could explain 77.5 percent of the variation in die-off rates between samples (Yates, et al., 1985).

Example Walkerton, Ontario

This brief example focuses on all the facets explained in this book. The city of Walkerton, Ontario is a community 4,800 people in a predominately rural area. The city relies on wells for its water supply. In the spring of 2000, nearly half the residents became ill with what was identified as *E. coli* O157:H7, and seven residents died of the infection. A formal inquiry of the matter was undertaken by Justice Dennis

Table 2-4 Factors influencing virus fate in soils

Factor	Importance for Survival	Importance for Migration
Moisture content	Survival time increases with moisture and high rainfall	Increases with saturation
Temperature	Survival time longer at lower temperature, longer in winter than summer	Unknown
pH	Stable viruses between pH 3 and 9; prolonged survival near pH 7	Increases with ionic concentration
Sunlight	Survival time shorter in the presence of sunlight	Unknown
Organic matter	Increased survival and regrowth with high amounts of organic matter	Soluble organic matter competes with viruses for adsorption sites
Microflora antagonism	Some viruses inactivated readily in presence of certain bacteria—bacteria can also protect	Unknown
Hydraulic conditions	Unknown	Migration increase with hydraulic loading
Virus type	Inactivation varies by species	Adsorption on soil sites and capsid surfaces affect migration
Virus aggregation	Improves survival	Increases migration
Soil properties	Inactivation based on sorption	Decreased migration with higher sorption availability in soil
Salt content	Cations protect certain viruses	Increased migration with higher cation concentrations, but same may increase sorption

Adapted from Yates, et al., 1987

O'Connor over the ensuing 2 years. Ultimately the investigation focused on a particular well that appeared to have a surficial connection that allowed contamination from run-off from a nearby field upon which manure had been spread.

Among many findings of the investigation, Justice O'Connor noted the following deficiencies in operating the system:

- Insufficient wellfield protection (manure field in the cone of influence of the well);
- Failure of the utility to address wellfield protection efforts as required;
- Poor operations by the utility staff (the water was insufficiently disinfected);

- Misrepresentation of water quality by operators, including concealing fecal coliforms in the water;
- Utility commissioners failure to respond to 1998 report of deficiencies by the province;
- City council did not appropriate adequate funding;
- Province's legislative budget cuts reduced funding for routine lab services and enforcement despite knowledge of improper utility and private lab practices and warnings of health consequences; and
- Province's Office of Environment did not adequately inspect treatment facility.

Much can be learned from this example, and most of the points covered in this handbook address these issues: the need for regulatory response (wellhead protection efforts and water quality monitoring); staff oversight; planning (or lack thereof); the need for fiscal responsibility (or failure to fund); and emerging issues (a new strain of *E. coli*). By conforming to the points covered in this book, a utility should be able to minimize well contamination and ultimately negative public perceptions.

Endocrine Disruptors

After three decades of focus on conventional priority pollutants, especially heavy metals, acute toxins, and carcinogens caused by herbicides, pesticides, or high volume industrial wastes, regulatory focus appears to be reorienting toward endocrine disruptors. These regulatory concerns are a result of the effects of very low levels of anthropogenic endocrine disrupting chemicals present in the environment on aquatic wildlife. The USGS has recently completed a multiyear project to study the occurrence of these chemicals in rivers (Koplin, et al., 2002). Their results found endocrine disruptors, especially pharmaceutically active substances (PASs), in many water bodies. The endocrine disruptors receiving attention from the USGS and USEPA include polychlorinated biphenyls, phthalates, alkylphenols, and PASs, such as drugs, estrogens, diagnostic agents, personal care products, fragrances, and sunscreens.

Wastewater treatment plant secondary effluents contain measurable concentrations of more than 1,000 man-made compounds, including a variety of pesticides, herbicides, cleaning solvents, laundry detergents, household products, surfactants, and PASs and their residues. These are only a portion of which have been identified (Harries, et al., 1996). Initial screening of endocrine activity of herbicides, PCBs, and pesticides has identified over 50 compounds as being endocrine disruptors, most of which appear to have an estrogenic (feminizing) effect of aquatic vertebrates. Plastic products like phthalates, bisphenol A and phenylphenol, and PCBs are weak estrogens, as are laundry detergents, household cleaning products, and surfactants that break down to alkylphenols. All are weak estrogens found in the 10^{-9} (μg/L) range.

To date however, research conducted by the USEPA, USGS, various state agencies, the Water Environment Research Foundation, and the Awwa Research Foundation remains focused on detection methods and finding chemicals in the environment, not on treatment. Little research has been focused on removal or inactivation of the chemicals as a result of the lack of adequate screening methods to determine removal efficiency of treatment.

The concentration of PASs in the environment is low compared to conventional priority pollutants—in the μg/L or ng/L range. Until analytical methods were developed to detect low levels of pharmaceuticals in the environment and the associated responses were found, PASs were not viewed as a potential environmental problem. Creating detection methods for all PAS formulations is unreasonable because many formulations are not available because of patent limitations and proprietary knowledge. However, it is now understood that noticeable environmental responses can be elicited from aquatic organisms in the 1 ng/L (10^{-12}) range, which raises questions about the cumulative effects of the hundreds of PASs that may be present in wastewater (Daughton and Ternes, 1999). It is evident that the regulation of PASs will be a major focus of regulatory limitations and research in the near future.

Municipal wastewater effluent containing PASs may constitute a major pollution source in the aquatic environment. Unused prescriptions are also often disposed of through the sewage system. It is also not uncommon for 40 percent of a drug dosage to be excreted to the sewage system after normal therapeutic use. The actions of these chemicals may be compounding (Harries, et al., 1996), because PASs are by nature biologically active compounds that are used and excreted in large quantities by modern society. Naproxen, estrogens, clofibric acid, and diclofenic were frequently detected downstream of treated effluent discharge in surface waters at the μg/L level in Europe (Stumpf, et al., 1999).

While wastewater facilities are major contributors to water contamination, they are not the only ones and perhaps not even the major one. Agricultural enterprises practicing animal husbandry (chicken, turkey, hog, cattle, and dairy farms) have made significant contributions. Over 70 percent of antibiotics used in the United States are used on chicken farms. Estrogens are used to improve growth rates and fecundity of animals.

Table 2-5 outlines the major PAS families and observed impacts to organisms. These PASs are discharged to the environment, where they remain available to other organisms. Aquatic organisms are particularly at risk, and have been studied the most. The impact of discharge into a water body upstream of a source for drinking water supply has not been studied, nor has the recharge area for groundwater that is a groundwater supply. The long-term effects on organisms in the receiving water,

Table 2-5 Summary of PAS occurrence and activity levels

Substance	Use	Quantity	Impacts
Estrogenic compounds	Contraceptive	1–5 µg/L	Feminization
Steroids	Muscle development, various	>1 µg/L	Masculinization
Antibiotics	Reduce bacterial infection	Varies	Resistant pathogens
Blood lipid regulators	Cholesterol control	to 0.165 µg/L	Unknown
Nonlipid analgesics	Anti-inflammatory	0.5–1 µg/L	Unknown
Beta blockers		0.2 µg/L	Stimulate reproduction
Antidepressants	Increase serotonin, control behavior (Prozac, Ritalin)	Varies	Stimulate reproduction
Anti-epileptics	Epilepsy control	to 6.3 µg/L	Unknown
Anti-neoplastics	Chemotherapy	0.017 µg/L	Toxicity, birth defects
Impotence drugs	Erectile dysfunction, blood stimulant	Unknown	Unknown
Retinoids	Skin diseases, anti-aging, cancer	Unknown	Birth deformaties
Contrast media chemicals	X-rays, CAT scans, diagnostics	15 µg/L	None
Fragrances and musks	Perfumes, colognes	to 0.4 µg/L	Toxicity
Preservatives	Antimicrobial	Unknown	Feminization
Disinfectants	Bactericides	0.05–0.15 µg/L	
Herbal remedies	Various	Varies	Various
Sunscreens	Protect skin from UV light	Unknown	Unknown

Source: Bloetscher and Fergen, 2001

including on humans, is a concern. Two PAS groups have received the most scrutiny—steroids and antibiotics—as they have existed in the environment the longest and have the most obvious effects.

The PAS family that has attracted the most attention from a toxicological perspective is the estrogen family. Both natural estrogens and synthetic compounds that mimic estrogens reach the environment. Natural estrogenic compounds, such as those used in estrogen replacement therapy, milk production enhancement, prescribed growth enhancement in animals, athletic performance enhancement, and oral contraceptives were among the first PASs detected. Unlike plastics and pesticides, what little data exists indicates that these drugs are strongly estrogenic at concentrations of 10^{-12} (ng/L) and have been shown to alter local biota. The synthetic steroids most commonly found in wastewater discharges are 17β-estadiol (natural estrogen) and 17α-ethynylestradiol (the "pill").

USE OF RISK IN REGULATORY ENVIRONMENTS

What quantities of a contaminant is permissable in drinking water? The answer is unclear, which is why there are risk factors and safety factors built into the current regulatory standards. *Risk* and *risk assessments* are buzzwords used in Washington, D.C. and many state regulatory agencies. The use of these terms and their placement into laws and regulations does not mean that anyone necessarily understands how to conduct a risk assessment; however, it does create a tool for the regulatory community to use in an attempt to quantify the effects of a given activity. The most important aspect of risk is that there are no zero-risk alternatives. Only comparative risks can truly be calculated—the preference of one alternative over others and the choice by utilities to strive to minimize those risks that may exist.

Because there are no zero-risk alternatives, and because there are finite limits to the amount of resources that can be used to either define risk or maximize risk reduction, the concept of *acceptable* risk has been developed. According to USEPA, an acceptable risk is the 1:1 million lifetime chance that an impact will occur to the general public as a result of an activity. Acute responses (immediate impacts), for instance microbial water quality regulations, may be written according to the probability that less than 1 in 10,000 will contract a disease from drinking water in a given year. Carcinogens tend to use the 1:1 million lifetime (chronic) risks more frequently than acute exposures, because the effects may not manifest themselves for many years. Regulations are typically written according to these acceptable risks.

In environmental impact assessments, risk–cost assumptions may be used. Figure 2-5 shows an example of such an analysis whereby the acceptable risk is defined, and the associated cost of compliance is calculated. As risk decreases, the cost rises. To some, much of the focus is whether the acceptable risk or the cost should be the limiting factor in determining acceptable risk. Obviously, if cost is used as the limit, the risk would likely be much higher. Political conflicts over resources are one of four problems encountered when determining acceptable risk. Limited data and conflicting data create confusion and uncertainty in the risk assessment process.

Risk assessments generally include two parts: the scientific investigation and the risk management portion. Scientific assessment methods include measuring the effects of exposure or the activity to the ecosystem or humans, determining the level at which the impacts are negligible, and creating methods to replicate and measure the impacts. Management of the risk includes taking the steps necessary to limit exposure. The latter is for local officials and includes the proper training of employees, maintaining appropriate records of operations, and providing those facilities and tools needed to minimize risks to the community. When making local

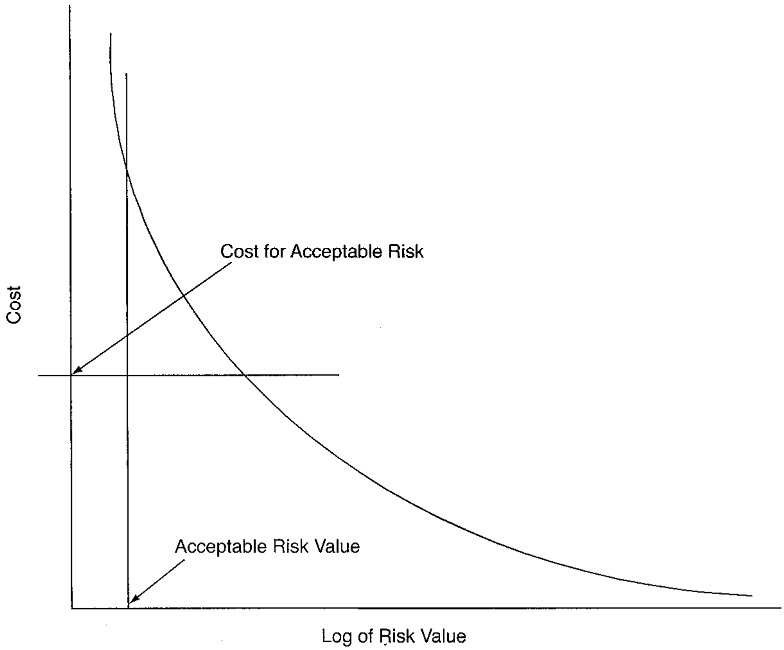


Figure 2-5 Risk–cost analysis

decisions on expenditures, it should be noted that neither the preface to the Clean Water Act nor the 1996 amendments to the SDWA mention cost as a part of the laws, only protection of the public health and the ecosystem.

PERMITS

Permits are required for any well drilling operation. Exploratory drilling permits must be secured and fees paid, generally at the state or county level. Obtaining permits is usually the responsibility of the well driller or the engineer or hydrogeologist in charge of the project for the owner. A hydrogeologist normally supervises the work in the field, including the procurement of well construction materials, well logging, conducting or overseeing geophysical logging, interpreting logs, well designing, and certifying as-built well construction drawings.

After the exploratory work is completed, the production wells are drilled. To do so, permits must be filed, fees must be paid, and monitoring must be conducted. Federal, state, and local laws require information to be filed on a periodic basis throughout the well construction process. Documentation of initial investigations, pilot testing, and water supply development must be detailed and complete. Multiple copies of reports pertaining to groundwater development may be required by different agencies for differing purposes. A permit is generally required for well completion reports, results of logging during construction, and field testing reports.

In addition to drilling and well completion reports, water quality reports should be developed. More extensive testing of groundwater for contaminants that may impact future implementation of regulatory requirements is recommended. Information must also be filed with various government agencies involved in groundwater monitoring of facilities that produce, handle, store, treat, or dispose of chemicals determined to be hazardous to health or the environment. This information, when combined with information provided by the groundwater well developer, can increase understanding of the regional groundwater system under study and its potential and reliability as a water supply.

Regulatory agencies are concerned about well construction and closure of a well because of the possibility of cross contamination between shallow zones and deeper high-quality aquifers. Reports that document field work can be very valuable in later phases of groundwater development or protection. Proper land survey location, global positioning system locations and description of the wells, and complete as-built drawings of construction are desirable.

Permits, reports, and drawings should be planned as a part of the project. There is a cost to provide this service on the part of engineers and hydrogeologists. Where there is the potential for conflicts over water use, it may be desirable to consult an attorney knowledgeable in aspects of the law involving groundwater and permit procedures. Reports from the drilling process may be of great value in litigation and, therefore, should be prepared with care and be subjected to appropriate legal, technical, and managerial review.

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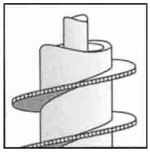


3

Drilling Methods

Wells can be viewed as large holes in the ground, deeper than they are wide, and the water supplied by them is relied on by water customers, agriculture, and other interests. In addition to providing available water supply reliably, wells are designed to last for 50 years or more, and the steps initially taken to design and drill the well play a large role in the longevity of a well. Proper well construction should be based on a thorough engineering study and designed to best accommodate existing conditions and requirements.

There are many drilling and well construction methods that have been developed depending on the purpose for which the well is to be constructed. Some purposes for wells include

- Water production (the focus of this handbook),
- Oil and gas wells,
- Geothermal wells,
- Injection/disposal wells,
- Aquifer storage and recovery wells, and
- Environmental remediation and monitoring wells.

Environmental remediation wells are the shallowest of this group, often less than 20 feet deep, but oil and gas wells may be tens of thousands of feet deep. Water supply wells fall somewhere in between.

Just as there are many purposes for wells, there are even more options for their construction, including the following:

- Hand dug
- Cable tool
- Hollow stem auger
- Large diameter auger
- Screened stem auger
- Solid flight auger

- Hydraulic rotary
- Reverse-air circulation
- Casing hammer air rotary
- Rotary down-the-hole hammer
- Dual-tube rotary
- Direct push
- Mud rotary
- Reverse circulation (mud)
- Bucket-type drilling
- Direct-air circulation
- Reverse circulation
- Percussion hammer
- Horizontal/directional/angle
- Sonic
- Jetting and driving

Many of these drilling methods are used for construction of water supply wells. Selection of the proper drilling method depends on many variables including

- Well diameter and depth,
- Capacity of drilling rig,
- Height of drilling mast, and
- Types of formations.

TYPES OF WELLS AND THEIR CONSTRUCTION (from AWWA, 2003)

A variety of wells have been used at times for water supply purposes, albeit most are used only for small installations and under certain conditions. These include dug, bored, driven, or drilled wells.

Dug Wells

Hand digging wells is the oldest method of water well construction. As is to be expected, hand digging a water well is extremely labor intensive, dangerous, and time consuming. A dug well is frequently excavated using a pick and shovel, and a hoist with a bucket. They are large in diameter, but relatively shallow (i.e., less than 30 ft in depth). Most dug wells are circular because this shape adds strength and is usually easier to dig. Such wells can furnish relatively large supplies of water from shallow sources. Depending on the formation, the well may be able to stand without reinforcement, but more commonly, pilings, concrete, or bricks are used to create support walls.

Once the top of the water table is encountered, it is very difficult to advance the depth of the well into the aquifer. The limited production horizon severely limits the quantity of groundwater available for extraction. The narrow production zone also leaves the well vulnerable to changing water level elevations. During times of little precipitation or drought the water table will become lower and lower. Eventually the top of the water table will be located below the bottom of the open

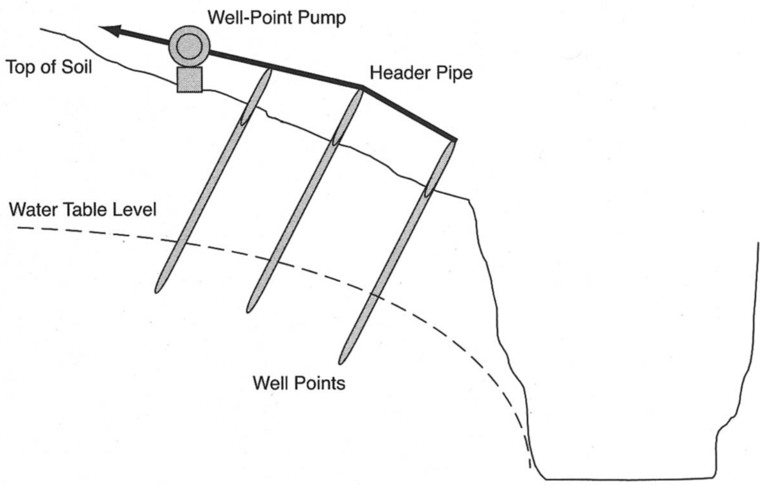


Figure 3-1 Operation of well points

hole, resulting in a dry well. The negative impacts of a well "gone dry" on a local community are obvious.

Hand dug wells are rarely adequately protected from contamination. Impacts to the well from surface run off, airborne material, animals, insects, and objects falling into or finding entrance into the well are common. Concrete curbs are commonly constructed around the edges because dug wells are easily polluted by surface water. Although hand dug wells are still constructed in many parts of the world, they are not commonly used as a source of groundwater for a modern water supply system in developed countries and are rarely used in the United States.

Driven Wells

A driven well consists of a pointed steel screen, called a *drive* or *well point*, and lengths of pipe attached to the top of the well point (see Figure 3-1). Well points are driven into the formation with a weight, derrick, and pulley system. The driver weighs between 30 to 75 lb and well points can be mechanically driven as deep as 50 ft. If the diameters are small, they can occasionally be installed by a hand driven system. Figure 3-2 presents instruction as provided by the C.L. North Company of El Paso Texas for the installation of driven wells. When constructing a driven well, an outer casing is first installed by pounding the pointed screen into the formation. The steel tip breaks through pebbles and thin layers of material and opens a passageway for the screen. For small municipal water supplies, the driven well may be used in thin deposits of sand and gravel found at shallow depths. The outer casing protects the inner casing to which the pump is attached.

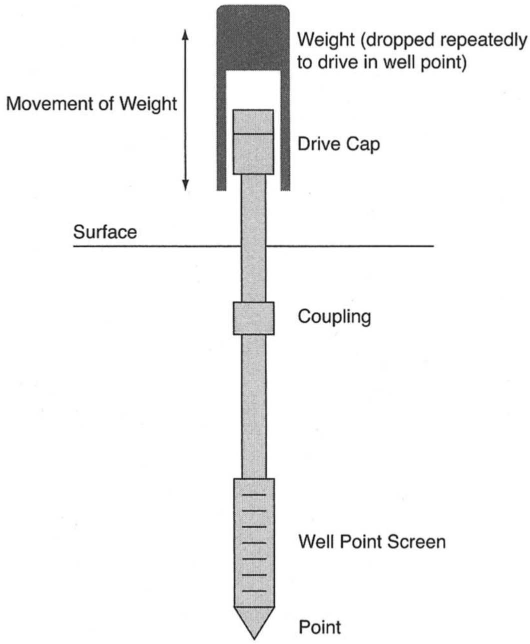


Figure 3-2 Installation of driven well points

In sand and gravel formations, the outer casing should extend to just above the drive point. The outer casing can be driven with a sledgehammer, or for larger pipes, a tripod and pulley can be used. The tripod and pulley set-up raises and lowers a heavy block onto a drive cap placed on top of the outer well point casing. Extra heavy pipe should be used to withstand the load. If the ground is clay, the outside casing should be set in a hole prepared by an auger prior to inserting the well point. After the outer casing is set, the annular space between the bore hole and the outside of the casing should be sealed with cement grout.

Driven wells range from 1 to 4 in. in diameter and rarely are driven more than 30 ft. The screen is an integral part of the portion driven into the ground, therefore, only soft materials are easily penetrated. As a result, the production rate of driven wells is limited. Instead of a single well, a battery of well points, with the wells located a reasonable distance apart and connected by a common header to the pump, can develop sufficient water to supply a small community. However, driven wells are typically used to dewater construction sites.

California

The California, or stovepipe, method of well construction was developed in California for water wells drilled in unconsolidated alluvial materials. Large wells, 16 to 20 in. (400 to 500 mm) in diameter and up to 300 ft (90 m) in depth, are constructed using this method. The California drilling method uses the same general principles used for cable tool rigs. Short lengths of sheet metal, either riveted or welded together, are used for casing. After the casing is in place, it is perforated using a Mills knife or similar device that tears the metal. The openings must not be too large or the area perforated too much.

Jetting

Jetting is used to construct wells when water is found in sand at shallow depths, although the method is applicable for deeper wells. Jetting equipment consists of a drill pipe, or jetting pipe, that is equipped with a cutting bit on the bottom end. Water is pumped into the well through the drill pipe and out of the drill bit against the bottom of the drill hole. The casing usually is sunk as drilling proceeds. Jetted wells are usually small in diameter, therefore deeper well construction becomes more difficult to manage and control. To solve this problem, several lengths of casing with different diameters may be telescoped one inside the other to reach the full depth.

Certain conditions make this method of well construction difficult. Rock and boulders are barriers that cannot be overcome by water pressure, regardless of how high the pressure might be. Formations of clay and hardpan become soft and sticky.

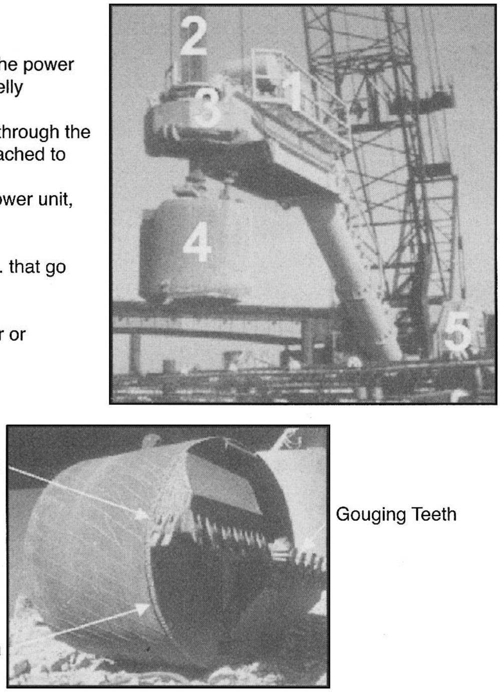
BUCKET-TYPE DRILLING

Although the previously described methods are used in many areas, they are rarely used to supply treatment facilities serving local communities. The following methods are more commonly used to establish well fields capable of meeting local demands.

Bucket-type drilling uses a rotating cylindrical bucket. Cutting blades mounted on the bottom of the bucket cut the sediments, and the pieces of sediment are retained in the bucket. When the bucket is full, it is withdrawn from the borehole, swung to the side, and the hinged bottom is opened releasing the cuttings. Bucket-type drilling can be used to drill wells from 10 to 60 in. in diameter and to a maximum depth of about 100 ft.

Sediment samples recovered during borehole advancement are used to identify the penetrated formations. Bucket drilling requires little or no fluid to be added to the borehole during drilling, allowing for the recovery of water samples for analysis. Bucket-type rigs are relatively simple in design and are capable of drilling quickly. Figure 3-3 shows an example of a bucket-type drilling rig. Often, casing is advanced into the borehole as part of the drilling activity. An advantage of this method is the reduced possibility of cross contamination of fluids during drilling.

Bucket-type drilling produces a large quantity of cuttings and, once the saturated zone has been penetrated, large volumes of fluids. Generally limited to poorly lithified cohesive sediments, bucket drilling may be continued into sand and sometimes gravel if the casing is advanced into the borehole during drilling, or if the



Source: http://images.google.com and www.fhwa.dot.gov

Figure 3-3 Bucket-type drilling rig and close-up of bucket

borehole is kept full of water. Once even moderately lithified sediments are encountered, they will usually prove to be too resistant for bucket-type rigs to penetrate.

The use of bucket-type drilling is dependent on the sediment types anticipated to be encountered. Good results can be realized on generally unlithified cohesive formations, such as glacial tills. Formations consisting of large boulders, competent shale, chalk, or sandstone are extremely difficult if not impossible to penetrate using this method, and it is impossible to penetrate well-lithified sediments, igneous, and metamorphic rocks.

CABLE-TOOL METHOD

Cable-tool methods are also called *percussion*, *spudder*, and *solid tool methods*. The cable-tool method was used as early as 300 BC to drill salt wells in China to depths as great as 3,000 ft. Cable-tool drilling methods are commonly used today for shallow wells but can be used for wells as deep as 1,000 ft. Cable-tool methods are straightforward. The technical expertise required is less than for some other methods although the details of construction and operation of the drilling machines

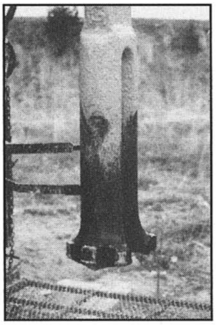
Source: www.esd.lbl.gov

Figure 3-4 Cable-tool drilling

vary widely. This drilling method is older than most other methods and is well understood.

All cable-tool rigs create the borehole using the percussion and cutting action of a drill bit. Figure 3-4 shows a cable-tool drilling rig. Cable-tool drilling is accomplished by alternately raising and dropping a heavy drill bit (Figure 3-5) suspended at the end of a cable, thereby pulverizing the formation below. As shown in Figure 3-4, a casing is often used to keep the hole open when drilling in loose material. The drill bit, a club-like, chisel-edged tool, breaks the formation into small fragments. The bit turns with each blow. The bit is then returned to the bottom of the borehole and the process is repeated until the desired depth is achieved. Cable-tool wells can be from 4 to 18 in. in diameter. The length of the drill cable is adjusted so that the bit will strike with the right amount of weight and stroke. The cable is monitored to determine how well the tools are operating. The length of stroke and rapidity of blows are continuously adjusted to maximize the rate of penetration.

After several feet (one to two meters) of borehole are drilled, the bit and drill string are pulled from the hole and swung aside. A bailer is used to remove the slurry. The bailer consists of a 10- to 25-ft (3- to 8-m) long section of tubing with a check valve in the bottom (see Figure 3-6). The bailer is smaller in diameter than the drill hole so that it can move up and down freely (AWWA, 2003). Once the borehole has



Source: http://mo.water.usgs.gov

Figure 3-5 Cable-tool bit

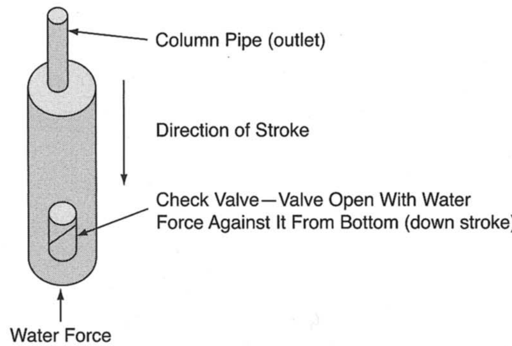


Figure 3-6 Bailer

been cleared of cuttings the bit is returned to the bottom of the borehole, and the process is repeated until the desired depth is achieved.

The borehole must be straight and vertical, or plumb, for ease of operation and for installation of casings, pumps, screens, and column pipes. In extreme cases, lowering a pump into a well or pulling it out may become impossible if the well is not plumb. The first indication that the hole is not plumb is that the drilling tools begin to stick. When this happens, drilling should stop and the hole realigned.

Although used less frequently, cable-tool rigs have certain advantages. The ruggedness and simplicity of the drill rigs makes them easy to move across rough terrain. Ease of repair also makes them ideal for isolated areas without access to repair parts or power. Because little or no outside drilling fluids are introduced to the well during drilling, representative water and formation samples can readily be recovered as drilling progresses. Water is usually not necessary as drilling mud is not used during operations, minimizing plugging of the formation and simplifying development of the well. The use of a bailer to remove the cuttings from the well aids in keeping the native formations clean of sediments produced during drilling. Each time the bailer is removed from the borehole it is filled with cuttings and formation fluids. Removal of these solids and fluids allows the formation fluids to flow from the formation into the borehole, keeping the borehole wall clean. Most types of formations can be drilled unless they are either very hard or very soft (clays). Limited damage to the formation adjacent to the borehole occurs as the borehole force is downward. In most cases, a cable-tool rig is light and can traverse rough country easily.

Cable-tool drilling methods are slow, providing poor productivity in hard formations or deep wells. The limitation of diameter may be a concern for high productivity needs. The casing must often be advanced with the drill bit to maintain the competency of the borehole and to prevent formation fluids and previously drilled sediments from migrating within the hole. The action of the bit can damage the borehole wall, resulting in a lower well efficiency than desired.

Caisson Well Construction

Caissons are used in shallow, very loose and permeable alluvial formations because of the potential to lose large quantities of drilling fluid or mud into the loose formation. A hole is made by sinking a very large (typically concrete) diameter casing to about 15 ft (4.6 m). The next casing is installed in a concentric manner, one size smaller in diameter than the previous, using the same bailing method (Figure 3-6) until it is extended another 15 ft below the first casing. This process is continued until the bottom of the desired formation or the desired depth is reached. The last casing installed should be of the minimum diameter of the bore hole designed or specified. The concept of ever smaller casings inside and below the prior casing is termed *telescoping*. Drilling may only be involved in the later stages of caisson construction as well as radial wells, an extension to caisson construction.

HOLLOW STEM AUGER

Several types of augers are used in the drilling industry including large diameter augers, solid flight augers, screened stem augers, and hollow stem augers. Of these various auger methods, the hollow stem auger is most commonly used in the construction of water production wells.

Hollow stem augers use continuous flight augers generally up to 14 in. in diameter that use mechanical methods to remove drilled materials from the borehole. Axial openings in the center of the auger, up to 10.25 in. in diameter, allow access to the bottom of the hole without removing the augers. The augers also act as a temporary casing during well construction allowing for recovery of soil and water samples as well as aiding in construction of the well. This well drilling method is generally used for small diameter, shallow wells up to 150 ft (45 m) deep.

Hollow stem auger methods of drilling are commonly used for short-term wells, such as for construction dewatering or for recovery wells for cleaning up groundwater contamination. Each section, or flight, of augers is usually 5 ft in length. As shown in Figure 3-7, a cutting bit is attached to the first flight. Either a plug, or more often a pilot bit, is inserted through the hollow stem of the augers. The pilot bit, held in place by drill rods, helps cut the formation and also prevents cuttings from entering the bottom of the auger.

Once the desired depth is reached, the drill rods and pilot bit can be removed from inside the augers, allowing split spoons or thin walled samplers to be used for sample recovery as shown in Figure 3-8. Water samples may also be recovered from inside the augers using a sampling device such as a Hydro-punch. The pilot bit is placed back inside the auger and drilling can resume. Once the desired total depth

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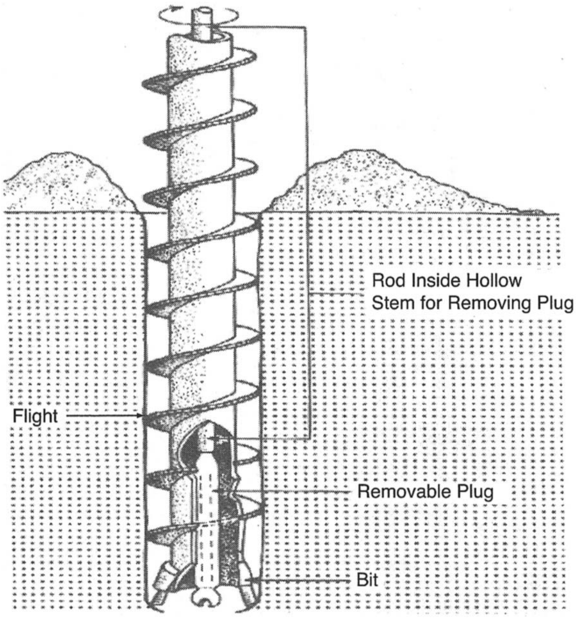

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Figure 3-7 Hollow stem auger

has been achieved and the pilot bit has been removed, the well screen and riser can be easily lowered down through the center of the augers. The well-screen gravel pack is placed as the augers are pulled, not rotated, out of the borehole.

Advantages of the hollow stem auger drilling method include the following:

- Drilling fluids are not introduced.
- The borehole is drilled and the casing can be placed simultaneously.
- Representative samples of aquifer fluids and formation material are easily collected in uncontaminated condition.
- The drilling technique is fast.

However, hollow stem drilling methods are limited to softer formations, such as loose sand, gravel, or unconsolidated formations. An auger can be used only where formations, though relatively soft, will permit an open hole to be bored to depths ranging from 25 to 60 ft (8 to 18 m) without caving. The most suitable formations for bored wells are glacial till and alluvial valley deposits. The depth and diameter are limited as well. Wet formations, such as running sands, will make drilling nearly

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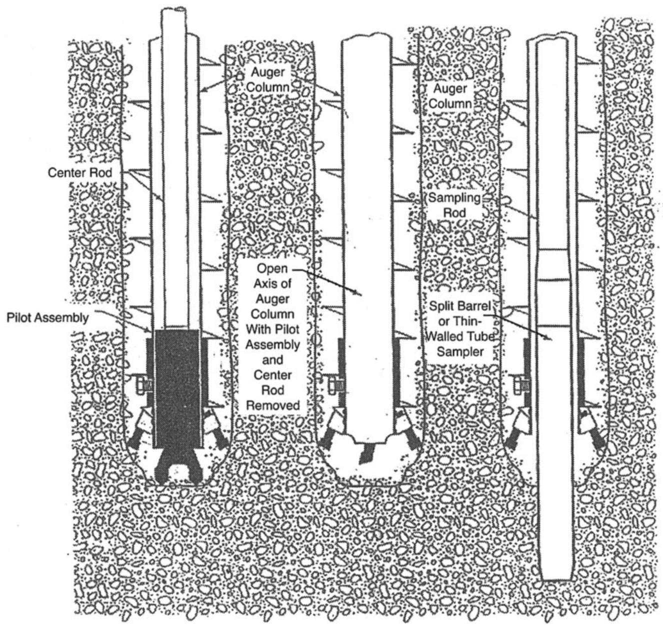


Source: Scalf, et al., 1980

Figure 3-8 Split spoon sampling devices

impossible and will contaminate water quality samples and formation samples. Generally speaking, this type of well is not used for municipal supplies.

HYDRAULIC ROTARY DRILLING

Rotary drill rigs have a long history. They were used by the Egyptians for cutting stone for the pyramids (Lehr, et al., 1988) and in the 19th century for well drilling. Hydraulic rotary drilling methods are used for larger production wells and where construction methods must proceed faster. Extensive use of hydraulic rotary drilling for oil and gas exploration has led to many advances, some of which are applicable to water well drilling. However, the method requires more technical equipment and expertise than cable-tool and hollow stem auger methods. Hydraulic rotary methods, as the name suggests, involves the introduction of fluids to improve drilling efficiency. Water and drilling mud are typically used, but in some cases air or foam are used as the drilling fluid. When the fluid used is drilling mud, the method is usually referred to as *mud rotary.*

The drill string usually consists of a bit, drill collars, stabilizers, and drill pipe. Rotation is transmitted from the surface along the drill string to the bit. As shown in Figures 3-9 and 3-10, as the bit is rotated, drilling fluid is pumped down through the

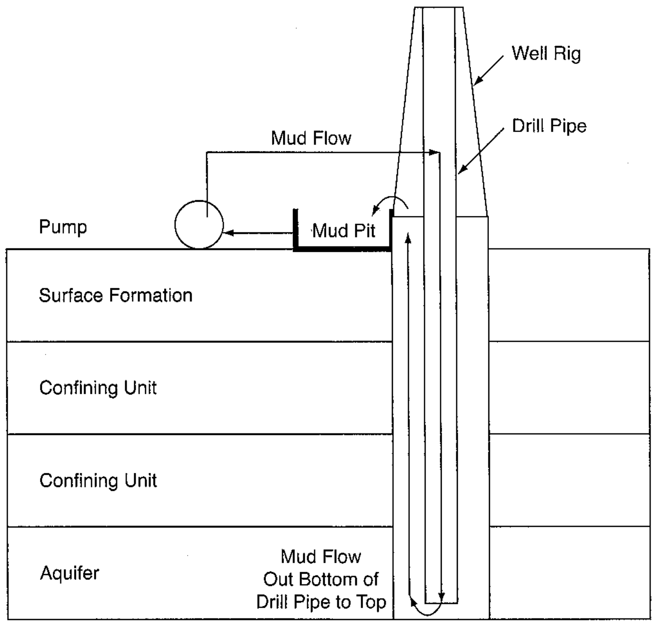
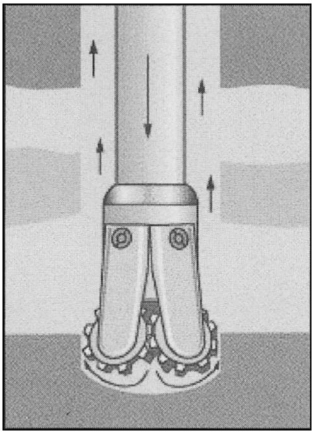


Figure 3-9 Mud rotary circulation

drill string and out of the bit. The cuttings are returned to the surface by the drilling fluid as it rises in the annular space between the drill string and the drilled formation. The drilling fluid is cleaned and recirculated through the drill string.

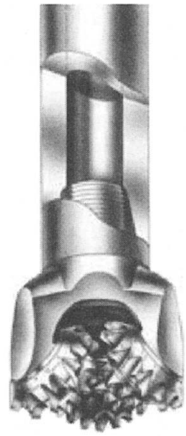
Bit selection depends on the anticipated formations to be encountered. Figure 3-11 shows a cutaway view of a typical tricone mill-tooth rotary drill bit. The bit size is roughly the diameter of the borehole drilled. Different types of bits are used depending on rock hardness and composition. Figure 3-12 shows a chart for bit selection. Figures 3-13 to 3-15 show various bits and the type of rock for their appropriate use. Drag bits have no moving parts; the blades (see Figure 3-13) are designed to cut into soft formations, such as clay and poorly consolidated sands. Mill tooth tricone bits (Figure 3-14) are used for moderately hard formations, while tricone bits with carbide button inserts are used for harder formations, such as well-cemented sandstone, micritic limestones, and dolomites. For very large diameter drilling applications flat bottom bits are used (Figure 3-15). These are large drill bits with many cutting heads.

Drill collars are heavy walled pipe machined from solid bars intended to keep the borehole straight and plumb by placing weight directly on top of the bit (see Figure 3-16). Drill collars allow weight to be placed directly downward to keep pressure on the bit and force it into the rock. The combination of directing weight



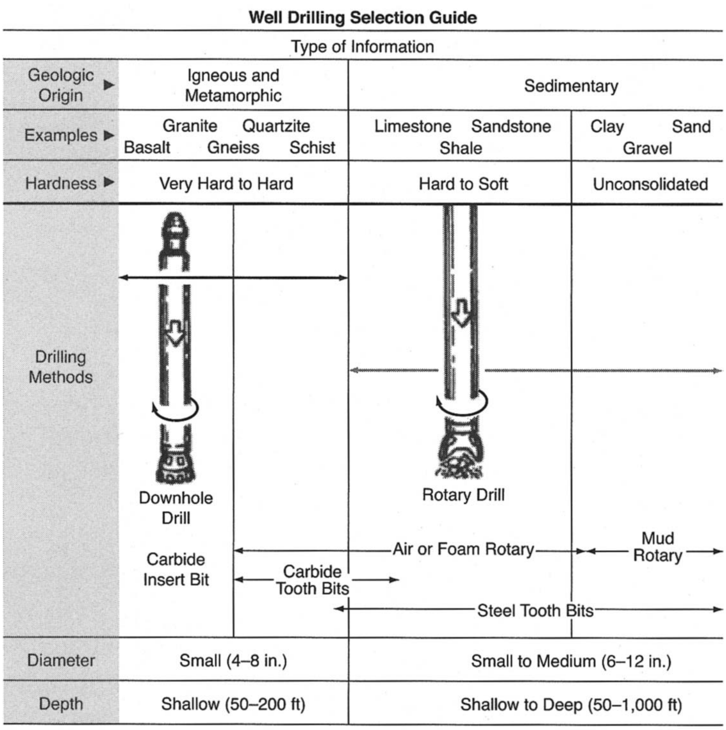
Source: Adapted with permission of the Energy Institute, UK

Figure 3-10 Mud rotary method with cuttings carried to surface



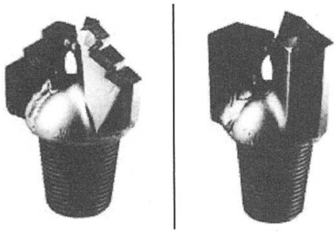
Source: www.torquato.com

Figure 3-11 Typical rotary drill bit and drill collar



Source: www.globalsecurity.org

Figure 3-12 Chart for bit selection



Source: www.torquato.com

Figure 3-13 Drag bits for unconsolidated and soft sediments

Source: John Largey

Figure 3-14 Tricone bits for moderately hard to hard formations (rear, mill tooth; front, button)

downward and preventing bit wandering improves the efficiency of the bit action in crushing the rock. Stabilizers (Figure 3-17) are positioned at various locations within the lower part of the drill string. They are used to maintain borehole geometry by keeping the bit and drill collars straight and plumb.

The drill pipe is normally in 20 or 30 ft sections referred to as *joints* of pipe (see Figure 3-18). It is usually made of manganese–carbon steel or a molybdenum alloy steel. Drill pipe used for water well drilling is generally is 2.375 to 4.500 in. in diameter. Proper size is important to minimize friction loss and therefore reduce power required to rotate the drill string. The drill pipes are connected together with threaded tool joints, which should be cleaned and lubricated before each connection to prevent the threads from seizing.

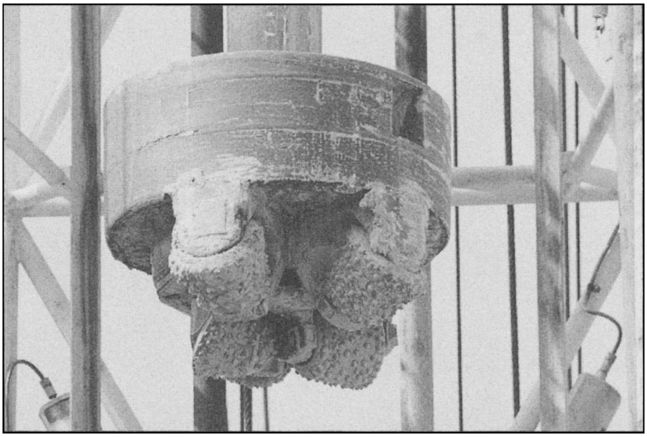


Figure 3-15 Flat bottom bit for large diameter drilling applications

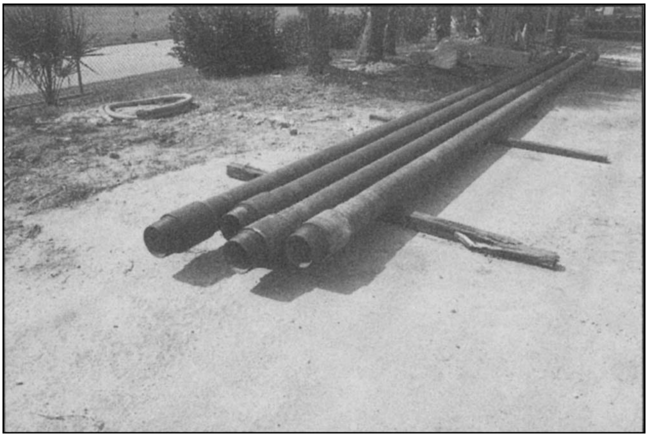


Figure 3-16 Drill pipe and drill collars

As previously mentioned, the drill string is hollow to allow fluid to be pumped to the bit at the base of the borehole. The fluid migrates up the annulus carrying the cuttings to the surface. When drilling in clay soil or mud, fluid of sufficient viscosity is required to lift cuttings to the surface. For soft formations, less dense fluids can be used, but in many cases, drilling mud is used. In addition to removing the cuttings from the borehole, drilling mud serves to cool and lubricate the bit and drill string, build a filter cake on the borehole, prevent fluid loss into upper formations, and prevent borehole collapse. Figure 3-19 shows a typical basic mud circulation system that has been used for quite some time. It must be noted that ditches, settling pits,

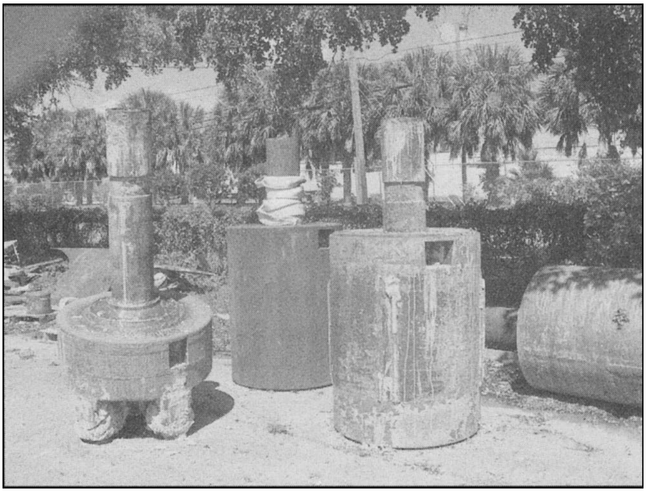
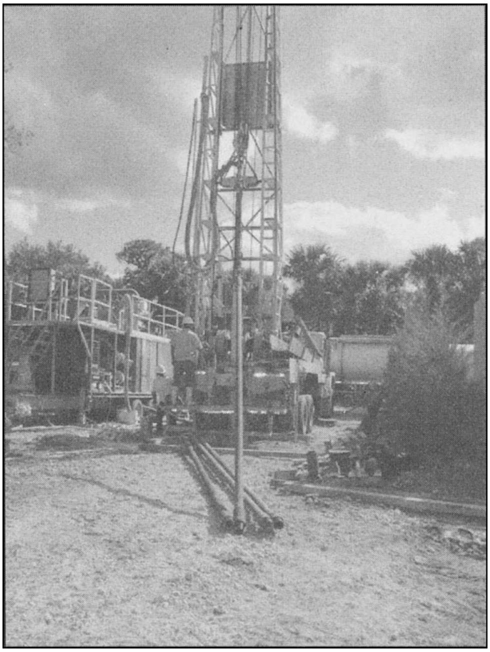
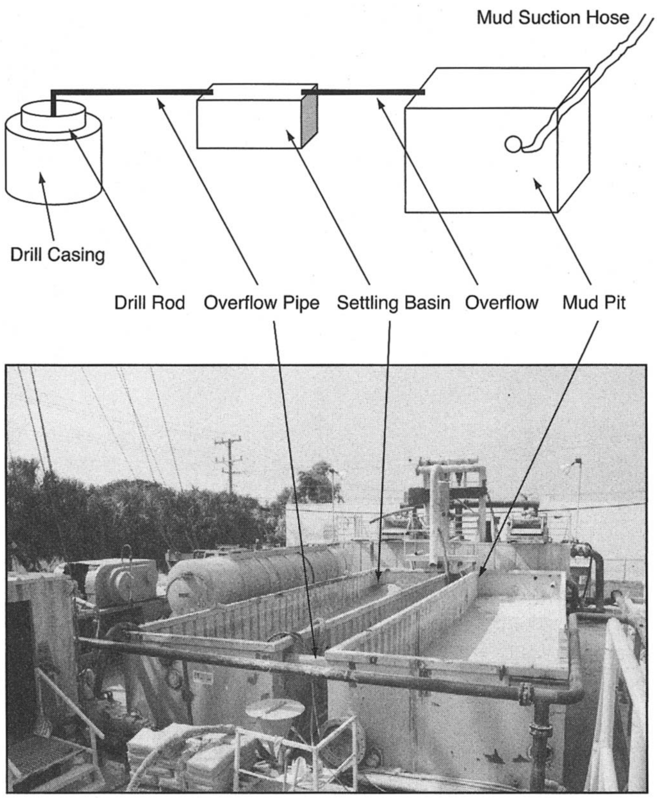


Figure 3-17 Three stabilizers and a 42-in. drill bit (left)



Source: John Largey

Figure 3-18 Picking up drill pipe



NOTE: The overflow pipe, settling basin, and mud basin generally sit on the surface (as shown) or are cut 2–3 ft into the surface

Figure 3-19 Typical mud circulation system

and storage pits are simply dug into the ground and not lined. In many locations, this type of circulation system is prohibited to prevent discharges that may affect a surficial aquifer.

Drilling fluids perform four primary functions (Lehr, et al., 1988)

1. Remove the cuttings below the rotating bit.
2. Transport the cuttings up the borehole to the surface.
3. Maintain borehole stability.
4. Cool the bit.

In addition, additives such as drilling mud (Lehr, et al., 1988) assist to

- Prevent fluid entry from the porous rocks,
- Reduce drilling fluid losses into the formation,

- Lubricate the mud pump, bit bearings, and drill string,
- Reduce wear on the drilling equipment, and
- Control formation fluid pressures.

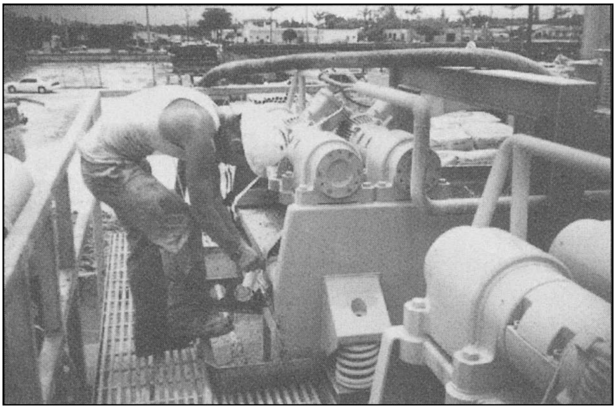
One of the primary purposes of the drilling mud is to form a seal, known as a *filter cake*, on the borehole wall. The density of the mud is related to the ability to form a proper filter cake, thus increasing borehole stability and reducing fluid loss to the formations being penetrated. The density of the mud, measured in pounds per gallon, is generally designed to be pumped into the borehole at a slightly higher hydraulic head than the surrounding formation pore pressure, thereby allowing both the formation of a proper filter cake and control of artesian pressures. Proper monitoring of the mud density (mud weight) is important as mud weight will prevent the proper formation of a filter cake, and too high a mud weight may result in high fluid loss and plugging of porous formations while a too-low mud weight will not bring cuttings to the surface. When highly porous formations are encountered, the drilling mud may stop returning to the surface and flow directly into the surrounding sediments. This condition is known as *lost circulation*. Several additives, known as *lost circulation material*, are available to plug the formation pores and help regain circulation of the mud to the surface.

The drilling mud is usually prepared using a hopper attached to a suction pit located near the drill rig. The preferred drilling mud material is commercial colloidal material (bentonite clay base) that is purchased in powdered form and mixed with water. Controlling the mud during drilling is an important factor in borehole control and conditioning the borehole for logging. Too much mud caked on the borehole will make logging inaccurate, while too little will not properly seal the borehole to prevent the intrusion of mud into upper formations or loss of the mud into fissures above the bit. Key factors in preparing drilling mud include

- Mud weight
- Mud viscosity
- Gel strength
- Sand content of the mud

The lightest mud weight possible should be used considering potential formation pressures and potential for borehole collapse. Lighter weight drilling mud will intrude into permeable zones less than heavier mud, making development of the well easier. Addionally, unwanted mud may be formed by normal drilling operations when native clays are encountered. In other formations, clay additives may be used initially to increase mud viscosity.

Viscosity is related to up-hole velocity of the drilling mud and the ability of the drilling mud to carry cuttings to the surface. The intent is to have a mud that is



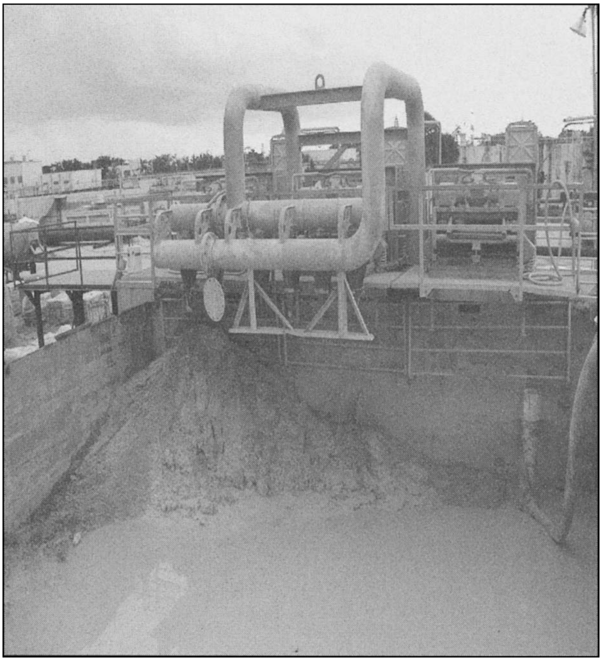
Source: John Largey

Figure 3-20 Collection cuttings at the shale shaker

viscous enough to carry the cuttings to the surface given a certain up-hole velocity, but to drop the cuttings quickly once it is returned to the mud system. Drilling fluid viscosity is measured with a Marsh funnel. The drilling fluid is poured into the funnel and the viscosity is determined by the amount of time (in seconds) it takes to drain one quart out of the funnel. Lehr, et al. (1988) indicates that a good Marsh funnel viscosity ranges from 35 to 45 sec. If the circulating mud begins to pick up sand, the weight will increase, and viscosity will decrease. Under such conditions, additional water or other additives should be mixed into the mud.

Settling is needed to remove the cuttings and allow recovery of the cuttings for professionals to determine formation type and to make decisions about the formations most likely to yield water. Once the mud is returned to the surface, it is directed to the cleaning portion of the mud system. Shale shakers are used to first remove the large cuttings (see Figure 3-20). Upon returning to the surface, the drilling mud is directed over vibrating screens. In sandy formations, de-sanders can also be used to remove excessive sand from the drilling mud (see Figure 3-21).

Drilling mud that is too thick will be difficult to clean and to remove from the borehole wall once drilling is complete, extending the amount of time required for well development. Low viscosity mud often has 10 to 15 percent solids, composed mostly of heavy sand. If the viscosity is too low, cuttings will not be brought to the surface, and lubrication will be inadequate for the drill bit and collars. Such a situation increases the likelihood of the drill string getting stuck and the loss of drilling fluids into the formation. Observation of the recovered cuttings can provide insight into the efficiency of the mud cleaning system. Because the drilling mud continuously circulates through the hollow drill pipe to the bit and back to the surface, sand grains that are recirculating will become smaller and more rounded.



Source: John Largey

Figure 3-21 De-sanding operations

In highly porous formations, the low viscosity mud can migrate into cavities in the formation prior to the mud building up on the borehole wall. This loss of drilling mud can be a significant problem for the drill crew and may create regulatory compliance concerns. At the same time, the sand content may decrease where clays or other fines are introduced into the mud and not settled in the settling basin. In such cases, the mud may need to be reconditioned.

Gel strength is a measure of the ability of the mud to suspend the cuttings in the mud. Proper gel-strength drilling mud will suspend the cuttings in the mud when circulation is stopped to add another section of drill pipe (make a connection), thereby preventing the cuttings from settling on the bit, potentially causing it to seize. However, if the gel strength is too high, large volumes of mud will be lost over the shale shakers and the cuttings will not settle in the settling pit.

Mud rotary drilling systems use two basic drive systems. Rotary table drives rely on a rotary table recessed into the floor of the drilling rig. A kelly bushing fits into the rotary table. A multisided pipe, called the *kelly*, is attached to the top of the drill string and slides through the kelly bushing. The rotational forces are transferred from the rotary table, to the kelly bushing, to the kelly and through the drill string. Top drive rigs have a hydraulic motor suspended from the traveling block. The drill

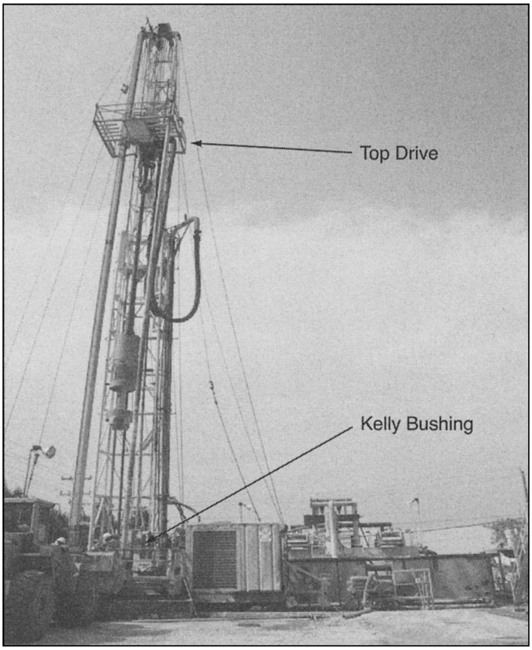


Figure 3-22 Top-head hydraulic drive system

string is directly connected to the hydraulic drive motor (see Figure 3-22). Rotary table systems use higher rotation speeds with lower torque resulting in higher rates of penetration, but they also have a greater tendency for the borehole to deviate from a vertical track. Top head drive systems, with lower rotational speeds and higher torque, tend to drill a little slower than rotary table systems but generally drill a more vertical hole.

Mud rotary drilling systems have a number of advantages over cable-tool and auger systems. The first advantage is that they are much faster and can drill deeper holes with much larger diameters. Good quality lithologic samples can be gained if careful attention is paid to the amount of time it takes for the drilling fluid to reach the surface (lag time). Because a casing is not installed during the drilling operation, high quality geophysical logs can be conducted on open-hole sections.

However, mud rotary drilling has several disadvantages over cable-tool and auger systems. Extensive knowledge of and experience with drilling mud properties and interaction with various types of formations is essential. Problems with rotary drilling methods occur when lost circulation zones are encountered and large quantities of the mud are lost in highly porous formations, caverns, and fractures, and become difficult to remove during development. Sidewall pressure is not maintained under these circumstances, thereby allowing the potential for the collapse of the borehole. A thick filter cake may also reduce upward velocity of the drilling fluid and may interfere with the movement of the drill pipe and the installation of casing. Use of drilling mud requires a significantly larger site to stage, service, and condition the mud. Potable water is also required, a problem in undeveloped areas. Likewise, the mud must be brought in and hauled out after use, another problem in many areas. Water samples cannot be secured during drilling operations—a packer test must be used on completion of the drilling operation to isolate potential water production zones.

Extensive development is required for mud rotary drilling operations because of the introduction of drilling mud into permeable formations (the ones that are most likely to yield water). The inability to remove the mud will reduce aquifer yield. Monitoring the mud, mud quality, and drill string are among the reasons that more technical expertise is required on the drill rig for rotary drilling methods.

Caution must be exercised when planning for the use of the mud rotary method in an active well field. In such a situation, the borehole may intercept the cone of influence of nearby producing wells. This can cause drilling mud to migrate from the borehole being drilled toward the active wells, resulting in contamination of these wells and a reduction in the yield from the aquifer. As a precaution, it is recommended that active wells be taken out of service during the drilling of the new wells. Preplanning and coordination with the facility affected by shutting down the production wells will result in smoother running field operations.

A variation of the mud rotary method is the air rotary method. Air rotary drilling entails using air as the drilling fluid instead of mud. Air rotary systems have higher operating costs as a result of the power required to force air into the borehole with enough force to dislodge the formation materials. Over time, these costs have decreased. Pressures are 40 to 50 psi. Annular velocity is 2,000 to 5,000 ft per minute for dry air. The annular velocity is based on borehole size, drill pipe size, and air compressor capacity. Although air rotary drilling can result in very high drilling costs, this drilling process can only be used where borehole stability is not a concern.

Introduced in the late 1970s, drilling with foam is also an option. Foam is created by aerating the drilling fluids. It increases penetration rates when compared to mud rotary drilling and does help stabilize the borehole to some degree. The foaming agents must be a biodegradable liquid mixture of anionic surfactant, which is added to fresh, hard water. The slow-moving foam has greater capacity for carrying cuttings to the surface when compared to conventional air rotary drilling. Other advantages include

- Reduced air volume,
- Reduced pressure requirements,
- Increased well cleaning capabilities,

- Reduced hydrostatic head, and
- Reduced loss of drilling mud.

REVERSE-CIRCULATION ROTARY

The reverse-circulation rotary method is virtually identical to the hydraulic rotary method of drilling except that the drilling fluid circulates in the opposite direction. Reverse-circulation drilling is best for large diameter, high capacity wells for large water use projects. It is also less expensive than some other methods. Lehr et al. (1988) notes that many wells have diameters of at least 24 in., with some having diameters of more than 60 in. The reverse-circulation method typically uses clear water with no mud additives. A pit is constructed so that the drilling fluid will flow down the annular space between the bore hole and the drill pipe and return through the bit and the inside of the drill pipe to the surface, carrying the cuttings with it. A high-capacity pump is attached to the drill pipe to keep the fluid moving at high velocity.

The borehole is stabilized by the hydrostatic pressure of the fluid in the borehole. The fluid level is maintained at the ground surface. Keeping the borehole open requires a large volume of water to maintain a head above the natural static water level, which results in a flow into the formation. This higher head prevents the wall from caving. Significant damage or collapse of the borehole may occur if fluid circulation is lost. Caving may result from movement of fluid down the borehole when formation materials will not accept water. If the formation is highly permeable, the required head will be difficult to achieve. In such cases, processed clays may be added to create a filter cake similar to the straight rotary process. However, this defeats the primary advantage of the reverse-circulation method of construction. In wet clay soils, collapse is a problem. Caustic soda is used to raise the pH. Another option is to increase the amount of sodium silicate in the mud. Bentonite mud can also be used to prevent collapse of clay formations. In some instances, 20 to 50 gpm of make-up water may be needed in highly permeable soils. This is in addition to the 500 gpm circulation rate of the mud.

Advantages of the reverse-circulation method include its ease of use in situations where artificial-gravel-pack wells are specified because less mud cake forms on the face of the borehole. Less development time is required because mud does not intrude into porous formations. Test wells can be drilled and abandoned at a minimum expense by plugging. The reverse-circulation method is also generally faster than cable-tool drilling for drilling larger diameter wells, greater than about 18 in. However, the reverse-circulation method may prove problematic in soft, loose, unconsolidated materials, such as dune sand and quicksand, because the water pressure cannot keep the hole open.

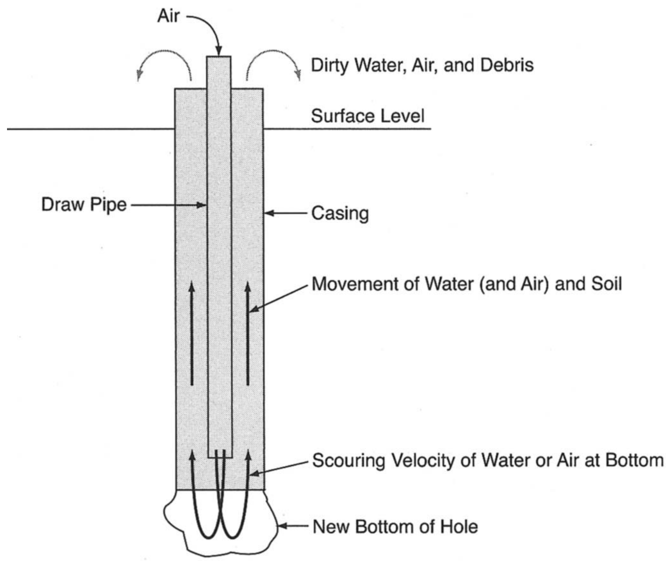


Figure 3-23 Reverse-air drilling method

REVERSE-AIR CIRCULATION

Reverse-air drilling methods have many of the characteristics of hydraulic rotary drilling except that drilling mud is not used; air is. With reverse-air drilling, a small steel or PVC air line connected to an air compressor is run inside the drill pipe. The formation cuttings and formation water are lifted inside the drill pipe (see Figure 3-23). Reverse-air drilling is capable of drilling large diameters wells in many formation types. The wells can be drilled quickly and high quality lithologic samples can be gathered. High quality water samples can also be obtained because there are no drilling fluids recirculated into the borehole.

Advantages of reverse-air drilling include speed of drilling and the ability to drill a wide variety of formation types. Reverse-air circulation is highly effective in cavernous and karstic formations. Uncased formations from reverse-air drilling permit excellent geophysical logs to be obtained. Sampling of water and obtaining high quality cuttings are major reasons for pursuing reverse-air circulation methods.

The disadvantages of this method include the potential for bit plugging, cross contamination of the aquifer, and intermixing of unconsolidated sediments in the borehole. Stability of the borehole in deep, unconsolidated formations may be a problem as no mud cake forms on the borehole.

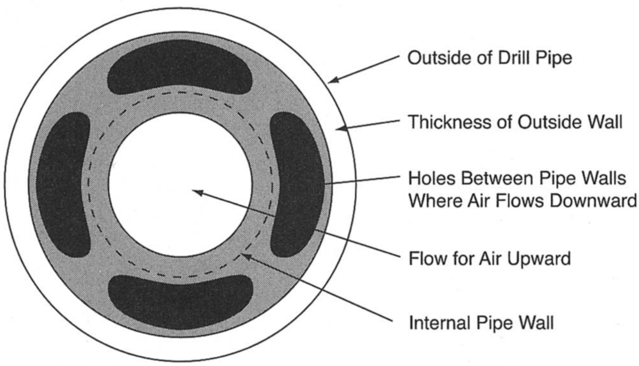


Figure 3-24 Dual-walled drill pipe

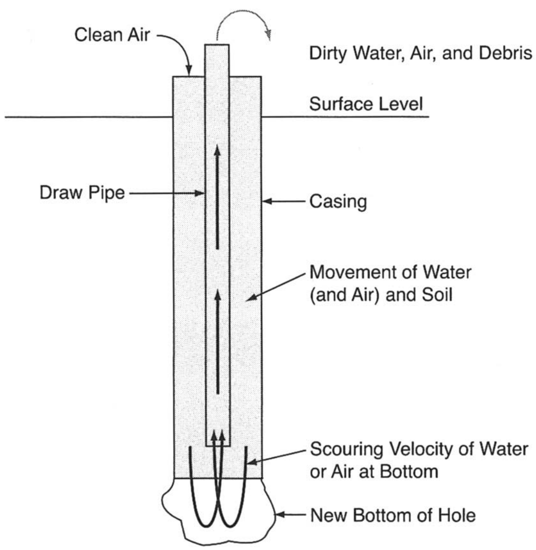
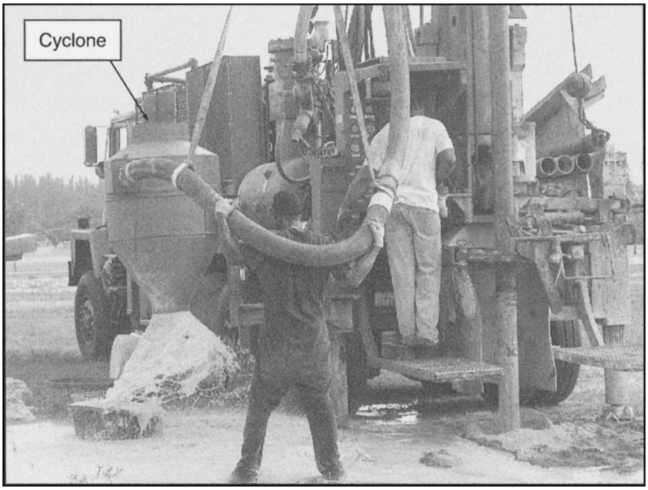


Figure 3-25 Dual-tube circulation system

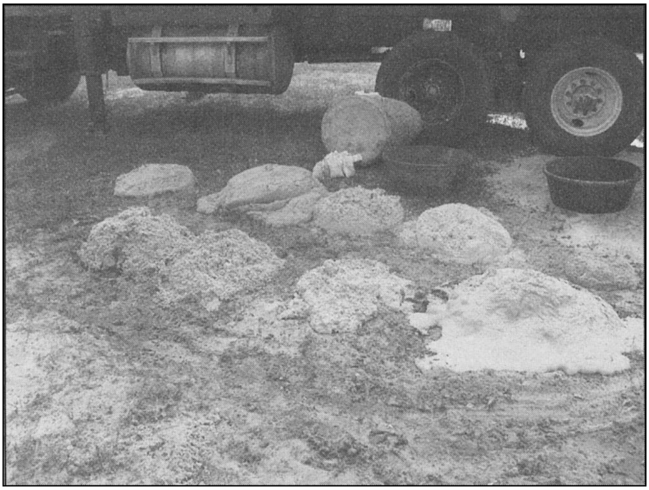
DUAL-TUBE (REVERSE-AIR) METHOD

Dual-tube/air circulation is a variation of the reverse-circulation drilling method. The drill bit and stem are rotated by a top head hydraulically driven drive. Reverse-air, dual-tube drilling methods are similar to reverse-air circulation. Instead of an air line inside the borehole, a dual-walled drill pipe is used (see Figure 3-24). As shown in Figure 3-25, the air channel delivers the air to the base of the borehole through the bit. Figure 3-26 shows a typical dual-tube drill rig and how samples come out of the sampling cyclone, respectively. The air and cuttings return to the surface through the inner tube to a sample cyclone where lithologic samples are recovered (see Figures 3-26 and 3-27). Significant cores of the formation are recoverable with



Source: John Largey

Figure 3-26 Typical reverse-air, dual-tube drill rig with cyclone



Source: John Largey

Figure 3-27 Sample from cyclone on typical reverse-air, dual-tube drill rig

reverse-air, dual-tube methods. Excellent quality lithologic samples are obtained by this method. A small diameter well can be installed through the inner tube as well. As a result, the dual-tube method is also successfully used for test wells.

Additional advantages of the dual-tube method include

- Fast drilling rate and minimal impact to aquifers.
- Well installation can be accomplished on small sites.
- Accurate, continuous water and formation samples can be recovered.
- A clean borehole when drilling is complete.
- The loss of circulation is minimized.
- Reduced potential of cross contamination.

The method is commonly used when high quality wells, with high quality water quality and lithologic samples are needed. However, because of the precision required for reverse-air, dual-tube methods, the cost is high, and there are limitations to the depth and size of the well. Other disadvantages include

- Limited availability of equipment.
- Large quantities of pressurized air are required.
- Sloughing of the formation and water saturated sands may cause the drill pipe to bind and become stuck.
- A high volume of formation fluids are generated as a result of the drilling method.
- Dual-tube is not applicable to certain types of formations, such as clays.
- Plugging of the formation is possible, so extensive development of the well may be needed.

DOWN-THE-HOLE-HAMMER

As with many other industries, well drilling has seen the introduction of new methods in recent years. One of the more popular, and useful, is the down-the-hole-hammer (DTHH) method shown in Figure 3-28. This drilling method combines some of the elements of hydraulic drilling with those of the cable-tool method. The turning action of the rotary rig is combined with the percussion action of cable-tool drilling. A pneumatic drill is located at the bottom of the drill string. Air delivered from an adequately sized compressor actuates a down-hole air piston, transmitting blows from the bit to the formation. The repeated blows are similar to those delivered by a cable-tool rig. The air used to actuate the hammer also removes the cuttings from the borehole similar to reverse-air rotary drilling. Occasionally, as in air rotary drilling, foaming additives are added to aid in removal of the cuttings. This eliminates the need to remove the bit from the borehole and recover the

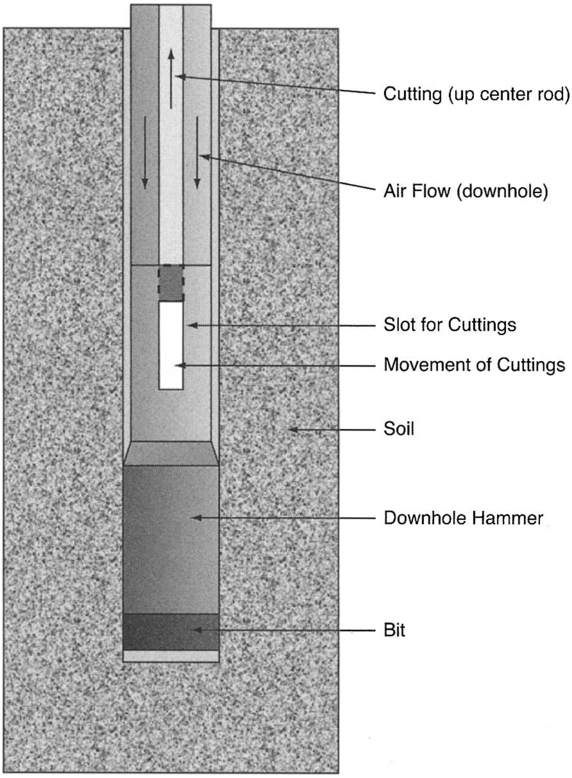
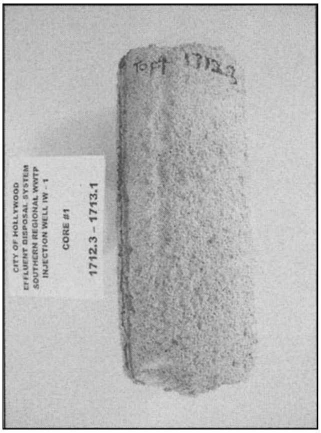


Figure 3-28 Down-the-hole-hammer method

cuttings by using a bailer. As the blows are delivered, the drill pipe is slowly rotated by either a top head drive or a rotary table. The rotating motion and the removal of the cuttings allow the bit to deliver each successive blow to a different, clean surface instead of repeatedly striking the same surface or previously cut rock fragments. DTHH works well in situations where hard formations are anticipated and borehole stability is not an issue. Wells drilled using this method are commonly 6 in. in diameter although hammer sizes range to about 17 in. in diameter.

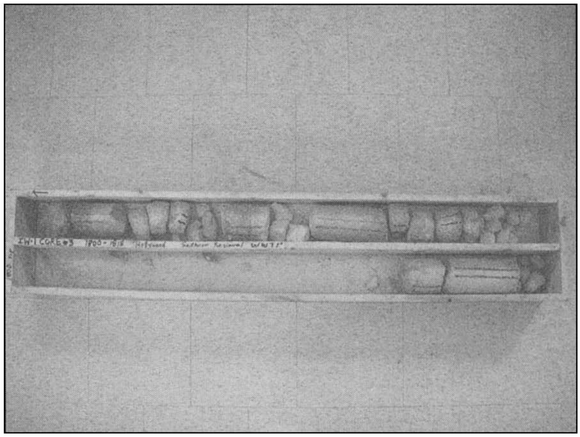
Advantages of the DTHH method include

- Rapid removal of cuttings,
- Drilling mud not used,
- High penetration rates in resistant formations,
- High quality water and lithologic samples recovered,
- Excellent geophysical logs obtained, and



Source: John Largey

Figure 3-29 Core sample



Source: John Largey

Figure 3-30 Boxed core

- Yield estimates obtained at selected depths during drilling.

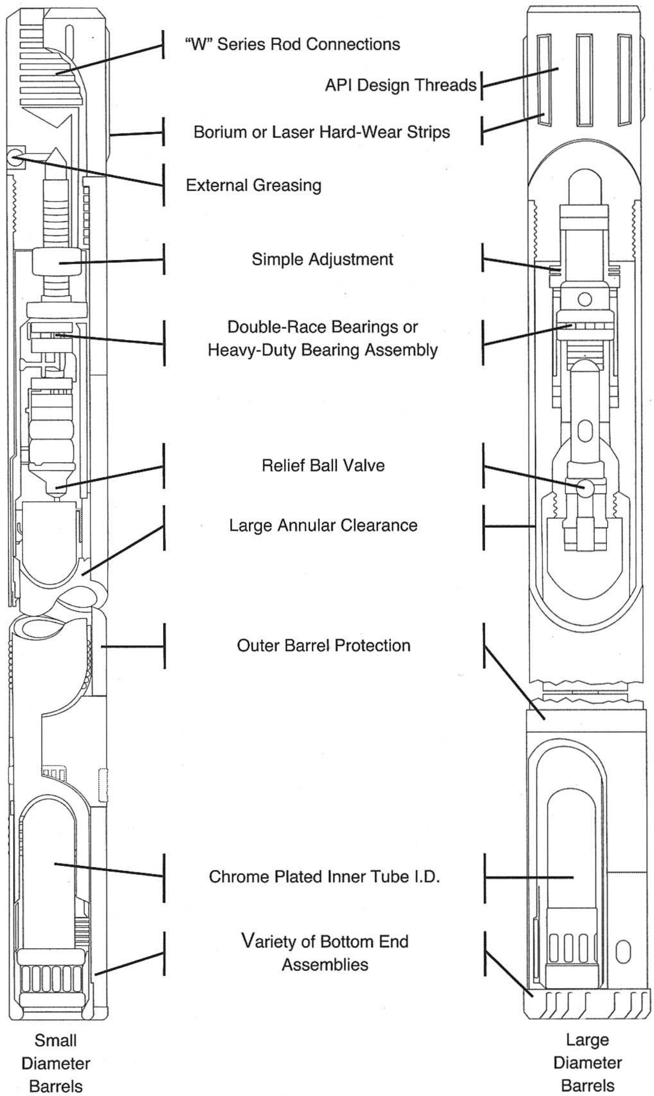
Disadvantages of the DTHH method include

- Restricted to semiconsolidated to consolidated formations,
- High volumes of air needed to activate the pneumatic hammer, and
- High volumes of water produced during drilling.

CORING

Coring, which is not a primary method of drilling, is used extensively to collect high quality lithologic samples. Cores are cylinders of rock recovered from the formation (See Figures 3-29 and 3-30). A number of tests maybe conducted on cores, including hydraulic conductivity, porosity, permeability, and compressive strength. This information will help professionals determine the appropriate factors to include in designing the well pumps and determining the safe yield of the well. To recover a core, the following procedure is used:

- Drill a pilot hole to the top of the formation where the core is to be recovered.
- Trip out drill bit and drill pipe.
- Trip in core barrel and drill pipe (see Figure 3-31).
- Cut the core out of the formation where the core is desired. It is essential that the core be cut, not pushed into the barrel.
- Trip out the core barrel and drill pipe.
- Recover the core.



Source: Adapted from Christensen Products www.Christensenproducts.com/ste/html/core-barrel.htm

Figure 3-31 Core barrels

- The core should be placed in a box and labeled with core recovery date, depth, well, and relevant observations at the time of collection. For core recovery, it is essential that an experienced driller be used.
- Drill to the next point where a core is desired.

During drilling of an exploratory well and any subsequent supply well, it is often useful to collect geologic samples and rock cores of formations penetrated during drilling. Formation cores should be taken at selected intervals. The cores are typically 10 to 30 ft long and 4 in. in diameter. The recovered core should be described by a qualified geologist, and the data, samples, and descriptions should be submitted as directed by the regulatory agencies.

In addition to the description of the geologic strata and structural features, vertical and horizontal porosity tests should be performed on the samples at appropriate core intervals (i.e., the formations of concern). Porosity, compressive strength, modulus of elasticity, and specific gravity should be recorded. When the pilot hole is completed, geophysical logs and a survey involving the lowering of a camera down the well should be conducted on the borehole.

DRILLING METHOD SELECTION

When preparing to drill a well, the appropriate drilling method must be selected. Often a combination of methods may be required. A professional engineer, professional geologist, hydrogeologist, or a combination should specify the methods appropriate for a particular project. For example, bucket-type drilling may be used in setting relatively shallow starter casings for large diameter water wells, and mud rotary methods may then be used to drill to a predetermined depth above the production zone. After the second string of casing is set and cemented into place, the drilling mud will be displaced with potable water. Reverse-air methods may be used through the production zone. During the drilling, cuttings should be collected and analyzed by a competent hydrogeologist. Composite samples are used to determine formation characteristics over a predetermined interval of the formation. Grab samples maybe used for specific analysis. However, in either case, knowing the depth in the borehole where the sample was recovered is important. Without knowing the depth, the information derived from the samples is of limited value.

In addition to determining the borehole data, planning is needed for the proposed site for the well construction activities. Overhead and buried utilities must be located and accounted for before drilling commences. Large well diameters and deep wells require large drill rigs. Drill rigs for large wells may be very tall, requiring Federal Aviation Administration clearance near airports. Casing must be delivered to the location and staged prior to installation. If geophysical logging is required, additional areas will be required. Utilities and potable water supplies are useful for the drilling project, and access to them should be considered during drilling operations.

The type of drilling method used will impact the amount of area needed for the drilling process. Hydraulic rotary systems with mud will require more lay-down area for mud separation than reverse-air, dual-tube drilling. Table 3-1 outlines the benefits and issues with the methods discussed. Disposal of water, mud, and cuttings is also an issue that must be planned. Waste cannot be placed on the surface or disposed of on the ground. For instance, saltwater usually must be trucked off-site for treatment. Sewers are not often available where wells are being drilled and if they are, the utility may not want drilling fluids in the sewer system. Federal, state, and local regulations should be consulted prior to initiating a drilling project.

Table 3-1 Summary of drilling methods, benefits, and limitations

Drilling Method	Uses	Applications	Benefits	Limitations
Driving	Small, shallow wells	Dewatering	Simple and easy	Small wells
Jetting	Small, shallow wells	Dewatering and single family homes	Simple	
Cable tool	Up to 18-in. diameter and 1,000 ft in depth	Water supply	Minimal aquifer impact, favorable sampling, applicable to most formations, relatively simple	Slow, casing must be advanced with drill bit, pulverizes formation
Hollow stem auger	Up to 8-in. diameter and 300 ft in depth	Water supply	Good sampling, auger keeps borehole clean, high quality sampling, does not introduce drilling fluids	Limited to unconsolidated formations, limited to depth and size, running sand limits
Hydraulic rotary	Deep and large diameter wells	Water supply	Fast, most common, no formation limitations, multiple drill bits, good quality cuttings, high quality borehole for logging for uncased boreholes	Requires fluid (mud), large bit sizes needed, possible need for fluids, mud disposal, samples not of high quality, aquifer plugging
Reverse air	Large diameter, depth can vary	Water supply	Aquifer testing possible during drilling, high water quality and formation sampling, fast, excellent logs, supports telescoping	Borehole may collapse, possible cross contamination of aquifers
Reverse air dual-tube	Small diameter, limited depth	Water supply and test holes	Aquifer testing possible during drilling, high water quality and formation sampling, fast, excellent logs, supports telescoping	Cost, volume of cuttings, plugging while drilling

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4

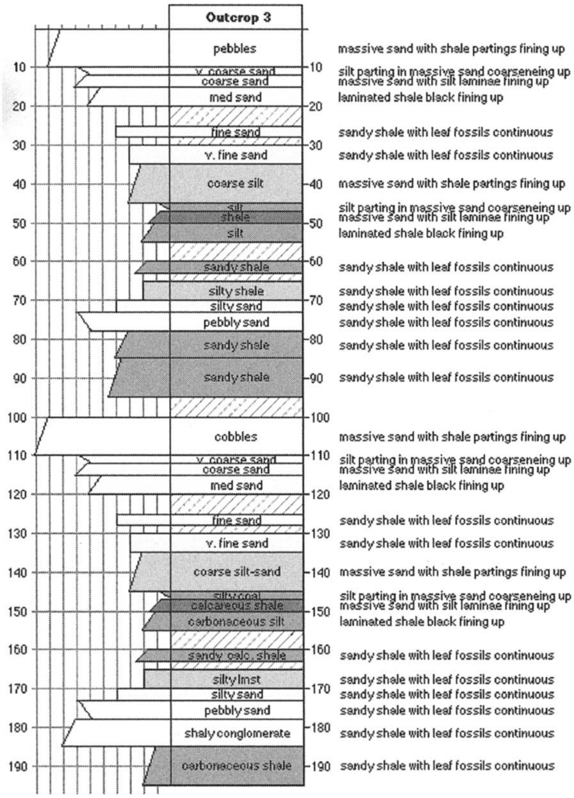
Geophysical Logging and Field Testing

Once the potential sites for the well location have been selected, a series of tests should be run to better define the parameters of the subsurface environment, including the quantity and quality of available water. These initial subsurface investigations generally begin with construction of an exploratory or test well. The goal of exploratory wells is to locate productive aquifers that yield sustainable high-quality water. The initial test wells are used for lithologic logging, geophysical logging, aquifer testing, and to collect cores and cuttings of the formation.

Lithologic sampling is the protocol used to obtain core samples and define the formation type by depth. Geophysical logging consists of a variety of electronic instruments used to define the rock types, water quality, porousness, and other aquifer characteristics. Geophysical logs were developed by the oil and gas industries for exploration. Depending on the needs from the well, a number of formations may yield sufficient quantities of water for some period of time. However, for water supply production wells, large, rechargeable aquifers are desirable. The following aquifer formations are more likely to provide sufficient water for public water supplies:

- Shell, unconsolidated sands, and gravels of alluvial or glacial origin
- Sandstones and conglomerates
- Limestone
- Porous or fractured volcanic rocks

Exploratory wells are drilled to determine an aquifer's characteristics, including hydraulic conductivity, water quality, thickness, and areal extent. Newly drilled wells can be used for borehole geophysical logging and aquifer testing. The drilling method is dependent on the type of water samples desired and formation types that are expected to be encountered during drilling (see chapter 3). As noted in chapter 1, hydrogeologic reports already exist in many regions. From these interpretations,



Source: Hazen and Sawyer, P.C., Boca Raton, Fla.

Figure 4-1 Example of lithologic log

potential aquifers can be identified. However, the increase in the need for new water sources requires investigation in areas where little historical information is available. Exploratory drilling efforts can fill in the details of the specific local hydrogeologic environment in which drilling is proposed.

LITHOLOGIC LOGGING

The information required to develop lithologic logs is gathered while drilling is in progress. Cores, cuttings, water samples, drill response, and other methods are used to identify the different formation types encountered while drilling. The result will be a lithologic log similar to that shown in Figure 4-1, which summarizes the encountered subsurface formations. As noted in chapter 3, to accurately identify the formation, the methods for drilling the well may be limited. Care must be exercised by the driller in collecting water and formation samples. As the cuttings rise, the quality of the cuttings may be affected by many variables such as the drilling method, the time it takes for the samples to reach the surface (lag time), and contamination from formations already penetrated. Therefore, the actual changes in lithology may be only generally known. While useful for targeting further investigations, only limited information about the aquifer parameters can be gained from the cuttings and cores. Most hydrogeologists use lithologic logs to identify specific areas where usable water is likely to be encountered in large quantities and therefore requiring further investigation and geophysical logging.

BOREHOLE GEOPHYSICAL LOGGING

Geophysical logging is the science of applying the principles of physics to investigations related to the structure and properties of rock formations. Geophysical methods use electrical instruments whose readings represent different properties of the formations to identify physical properties of the rock, such as porosity, water content, and metallic content. The variation of the logging results may permit interpretation of the formation without seeing the actual formation (AWWA, 2003), provided experienced people are performing the interpretations. Rather than lithologic logging, geophysical logging is useful in identifying the appropriate depths to drill wells and set casings and can aid in accurately locating the depth of variations in hydrogeologic characteristics.

While there is no established order for application of exploration methods, a planned and a balanced program of appropriate combinations will produce the most useful information. Knowledge gained through a geophysical investigation compliments the information gained from test drilling and sampling. Advantages to geophysical logging include (AWWA, 2003)

- Rapid results
- Relatively low cost (for most logging methods)
- Qualitative and quantitative results
- Evaluation of the aquifer over a large depth

At the same time, interpretation of the geophysics by an appropriate scientist is important as the results may be ambiguous or conflicting when first reviewed. Experienced people will be able to

- Interpret the logs based on assumptions of the materials, material homogeneity, and formation properties;
- Validate calibration of tools;
- Understand the contrasts in the logs; and
- Define the accuracy or precision of the logs. Experience with logging formations in the same area or of the same type is especially useful to determine nuances in the logging results.

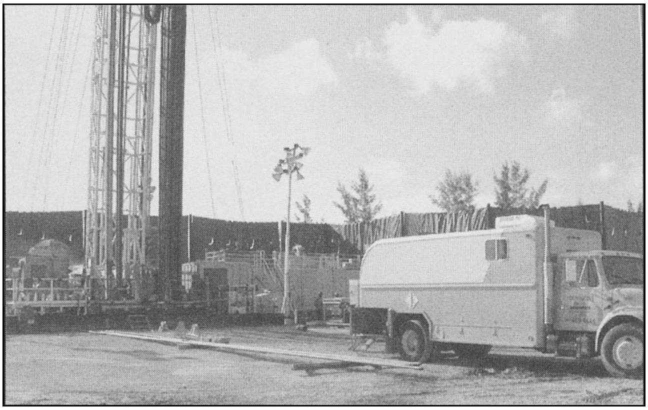
The purposes and uses of various geophysical logs are outlined in the following sections. Borehole logging is highly technical and quite involved, and no lay person should use the information provided herein to attempt to interpret logs based solely on the information provided. Log interpretation requires the use of experts using specialized equipment. Accurate lithologic logging during drilling is crucial, so an experienced geologist, hydrogeologist, groundwater engineer, and driller experienced in well logging should be employed. Often it is wise to retain the expertise of a logging specialist to evaluate logs. The equipment that is used is both extensive and expensive. Specialty companies are usually hired to perform the logging and interpretation the well site (see Figure 4-2). The discussion herein is designed to provide insight on the capabilities and limitations of the logging tools found to be most useful for groundwater exploration and to help water professionals understand why certain logs should be used.

Geophysical logging is extensively used in the oil industry, and it is for oil exploration that most of the logging techniques have been developed. As a result, the focus of many logs and the geophysical logging industry in general is geared toward petroleum, not clean water, which is rarely encountered in conjunction with oil. Most of the texts on borehole logging present information tailored toward petroleum exploration. The presence of low or nonsaline water in a formation mandates the use of special analyses for interpretation. For a detailed discussion of this subject, the reader is referred to *Borehole Geophysics Applied to Groundwater Investigations,* published by the National Water Well Association (Keys, 1989).

Single logs in a well are almost useless because there is limited basis on which to interpret the log variations. Therefore, the use of multiple logs (a suite of logs) in a single well will provide confidence in interpretations. Each type of log measures different physical properties, and a combined analysis may resolve ambiguities that might exist from a single log. The greater the number of wells logged in an area, the greater the statistical confidence in the data and interpretations as being representative of the subsurface environment. In addition, there are both surface and subsurface methods that may prove useful. Surface methods are used to guide subsurface logging.

SURFACE GEOPHYSICAL METHODS

Surface geophysical methods, principally electrical resistivity and seismic reflection and refraction logs, can be used to provide a picture of subsurface structure, given some prior knowledge obtained from surface geology and lithologic logs. The lithologic log outlines a model of the subsurface geology as a basis for a proper interpretation of the surface geophysical data. The successful use of any surface geophysical method depends on the presence of sharp changes in the physical properties of the formation (such as clay to limestone). The detectable physical properties provide indirect estimates of the likelihood that the formation may yield



Source: John Largey

Figure 4-2 Specialized equipment and companies perform borehole geophysical logging

water in sufficient quantities. The accuracy of geophysical estimates depends on how closely the physical properties can be separated from one another. Formations that often do not lend themselves to surface geophysical methods include areas consisting of large cobbles in alluvium, areas of severely distressed stratigraphy (areas where there is upheaval of the rock strata), or areas in which (in geologic time) high hydraulic energy was dissipated.

Electrical Resistivity

Electrical resistivity is probably the most commonly used surface geophysical method for groundwater investigations. To gather data, electrodes placed into the surface of the ground transmit current through the earth, and the voltage potential is measured between two points near the center of the generated field (see Figure 4-3). With the most common electrode arrangements, such as the Schlumberger array and Wenner array, readings can be gathered using constant electrode spacing (horizontal profiling), or the readings can be gathered at one location with expanding electrode spacing (electrical sounding). The first method will show apparent resistivities of materials at roughly the same depth along the transect (two-dimensional), while the second method produces a depth profile of resistivity (three-dimensional; AWWA, 2003).

Electrical resistivity is strongly affected by water content. As a result, data collected involving the unsaturated zone can make interpretation of the saturated zone quite difficult. Resistivity is largely determined by the rock-matrix density and porosity, or by the saturating-fluid salinity (electrical conductivity). Coarse sediments with low clay content will generally have higher resistivity than fine-grained

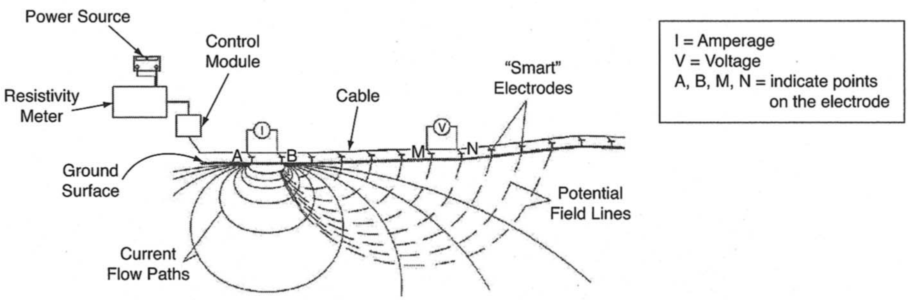


Figure 4-3 Surface resistivity method (AWWA, 2003)

sediments. Old streambeds are often laden with silt and clay, so as a result, the variations in response allow for surface detection and mapping of buried stream channels or the depth profiling of shale–sandstone sequences.

Surface resistance methods are generally limited to use in

- Simple geologic environments, with two or three distinct layers;
- Areas where depth of penetration is limited to about 1,500 ft (460 m);
- Areas where the depth to groundwater is small, because of the complications of unsaturated materials; and
- Non-urban or undeveloped areas as a result of the presence of buried metal pipes, wires, and similar obstructions, which dominate measurements with unwanted noise in developed areas.

Seismic Refraction and Reflection

The cost of seismic methods is high, but the information generated can be very useful to hydrogeologists. Seismic methods use the contrasts in the velocities of elastic wave propagation in different materials.

A variety of methods are used to generate seismic waves. One is the use of explosive *shots* in shallow borings. Truck-mounted hydraulic earth vibrators (*thumpers*) can also be used although these are generally used for oil exploration and raise significant environmental concerns because of the damage they can inflict on the surface.

Geophones are distributed on the ground surface to detect and record the travel times for sound waves refracted or reflected from subsurface lithologic boundaries. The travel time records are analyzed to produce a model of the subsurface. As with all surface geophysical methods, the interpretation of seismic data requires an assumed model of subsurface structure; the more preexisting information from surface geologic data and borehole logs that is available, the more reliable the results will be from seismic surveying. Unconsolidated sands and gravels exhibit low propagation velocities, whereas crystalline rocks exhibit the highest propagation velocities. Propagation velocities are higher in saturated materials, providing detection of the water-bearing strata.

SUBSURFACE GEOPHYSICAL METHODS

Borehole logging techniques are one of many tools that should be used in evaluation and identification of underground environments. Geophysical logs that are commonly used in water exploration include

- Caliper
- Resistivity
- Spontaneous potential (SP)
- Naturally occurring gamma radiation
- Neutron porosity
- Acoustic
- Fluid resistivity
- Temperature

Determining the types of logs to be used in an investigation is often difficult. Most groundwater investigations obtain adequate information using caliper, resistivity, SP, natural gamma, and lithologic logging. The cost of these techniques should be evaluated regarding the time available, accuracy needed, and the basic purpose of the survey. Resistivity, gamma, and caliper measurements are the most widely used.

All geophysical log measurements are obtained by lowering a probe down the borehole and recording continuous measurements with depth. Logging is normally performed during drilling operations and is often conducted in a small diameter pilot hole. The results of analyses of the logs by qualified personnel provide the basis for decisions regarding well construction and completion, including depth of casing and screened intervals. Some types of logs can be conducted in existing, cased wells, which are useful if expansion of a wellfield is planned. Certain logs can only be performed in an uncased hole, which prevents the use of drilling methods requiring casing to be advanced during drilling if these logs are desired. It should be noted that the method of drilling may dictate the appropriate type of geophysical log employed. For example, temperature and fluid resistivity logs are not very useful in mudded boreholes.

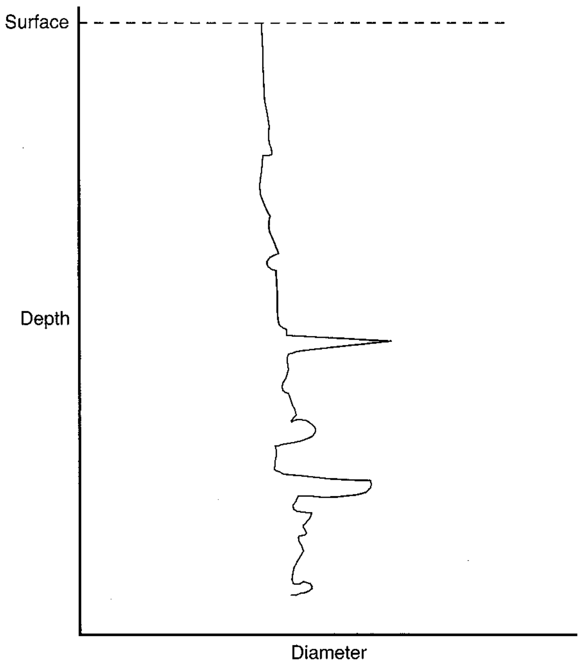


Figure 4-4 Example of caliper log

Caliper Logs

Caliper logs are among the simplest logs and can reveal useful information for interpretation of other logs. A multiarmed probe is lowered into the well to determine the geometry of the borehole and variances in diameter. Caliper logs can provide indications of the presence of high permeability fractured or cavernous zones (by the arms extending outward indicating a larger and rougher borehole), as well as the occurrence of swelling clays (the arms will tighten and indicate that the borehole is smaller than the diameter of the bit used to drill as a result of the expanding clays) and locally well-lithified layers in friable or unconsolidated rock or sediment (the changes in the diameter of the borehole may be significant in a very narrow horizon; see Figure 4-4). Caliper logs are important because the interpretation of other geophysical logs vary with the borehole diameter. A good quality caliper log will identify where compensations must be made.

Caliper logging is conducted using a probe that usually has either three or four levered arms. As the probe is brought up through the hole, a record of the depth and degree of extension of the arms is made. The results provide information about the variations in the diameter of the borehole after drilling. Asymmetry of the borehole can be measured using the four-armed probe but not with the three-arm probe.

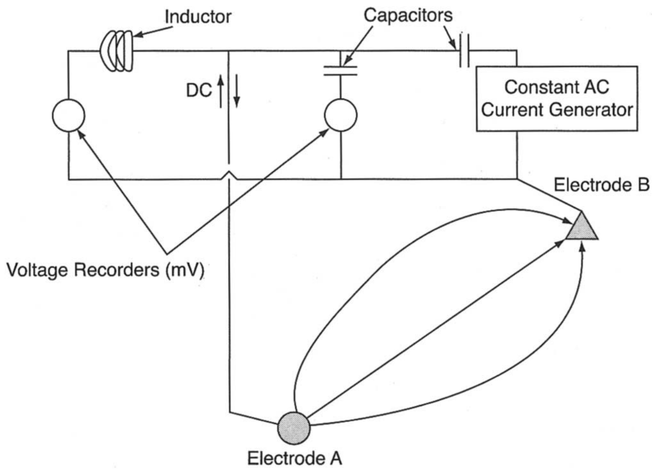


Figure 4-5 System used to make conventional single-point resistance and SP logs

Therefore, caliper logs are not useful for estimating diameter inside a casing as the calipers only measure the casing diameter. They can, however, be used to determine unknown well diameters and to determine the integrity of casings (i.e., collapsed casing). It is recommended, whenever possible, to run a caliper log before setting the casing as it will provide an indication of the annular space volume that must be filled with grout and provide an estimate of the cement requirements.

Electrical Resistivity Logs

Subsurface electrical resistivity logging is only slightly different than surface resistance logs. Resistivity logs are based on the principles of Ohm's law:

$$R = E/I \qquad \text{(Eq. 4-1)}$$

Where:

R = resistance in ohms
E = potential in volts
I = current in amps

The simplest and least expensive electric resistivity log is the single-point resistance log. The single-point resistivity log measures the potential drop between a surface electrode and a down-hole electrode, which are also the current electrodes (see Figure 4-5). The single-point resistivity log is used primarily for geological correlation and the location of bed boundaries, changes in lithology (rock characteristics), and fracture zones. Single-point resistivity logs have a very good

Table 4-1 Electrical resistivity of selected aquifer materials

Material	Resistivity (ohms - m)
Granite	5,000–1,000,000
Basalt	1,000–1,000,000
Sandstone	100–4,000
Shale	20–2,000
Porous limestone	100–10,000
Dense limestone	1,000–1,000,000
Clay	1–20
Wet sand	20–200
Dry sand	500–100,000
Fresh water	10–100
Sea water	0.1

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vertical resolution of lithologic changes but do not provide quantitative data on formation porosity or the salinity of formation water (AWWA, 2003). High conductivity in the formation is proportional to the potential voltage differential created in the formation. Silt, clay, and shale tend to have the lowest resistivities; sands, granite, basalt, sandstones, and limestones with nonsaline pore waters have the highest resistivities. For single-point resistivity logs, interpretation is required to determine the meaning of the results. Single-point resistivity logs will change with variations in the borehole diameter requiring a caliper log to compensate for these differences. Table 4-1 outlines the resistivity of common formation materials.

Normal resistivity logs function on the following variant of Ohm's law:

$$R = r \times S/L \qquad \text{(Eq. 4-2)}$$

Where:

R = resistivity
r = resistance
S = cross-sectional area normal to the flow
L = distance in the formation

Normal resistivity logs measure the apparent resistivity of a volume of the formation perpendicular to the borehole electrodes. The probes are commonly configured so that short normal (16-in. electrode spacing) and long normal (64-in. spacing) resistivities are measured simultaneously. Normal resistivity logs are commonly used in groundwater investigations as a source of qualitative information on water quality. True formation resistivity and salinity can be calculated from the

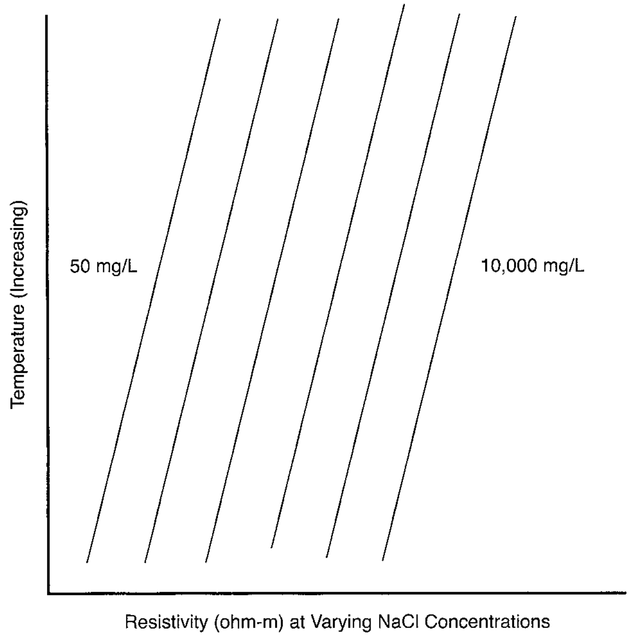

Figure 4-6 Example of temperature corrections required to electrical conductivity log as a result of increasing resistivity due to salt concentration in the aquifer water

measured apparent resistivities, but the calculations require the application of a number of mathematical equations to reach the actual salinity and resistivity (AWWA, 2003). Normal resistivity logs also require adjustments for temperature (see Figure 4-6). Other resistivity log types that are less commonly used in groundwater investigations are discussed by Keys (1989).

Spontaneous Potential Logging

SP logs measure the natural electrical potential of the lithology in millivolts. In practice, SP logs will show increasing salinity by increasingly negative responses (see Figure 4-7). The results are similar to a gamma log. Measurable differences in SPs occur where beds of different types of geological materials occur, such as between shale and sandstone beds. Negligible response may occur with certain localized sediments. SP logs provide information on bed-thickness determination and changes in lithology.

The SP logging apparatus consists of a surface and down-hole electrode connected to a voltmeter. The SP logging equipment is usually incorporated into the electric resistivity log apparatus. Log definition depends on the contrast in fluid conductivity between the borehole and the geologic formation penetrated. While SP logs are the most common logs used, if the borehole contains water that is fresher

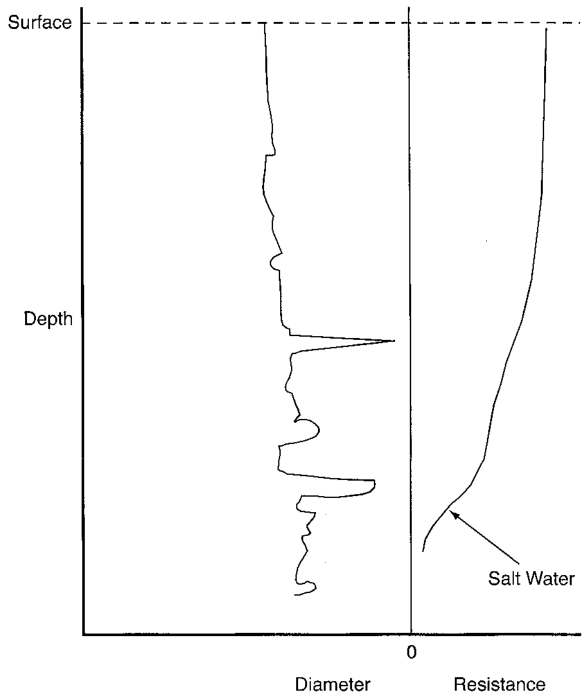

Figure 4-7 Example of caliper and electrical resistivity log for borehole

than the formation, the logs will not yield useful results, so this log should be used in conjunction with other logs noted in this chapter.

Electrical Conductivity

Electrical conductivity (EC) logs are based on a relationship between the specific conductance and the concentration of dissolved solids in the water. In most cases, calibrated logs will show that there is a relatively linear relationship between the two—more dissolved solids means higher conductivity (see Figure 4-8). The conductivity of specific ions are known, and a water quality analysis will permit investigators to determine if the logging results match the water quality and where there may be other constituents of concern.

Gamma Logs

Gamma logs measure the total gamma radiation that is naturally released from the formation. No radioactive materials are introduced into the well. Many naturally occurring elements have radioactive isotopes that are harmless to humans but measurable by gamma logging tools. The most significant natural source of gamma

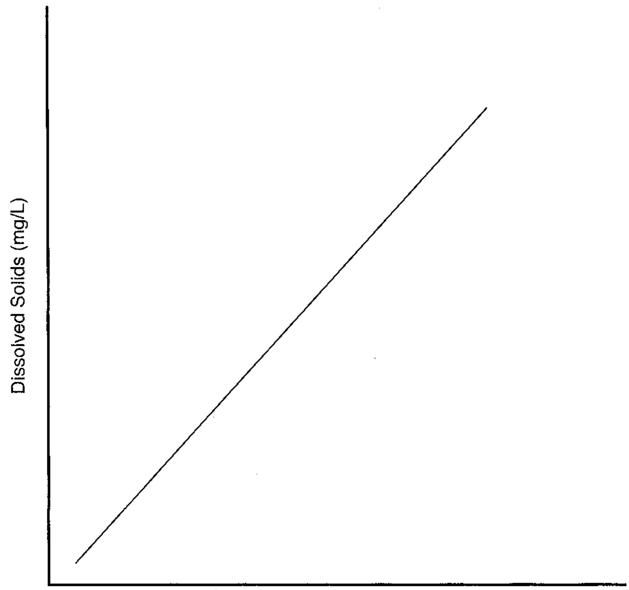

Figure 4-8 Conductivity relationship to dissolved solids for specific conductivity logs

radiation is the decay of potassium-40 isotope and the daughter products of the uranium and thorium decay series. Rocks and sediments with relatively high concentrations of potassium, uranium, and thorium have high gamma response. Gamma logs measure the ratios of three basic isotopes to one another: uranium-238, thorium-232 and potassium-40. Table 4-2 shows the energy for each. Gamma results increase linearly with silt and clay content (see Figure 4-9)

Clay-rich rocks, shales, and phosphatic rocks yield a high gamma response, whereas nonphosphatic limestones and dolomites, and quartz sandstones tend to yield low gamma responses (AWWA, 2003). The gamma log is the most commonly used nuclear log. Gamma logs can be correlated with rock types based on the radioactivity of the formation, cuttings, and cores. The amplitude of gamma logs can be modified by changes in the density of the material through which the gamma rays pass. As a result, the gamma log measures porosity as proportional to bulk density. The following will inhibit the usefulness of gamma logs:

- Large diameters wells,
- Wells constructed with cable-tool methods, and
- Wells already completed with casing and cement.

Table 4-2 Energy for gamma logs

Element	Energy of Major Gamma Peaks (million electron volts)	Photons per Second per Gram	Average Percent in Shale	Percent of Total Gamma Intensity
Potassium-40	1.46	3.4	2%	19
Uranium-238	1.76	280,000	6 ppm	47
Thorium-232	2.62	10,000	12 ppm	34

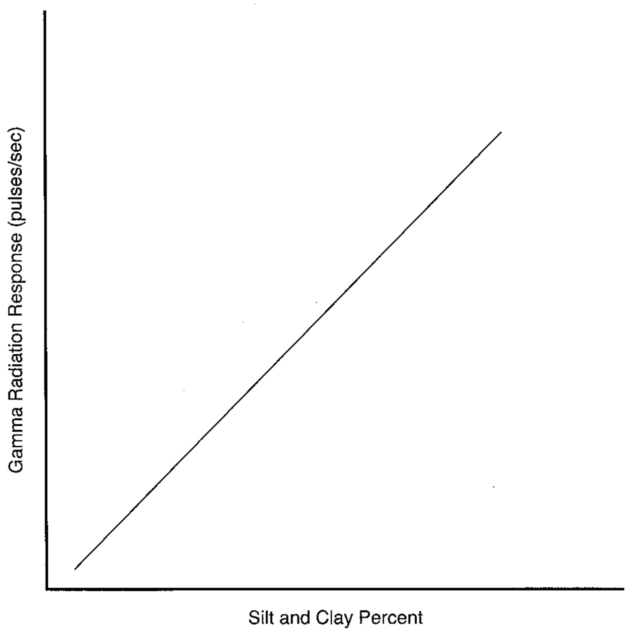

Figure 4-9 Gamma response to increasing clay and silt content

Figure 4-10 shows an example of a gamma log in conjunction with a caliper log. Limestone, alluvium, coal, gypsum, and anhydrite are all materials where the gamma log shifts to the left, while granite and other hard rocks shift to the right. The latter are not rocks likely to have much water useful for production. Figure 4-11 shows that as the silt and clay content increases, the gamma pulses also increase (shift right). SP logs used in conjunction with gamma logs will react similarly.

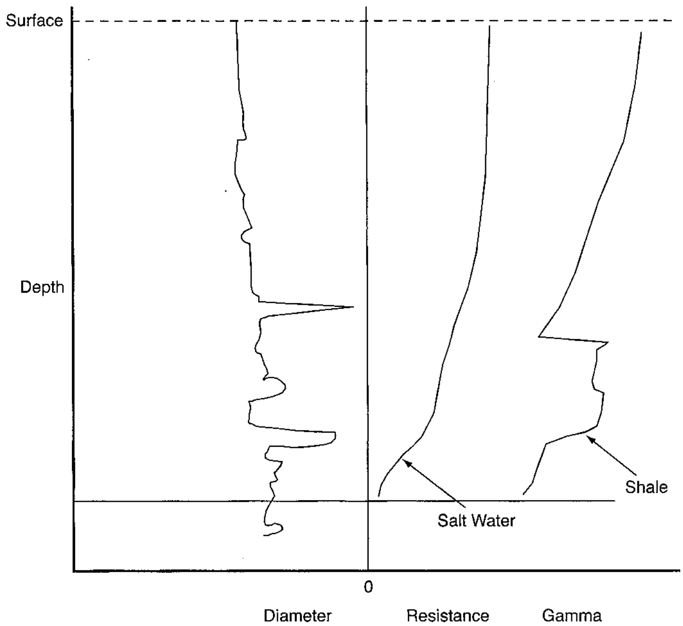

Figure 4-10 Example of comparison of gamma, resistivity, and caliper logs through shale

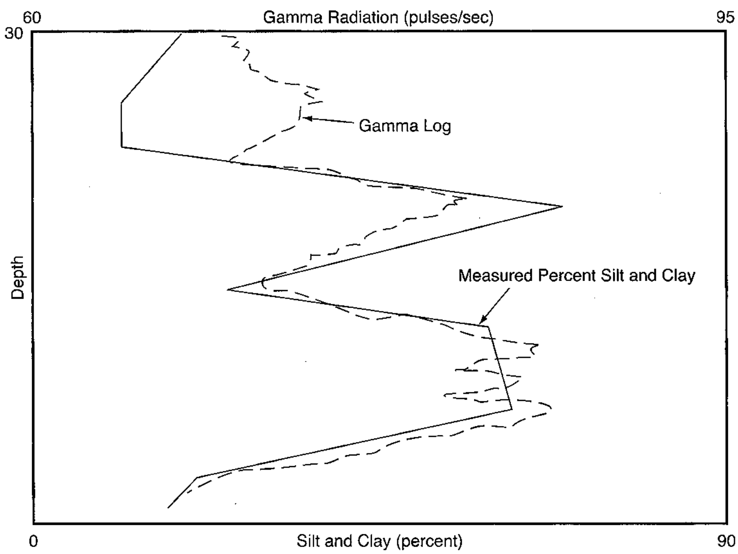

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Figure 4-11 Relationship between gamma radiation and silt and sand

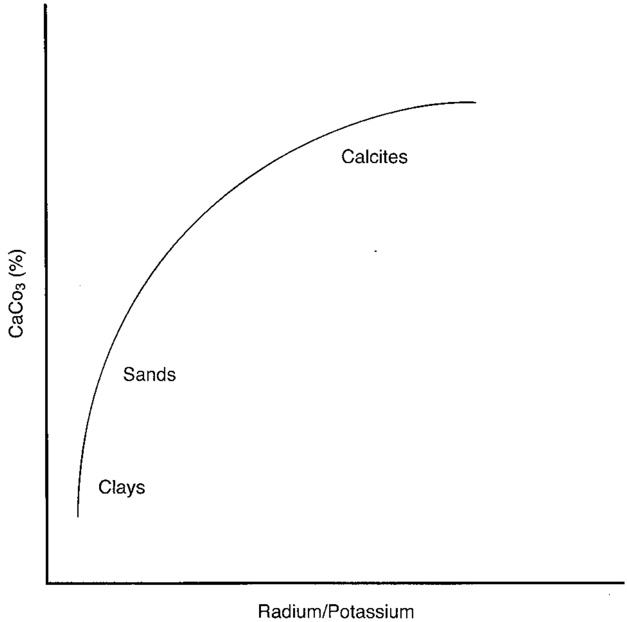


Figure 4-12 Comparison of radium/potassium gamma response to calcites

Gamma-gamma Logs

Gamma-gamma logs are radioactive tracer logs or surveys that are obtained by introducing a gamma radiation–emitting material into the borehole (usually cesium-137 or cobalt-60) and measuring the intensity of the backscattered radiation. Gamma-gamma logs provide information on lithology and porosity but should not be used in groundwater investigations because of their high costs and liabilities associated with the potential loss or rupturing of the radioactive source within the aquifer.

Gamma Spectrometry Logs

Gamma spectrometry logs are also used to measure radioisotopes in the formation. Counting gamma pulses can be useful in identifying many additional, slowly degrading elements. By knowing their gamma energy characteristics, specific elements can be identified. By identifying the elements and the ratio of elements, clay and shale can be differentiated from limestones and other water-bearing formations. Figure 4-12 shows an example of how the calcium carbonate percent and the radium/potassium ratio can be used to identify specific formation types.

Table 4-3 Neutron collisions for selected materials

Element	Average Collisions per Neutron (million electron volts)	Maximum Energy Loss	Atomic Number	Atomic Weight
Calcium	371	8%	20	40.1
Hydrogen	18	100%	1	1.0
Oxygen	150	21%	8	16.0
Carbon	115	28%	6	12.0
Chloride	318	10%	17	35.3
Silicon	261	12%	14	28.1

Neutron Logs

Neutron logs are used to find changes in porosity of the rock and sediments, which may be related to the amount of fluid in the formation. The concept is based on the emission of high energy neutrons from beryllium and an alpha-emitter (commonly americium). The emitted neutrons interact with hydrogen atoms and release gamma radiation, which is measured by a detector on the logging tool. The intensity of the measured gamma radiation is proportional to the hydrogen atom concentration and thus water content and the porosity of saturated rocks. Table 4-3 shows the neutron response for a number of common elements with an initial energy of 2 million electron volts. Calibration of neutron logs is critical to obtaining useful information.

Neutron logs work very well to indicate lithology by identifying suspected formations of sand, limestone, and sandstone that have pores and vugs that would indicate high porosity. These pores are usually filled with water, which contains hydrogen, a strong neutron absorber. However, coal, shale, and other formations with high hydrogen content will provide false readings despite yielding results that would indicate high porosity. The same problems that affect gamma-gamma logs also affect neutron logs. EC logs help to show where these formations provide false readings because the hydrogen effect is not a driving factor. As a result, the EC logs will deflect in the opposite direction from the neutron log. Shale or clay will be evident when a gamma log is used in conjunction with neutron logs because the bound water will reflect high water content, which the gamma log will not. Neutron logs are suggested to help determine how much of the conductivity is the result of salinity from salt (NaCl).

Table 4-4 Compression wave velocity transit time

Material	Velocity (feet per second)	Transit Time (μsec/feet)
Sandstone		
Slightly consolidated	15,000–17,000	58.8–66.7
Consolidated	19,000	52.6
Shale	6,000–16,000	62.5–167
Limestone	19,000–210,000+	47.6–52.6
Dolomite	21,000–24,000	42.6–47.6
Anhydrate	20,000	50
Granite	19,000–20,000	50–52.5
Gabbro	23,600	42.4
Fresh water	5,000	200
Sea water	5,300	189

Adapted from Keys, 1989

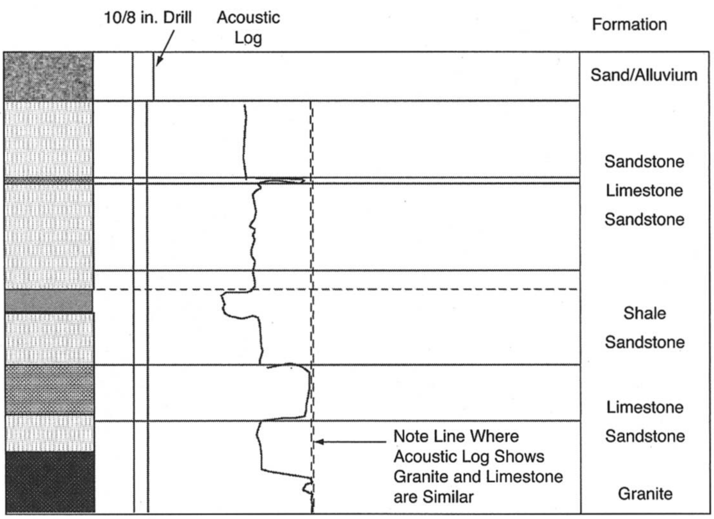


Figure 4-13 Response of sediments to acoustic waves. Note that the granite and limestone give similar results.

Acoustic Logging

Acoustic or sonic logging involves the recording of the transit time of acoustic pulses radiated from a tool in a borehole to one or more receivers also located on the tool. Acoustical techniques can be used to send sound through a formation to determine

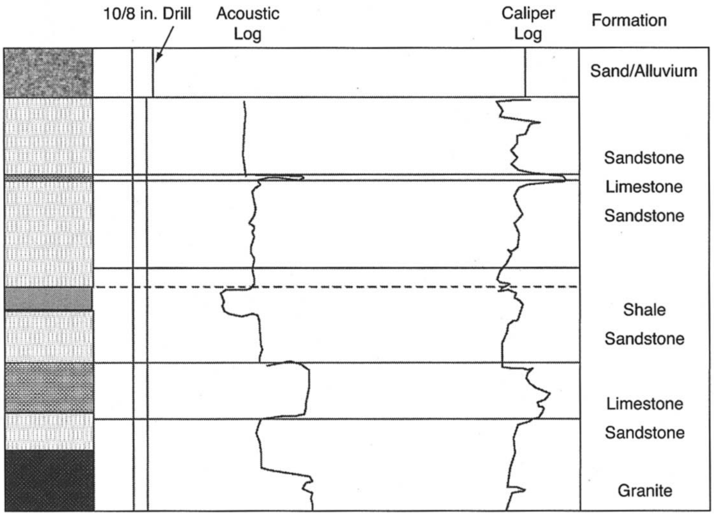


Figure 4-14 Acoustic velocity and caliper log example

changes in lithology and types of formations. Table 4-4 shows an example from Keys (1989). Table 4-4 and Figure 4-13 show that acoustical logging cannot be used alone as granite and limestone have similar velocities for the sound waves (because sedimentary rocks, cement, and hardness have similar responses), while the water bearing characteristics are vastly different. Transit times for the acoustic waves are related to formation mineralogy and the porosity of the rock. Most rock types have a limited range of acoustic travel times, which allows for acoustic logs to be used to determine lithology. The cement-bond log is a type of acoustic log that is used to determine how well a casing has been cemented to the formation.

Acoustical logging is useful for consolidated formations and provides useful information in uncased, fluid-filled boreholes. Figure 4-14 shows an example of an acoustic log in conjunction with a caliper log. Saltwater will shift the response slightly to the right. Limestone and granite provide similar responses so other logs must be used to confirm which is present. Limestone will generally yield water while granite generally will not.

Fluid Logs

Fluid logs include temperature, fluid resistance, and flowmeter logs. The tool used for temperature logs usually contains a glass bead thermistor. Temperature logs can be used to identify the boundaries of aquifer zones in boreholes; as water flows through permeable zones, the normal geothermal gradient will vary. Temperature logs are developed using a down-hole run. Temperature logs are useful in conjunction with EC logs as temperature changes often occur where there is moving water. Changes in conductivity in conjunction with changes in temperature logs would tend to indicate flowing water across the borehole. Temperature logs can also be used to detect interaquifer flow. The presence of cement grout in the annular space of a well can be determined by running a temperature log within 24 hr of grouting because the heat of hydration of the cement raises the fluid temperature inside the casing in cemented areas.

Flowmeter logs are used to measure flow velocity within the wells. The most common flowmeter logging tool is the impeller-type, where the rate of rotation of the impeller is proportional to the relative flow velocity of the tool. The relative flow velocity includes the actual flow velocity of water in the well and the rate at which the probe is raised or lowered into the well. Caliper logs must be run in conjunction with the flowmeter log because the flow velocity is a function of the cross-sectional area of the borehole. The relative contribution of individual aquifer zones to the total flow from a well can be calculated using data from flowmeter and caliper logs (AWWA, 2003).

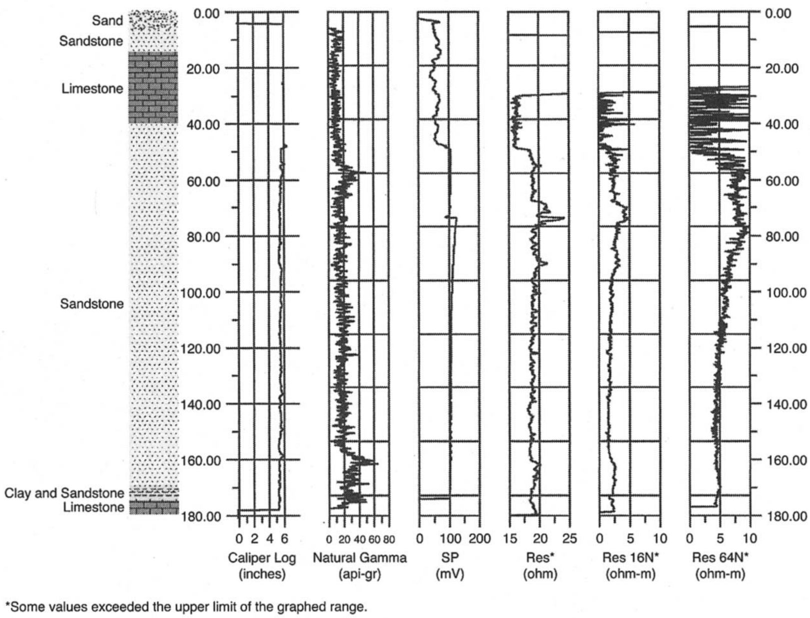
Log Suites

In no case should only one log be used because in no case can one log adequately describe the lithology and hydrogeology of the well. Individual geophysical logs do not provide unequivocal lithologic information. A high gamma response could be produced by a shale bed or phosphatic limestone layer. By running a suite of logs, more accurate qualitative and quantitative information of formation porosity, hydraulic characteristics, and fluid conductivity can be measured. Figure 4-15 shows a series of logs for a borehole (Bloetscher, et al., 2005). In a log suite, occurrences such as shale layers are identifiable by a low resistivity and high gamma log response, where those logs singly would provide no specific information indicating that the layer was shale.

Further details of the logs are summarized in several reference books, most notably Keys (1989). In determining which logs and tests should be required, the following geologic logs should be considered for surface casing intended to protect underground sources of drinking water:

- Resistivity (long and short, normal and single-point); spontaneous potential; gamma; and caliper logs before the casing is installed; and
- A cement bond, temperature, and density log after the casing is set and the annular space cemented, depending on casing material. If the hole is drilled without the use of drilling muds or other additives, the fluid resistivity flowmeter and temperature log should be performed under static and pumping conditions.

No radioactive source should be placed down-hole in the underground source of drinking water or where water for potable use or human consumption is anticipated.



Source: Bloetscher, et al., 2005

Figure 4-15 Typical suite of logs

Table 4-5 outlines the application of types of geophysical methods that should be used based on the formation type and investigation desired. Table 4-6 summarizes the response of four logs to porosity, an important property when looking for water supply sources. Table 4-7 outlines a set of criteria suggested by Keys (1989) for selecting logs to be run on a given project. It should be noted that the same suite of logs may not be appropriate or cost effective in every instance. Instead, careful consideration should be given to selecting the logs that will provide the most useful information for making decisions based on the anticipated geological environment where the wells are proposed to be constructed. In all cases, a caliper log should be run. Other information that maybe gathered includes a radial and side-view color television survey of the borehole under flowing and no-flow conditions to help identify flow zones and sanding problems (see Figure 4-16). Other geophysical logs should be considered depending on the formation, availability of tools, cost of the project, and perceived hazards.

FIELD TESTING (from AWWA, 2003)

Aquifer testing is very useful during construction of test holes, and many effective methods are now available for performing such testing. In the simplest form, a record of the water flow rates produced at different depths while drilling using the

Table 4-5 Recommended geophysical logs

Material	Seismic Refraction	Electrical Resistivity	Ground Penetrating Radar	Cross-hole Seismic	Electro-magnetics	Magnetics	Gravity
Subsurface geology	×						
Rock density	×						
Groundwater location		×	×		×		
Karst formation		×		×	×	×	×
Groundwater pollution		×			×		
Fracture zones		×					
Metallic objects buried			×		×	×	
Nonmetallic objects buried			×				
Seismic risk				×			
Foundation design	×	×		×			

Table 4-6 Response of logs to porosity

Log	Property Measured	Response to Total Porosity	Response to Effective Porosity	Response to Secondary Porosity	Spurious Matrix and Fluid Responses
Resistivity	Resistivity and volume or fluid connected pores	No current flow in isolated pores	Response only to effective porosity	Detects secondary porosity, shape of pores effects results	Boundary effects
Gamma-gamma	Electron density	Best response with highly porous rocks	Does not distinguish	Does not distinguish from primary porosity	Matrix composition, high salinity = error
Neutron	Hydrogen content	Best response with minimal porosity	Does not distinguish	Does not distinguish from primary porosity	Bound water and other neutron absorbers. Pores must be saturated. High salinity.
Acoustic	Average compression wave speed	Relates only to total porosity when primary and intergranular	Does not distinguish	Does not distinguish from secondary porosity under most conditions	No signal in gas

Table 4-7 Criteria for selection of logs

Type of Log	Property Measured	Application	Borehole Condition	Limitations
Spontaneous potential	Electric potential caused by salinity	Lithology, water quality, and water content	Uncased borehole with water	Need salinity differences
Single-point resistance	Resistance of rock, water, and filled voids	High resolution lithology and fractures	Uncased borehole with water	Not quantitative, borehole diameter impacts results
Multi-electrode	Resistance of rock and fluids	Quantitative date on salinity and lithology	Uncased borehole with water	Normal logs do not measure thin bed thickness correctly
Gamma	Natural gamma radiation in rock	Lithology, use clay and silt content for permeability	Any borehole less than 24 in. diameter	None
Gamma-gamma	Electron density	Bulk density, porosity, moisture content, and lithology	Uncased borehole	Severe borehole diameter effects
Neutron	Hydrogen content	Saturated porosity, moisture content and lithology	Uncased borehole	Borehole diameter and chemical effects
Acoustic	Acoustic reflectivity of borehole wall	Orientation of fracture, dip of bed	3 to 16 in. fluid filled borehole	Does not detect secondary porosity
Caliper	Diameter of borehole	Lithology and voids	All conditions	None
Temperature	Temperature of water	Flow and temperature gradient	Fluid-filled borehole	Accuracy varies with probe
Conductivity	Fluid resistivity	Water quality, contamination location	Fluid-filled borehole	Accuracy varies with probe
Flow	Fluid movement	Flow in borehole	Fluid-filled borehole	Accuracy varies with probe

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reverse-air method is a form of aquifer testing, yielding valuable information. Packer tests are used to determine transmissivity and storage coefficients for isolating water-producing formations. They can be used on both tight and permeable formations for comparative purposes in identifying confining beds. The diameter of the cone of depression and the drawdown varies with the size of the well, pumping rate, and the flow rate of water through the aquifer. In porous sand and gravel, the

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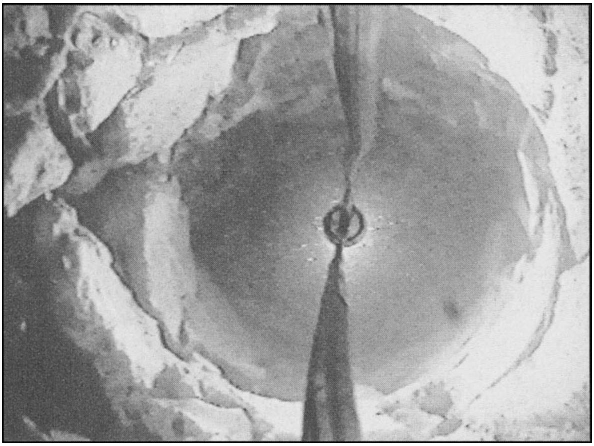


Courtesy of Youngquist Bros. Inc.

Figure 4-16 Example of borehole photograph

cone of depression may be small. In tighter materials, the cone of depression may be very significant.

Wells are normally placed far enough apart so that their cones of depression do not overlap significantly. Wells should be sized to minimize drawdown so that the aquifer can rebound quickly. Permanent drops in water levels can occur when the aquifer is pumped too much, a phenomenon called *mining of the aquifer*. The Black Creek aquifer in eastern North Carolina is such an example. When recharge to the aquifer is inadequate, a new water source will need to be located.

Ideally, wells should be pumped continuously without permanent drawdowns occurring. Where this is not possible, it is common practice to pump wells that have a significant drawdown for only a few hours each day to allow the aquifer to recover. An artesian well may be under enough pressure to cause the water to rise above the confining unit, which may eliminate the need for pumping initially. However, after an artesian well has been used for a period of time, the artesian pressure may reduce until the water no longer flows to the surface.

It is more important to determine the appropriate casing depth than to locate the pump depth. An improper casing depth may seal off highly productive zones. Determining the casing depth is dependent on the results of the design considerations, geophysical logs, and data collected during drilling. The data required to determine casing depth includes

- Lithology
- Core data
- Borehole geophysics

- Aquifer performance testing
- Water quality
- Drilling rate of penetration relative to weight on bit
- Cuttings
- Lost circulation zones

The first three were previously discussed. Determining transmissivity or the storage coefficient of an aquifer by any means other than actual performance tests in the field is expensive, time consuming, and of questionable accuracy. Field testing methods for determining these values have been developed and are well documented. All of these methods apply a regulated stress (pumping) to the formation and measure the effects (changes in water level) produced. These data are analyzed, and the transmissivity and storage coefficient are calculated.

To obtain the required data, one or more monitor wells tapping the aquifer serve as observation points in the area of investigation. The location of all wells must be accurately plotted on the area map so that the lateral distance and direction from the pumping well and the relative position with respect to other wells can be included in the analysis. No set number of wells is required but having more wells reduces the likelihood of making an error. For best results, the test well should fully penetrate the formation and be open only to the aquifer to be used as a source while the testing the well.

Cuttings are useful when retrieved during the drilling process to define the type of rock formation that lies beneath the surface. Chemical composition may be an issue—for instance, formations with high quantities of pyrite are often sources of leaching arsenic. Cuttings will indicate clay, voids, and other useful information for clarifying geophysical results. The more data that can be gathered from different sources, the more efficient the investigation. Caliper logs will help identify zones where significant voids may exist. They often are flow zones as well.

Water Level Measurements

The first step in determining the transmissivity and specific capacity of the aquifer is to create a method to determine water levels prior to pumping. A surveyor's benchmark should be used to determine the elevations of the wells using a level and survey rod. By accurately measuring water levels with respect to surface elevations, groundwater gradients prior to commencement of pumping can be determined. Before a pump test is run, static water levels should be taken for several days to determine if there are any ongoing changes in the aquifer that should be considered. Once the static, prepumping water levels are determined, these water-levels serve as a reference point that can be used for the collection of water-level data during an aquifer performance test. During the aquifer test, water levels must be recorded for each well. Data sheets should be used to record the water level changes during the pump test that include the date, time, depth to water, and casing elevations. Other data should be gathered and correlated to specific wells.

Water levels can be measured using a hand-held tape with a weight attached to the end to hold it straight and taut. The tape should be metal, and graduated in feet and in tenths and hundredths of a foot, or some similar metric unit. Such graduations facilitate calculations by eliminating conversion of fractions to decimal equivalents. By chalking the lower portion of the tape and lowering it into the water until an even foot graduation coincides exactly with the reference point, the precise distance to water from the reference is made by subtraction. The wetted chalk is easily identified, and direct readings to one hundredth of a foot can be made (AWWA, 2003).

Other methods of collecting water-level data include an electric tape that has an insulated wire with an open-end weighted electrode on the end. When the electrode enters the water, it completes a circuit that actuates a light, buzzer, meter, or other signal device. The distance to water is then read directly from graduations on the wire line. However, the graduations are not usually fine enough to permit a very accurate reading without some supplementary device. Float-actuated recording devices provide a means of collecting data continuously, but the time drive is not fast enough for the early periods of a test program. Pressure transducers combined with a data logger can provide an excellent record of water levels. Air-line devices have little value for controlled tests, except where water-level fluctuations are very large.

Collection Schedule (from AWWA, 2003)

While the aquifer test is run (pumped), water-level readings should be obtained using the following collection schedule:

1 reading at zero time	total elapsed time = 0 min
1 reading each 1 min for 10 min	total elapsed time = 10 min
1 reading each 2 min for 10 min	total elapsed time = 20 min
1 reading each 5 min for 20 min	total elapsed time = 40 min
1 reading each 10 min for 60 min	total elapsed time = 100 min
1 reading each 20 min for 80 min	total elapsed time = 180 min

Such a standard schedule can be easily followed and provides adequate data. All times are calculated from the precise instant that the pump is turned on or off, which is designated as zero. If the test extends beyond 24 hr, subsequent measurements can be made at 4-hour intervals. The timing of measurements at the onset of the test is critical. Each well should have at least one observer equipped with measuring devices and a synchronized stopwatch. After 180 min, measurements do not have to be made at a designated instant, but they must be accurate with regard to the exact time that each measurement is maintained.

The data collected provides information on the aquifer performance, not well performance. Each method involves turning a pumped well on or off and observing what happens to the water level in nearby observation wells. All methods use the Theis nonequilibrium formula or modifications thereto, which takes into account the time that has elapsed since pumping began or ceased.

Ideally, all wells used in the analysis should fully penetrate the aquifer. Some departures from this requirement can be tolerated, but the construction details of the partially penetrating wells are required, and modifications to the equations are required. Any wells in the area that are not involved in the test should be stabilized before an aquifer test and maintained at the same pumping rate for the duration of the test. During the aquifer test, well pumping should be at a steady, unvarying rate and carefully measured. The pumping rate and water-level data should be carefully computed and plotted. Each method uses the Theis formula to analyze variations in drawdown with time, or variations in drawdown with distance from the pumped well.

A family of curves has been developed to facilitate aquifer evaluation under a variety of conditions. The equations used for aquifer parameters are:

$$T = 114.6QW(u)/s \qquad \text{(Eq. 4-3)}$$

Where:

- T = the transmissivity of the aquifer, in gpd/ft
- Q = the discharge rate of the well, in gpm
- u = for any given formation, is proportional to the ratio of r^2/T
- $W(u)$ = the "well function of u," is determined from calculated tables for each value of u
- s = the drawdown at any point under study in the vicinity of the discharging well, in ft.

$$u = 1.87r^2S/Tt \qquad \text{(Eq. 4-4)}$$

Where:

- r = the distance from the discharging well to the point where the drawdown is being observed, in ft
- S = the aquifer storage coefficient
- T = the transmissivity of the aquifer
- t = the elapsed time since discharge began, in days.

The equations assume an aquifer that

- Is a confined or an artesian aquifer,

- Has confinement that occurs above and below by relatively impermeable materials, and
- Is homogeneous and isotropic-uniform in structure, with the same physical and hydraulic properties in all directions.

In practical terms, the thickness and actual extent of the aquifer should be known to permit the best possible interpretation of the test data. The formula is modified for leaky artesian conditions based on the conditions for confined aquifers and on several assumptions.

- The aquifer is confined between an impermeable bed and a bed through which leakage can occur.
- Leakage is vertical into the aquifer and proportional to the drawdown.
- No water is stored in the confining bed.
- The hydraulic head in the deposits supplying leakage remains constant.

An unconfined, or water table, aquifer does not have water confined or under pressure beneath impermeable rocks. Water is derived from storage by gravity drainage of the interstices above the cone of depression, by compaction of the aquifer, and by expansion of water in the aquifer. Properties of an unconfined aquifer can be determined by the Theis method with some limiting conditions. One of the basic assumptions of the Theis solution is that water is released from storage instantaneously with a decline in head. In a water table aquifer, this is not always true, because water is derived partly from gravity drainage, and the effects of gravity drainage are not considered in the Theis formula. However, with long pumping periods, the effects of gravity drainage become negligible so that the Theis solution can be used.

Drawdown Method of Calculation (from AWWA, 2003)

When the drawdown method of calculation is used to determine transmissivity, one well is pumped while the water levels are observed in two or more nearby wells. Figure 4-17 is a hydrograph—a plot of water level versus time—for observation well 1 (only the left half of Figure 4-17 should be considered at this point). Water-level measurements are taken in conformance with the schedule outlined previously. Baseline testing should occur for a minimum of 48 hr before the start of the test to identify any preexisting trends that would need to be considered during the test. If no upward or downward trend of water levels is found in the wells, the measurements are plotted as a horizontal line.

The drawdown represents the difference between the water level observed in the well and the level at which the water would have stood had no pumping occurred. Aquifer transmissivity and storage coefficients can be determined by comparing a logarithmic curve of time versus drawdown against one of a series of

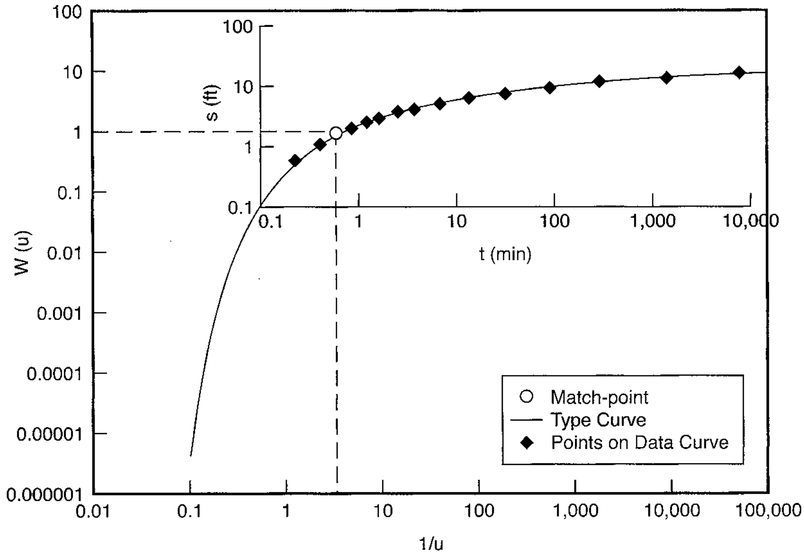


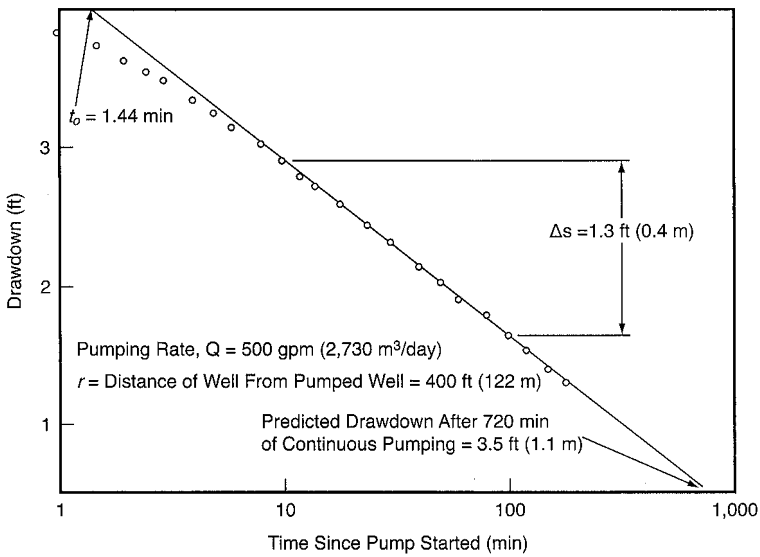
Figure 4-17 Type curve for confined aquifer (AWWA, 2003)

type curves developed from the Theis formula. The type curve is superposed over the field-data plot, keeping the respective graphical axes parallel. The curves are adjusted horizontally and vertically to obtain the best match of the two curves. An arbitrary match point is selected on the two graphs, and the field-curve and type-curve coordinates for substitution in the appropriate equation are selected. A different form of the type-curve solution is the distance–drawdown method. In this analysis, drawdowns in three or more observation wells at different distances from the pumped well are compared with one another to observe trends in the drawdown at each well in response to pumping.

An alternative solution is available for analyzing aquifer test data that is an approximate version of the type-curve solution. For this solution, well-test data is plotted on semilogarithmic paper and variations of the basic formula are used to compute the aquifer transmissivity and storage coefficient. The drawdown data tend to follow a straight line when plotted on semilog paper (Figure 4-18).

Recovery Method of Calculation (from AWWA, 2003)

The recovery method is exactly the same as the drawdown of calculation, only in reverse. The recovery method of analyzing aquifer test data involves shutting off a pumping well and observing the recovery of water levels in nearby observation wells. Recovery is the difference between the observed water level in the well at some time after pumping has stopped and the level at which the water would have been, had



Source: Johnson Screens, Inc., 1986

Figure 4-18 Example of alternative solution for drawdown response

pumping continued. The same curve options are available for this method of calculation as for the drawdown method, except that the concept has been inverted. The inverted curve indicates the rising levels in the observation wells. The recovery curve is compared with the inverted drawdown curve to determine the transmissivity and storage coefficient. The values should be similar to those obtained using the drawdown calculation method. The same time periods for the recovering water levels should be observed as for the drawdown method.

A straight-line solution can also be used. As in the drawdown methods, the data curves are plotted on semilog paper, showing a rising trend in the recovery period. With these modifications, the curves become straight lines. The same abbreviated equations are used to compute the transmissivity and storage coefficient. In practice, the recovery test is essentially the reverse of a drawdown test, therefore one drawdown curve and one straight-line plot will serve equally well for either kind of test data. Both kinds of data can be recorded on the same plot to check their agreement (AWWA, 2003).

Caution needs to be used in analyzing recovery data. Water extracted from the aquifer may recover very slowly from drainage from the unsaturated zone above. Therefore, when it is anticipated that the amount of time for full recovery is significantly greater than the duration of the pump test, a reduction in the pump test rate is recommended so that the test pumping rate is proportional to the ratio of pumping time to recovery time.

The reverse is also true. If a surface water source of infiltration or aquifer leakage is present, the recovery may occur more rapidly than the drawdown. In such cases, the pump test is unlikely to yield useful data. Further investigation is needed to determine the appropriate maximum water yield available.

Specific Capacity Method

An abbreviated well-performance evaluation can be performed using a relatively short test to determine the specific capacity of the well. The specific capacity method divides the total drawdown in a well into two components—drawdown in the aquifer and drawdown related to well loss. The drawdown in the aquifer is dependent on the aquifer's ability to transmit water. Drawdowns of this type do not usually change unless the aquifer is depleted. However, the drawdown caused by well loss may change considerably over time as a result of changes in flow regime (laminar to turbulent in the screen or column pipe) or changes in head loss as the water passes through the screen or well bore from corrosion, failure of the well screen or gravel pack, pump efficiency losses, water quality changes, and other factors. The potential for these changes to occur is the reason all wells should be tested annually for specific capacity to determine whether significant changes in well performance have occurred. Correction is recommended when capacity decreases by more than 50 percent. Tests for specific capacity should not be substituted for the more involved tests previously described when a more complete well and aquifer evaluation is necessary.

STEP-DRAWDOWN TESTING (from AWWA, 2003)

The purpose of step-drawdown testing is to evaluate the performance of the well. A step-drawdown test is performed on a well to determine aquifer characteristics. The data collected during the step-drawdown tests are used in the evaluation of the performance, efficiency, and specific capacity of wells at the different pumping rates. The data is also used for the calculation of the transmissivity and hydraulic conductivity of the aquifer; to quantify the deterioration in well performance over time; and yield information regarding well efficiency, well development, and well screen/borehole clogging. Step-drawdown testing should be performed yearly on each well and should be performed in conjunction with sand testing. Step-drawdown testing should also be performed prior to and after well disinfection. This procedure will allow evaluation of the effectiveness of the disinfection procedure. The results also help determine possible rehabilitative procedures and optimum pumping rates.

Step-Drawdown Testing Procedure

Step-drawdown testing involves pumping a well for a predetermined amount of time (approximately 60 min), until water level stabilization is reached, at each of three increasing pumping rates. Ideally, the three rates should be at 50, 100, and 150 percent of the design pumping rate. Before each increase in pumping rate, water levels are allowed to recover to static levels for at least the same amount of time as the well was pumped. The changes in water levels within the well are measured with an electric water-level probe (M-scope) during both the drawdown and recovery periods. It is imperative that the M-scope be disinfected before use in each well and after use in each well. The time increments for measurements are as follows: 1 min-readings for the first 10 min, 2-min readings from 10 to 20 min, and 5-min readings from 20 to 60 min and/or the end of the test.

From a measurement standpoint, the most important test measurements are the first and last water-level measurements. If for some reason the well does not stabilize at 60 min, the test readings should be measured until the well is stable. Each successive rate (and recovery period) must be extended out to at least the longest previous time interval, and a measurement must be obtained at the same time as the end of the first drawdown step. The recovery period should be equal to the longest time period in the drawdown step. Example: If step 1 lasts for 60 min, but the second step indicates the well is still drawing down at 60 min, readings should continue until the well is stable (for example, 100 min). Readings will then be obtained at 60 min and at 100 min. The recovery for the second and third step must also be 100 min, while recovery must be at least 100 min and readings must be obtained at 60 min and 100 min for each step and recovery period.

Discharge from the well should be controlled by a gate valve and should be measured using a calibrated flowmeter and/or an orifice manometer assembly. The total drawdown (measured in the field) in a well is a function of the drawdown due to aquifer characteristics and the drawdown due to the loss of efficiency from the well. Total drawdown(s) can be written as the following equation (Dawson and Istok, 1991):

$$s = BQ + CQ^2 \qquad \text{(Eq. 4-5)}$$

Where:

s = drawdown in the well casing, ft
Q = pumping rate, gpm
C = well loss coefficient, sec^2/ft^5
$B = (264/T)\log[(0.3Tt)/(r^2S)]$, gpd/ft

and

T = transmissivity, gpd/ft
t = time, min
r = radius of the well, ft
S = storage coefficient, dimensionless

Because the transmissivity and storage coefficient of an artesian aquifer or a leaky aquifer are constant, the BQ term in the equation does not affect the determination of well loss using Equation 4-5. In a water table aquifer, the transmissivity, storage coefficient, and specific yield values change (decrease) as the aquifer saturated thickness decreases. The drawdown equation does not compensate for the effects of partial penetration of the aquifer. However, if the degree of dewatering is small, changes in transmissivity, storage coefficient, and specific yield are negligible and can be ignored. Assuming that the well is not developing, the total drawdown can be used to determine transmissivity. However, this method gives lower transmissivity values than those calculated without accounting for drawdown caused by well loss.

Specific Capacity Calculation

The productivity (quantity of water produced) of a well can be expressed as specific capacity. The specific capacity of a well is defined as the ratio of the pumping rate to the drawdown at a given time, as illustrated in the following equation:

$$C_s = \frac{Q}{S} \qquad \text{(Eq. 4-6)}$$

Where:

C_s = specific capacity of the well, gpd/ft of drawdown at a unit of time
Q = pumping rate, gpm
S = drawdown, ft

Estimating the specific capacity of a well requires determining the drawdown from a static water level to a pumping water level within the well at a known pumping rate after a known span of time. Specific capacity is measured in gallons per minute per foot of drawdown at a given period of time (gpm/ft at a unit of time) to calculate well efficiency. The higher the specific capacity, the more efficient the well, as long as all other factors are equal. Specific capacity changes in a nonlinear fashion with increased pumping rates because a well cannot, in reality, be 100 percent efficient. Slight decreases in the specific capacity with increased pumping rates are to be expected in wells that have fully stabilized and are no longer developing. If the specific capacity increases at higher pumping rates, the well is still developing.

Well Loss Constant

Well loss is defined as head loss attributable to well inefficiency caused by the turbulent flow of water through the well screen and/or inside the casing to the pump intake (Jacob, 1946). Well loss can be expressed as a well loss constant (C) and the well loss in feet (S_w). The well loss constant is derived from a comparison of the drawdown data at the various pumping rates of the step-drawdown test. This constant is in turn expressed as well loss in feet or as well efficiency. The value of C

may be computed from step-drawdown test data using the following equation (Jacob, 1946):

$$C = \frac{(\Delta s^{i}/\Delta Q_{i}) - (\Delta s^{i-I}/\Delta Q_{i-I})}{\Delta Q_{i-I} + \Delta Q_{i}} \qquad \text{(Eq. 4-7)}$$

Where:

C = well loss constant, sec^2/ft^5
I = any given pumping step
Δs^i = incremental drawdown associated with step i, ft
ΔQ_i = incremental pumping that produces incremental drawdown (s^i) associated with step i, ft^3/sec

Changes in C values are affected by changes in discharge rates, shifting of the gravel outside the wells, and/or development of the formation.

Equation 4-7 assumes that the production well is stable and that the value of C does not change during the well production test. New wells, improperly designed and/or constructed wells, and old wells can be unstable, therefore the calculated value of C can be affected by changes in the discharge rate. The value of C calculated for flow rates 1 and 2 of the step-drawdown test may be greater or less than that calculated for flow rates 2 and 3. Sand and gravel often shift outside the production well during discharge periods under the influence of high discharge rates. This may result in either the development or clogging of the pores of the well face. If the value of C for steps 2 and 3 is considerably less than the value of C for steps 1 and 2, it is probable that development of the well has occurred during the well production (step-drawdown) test. A large increase in the value of C with higher discharge rates indicates clogging has occurred during the well production test. Clogging may occur for several reasons: fine-grained material clogging boreholes, the presence of bacteria, and/or formation collapse. Formation collapse may be an indication of sinkhole formation. If the production well is unstable, C may be calculated with Equation 4-7 and data for flow rates for steps 1+2 and 3 or 2+3 and 1.

Borehole clogging as a result of incomplete well development or well deterioration by bacteria or other concerns is generally negligible when C is less than 5.0 sec^2/ft^5. Values of C between 5.0 and 10.0 sec^2/ft^5 indicate mild clogging or well deterioration, and clogging or well deterioration is severe when C is greater than 40.0 sec^2/ft^5 (Walton, 1962, p. 27). Deteriorated wells may be returned to near original yields by one of several rehabilitation methods. The success of the rehabilitation can be appraised with the results of well production tests conducted prior to and after rehabilitation.

Well Loss in Feet

Well loss is used to calculate the well efficiency. It is computed in feet using the following equation (Jacob, 1946):

$$s_w = CQ^2 \qquad \text{(Eq. 4-8)}$$

Where:

s_w = well loss, ft
C = well loss coefficient, sec^2/ft^5
Q = production well discharge, ft^3/sec

Well Efficiency Calculation

Well efficiency is defined as the percentage of total drawdown that is attributable to well loss. This number can be obtained by dividing the theoretical drawdown by the total drawdown and multiplying by 100 to obtain the percentage.

$$\frac{s_t}{s} \times 100 = \text{Percent Efficiency} \qquad \text{(Eq. 4-9)}$$

Where:

s_t = theoretical drawdown, ft
s = actual drawdown, ft

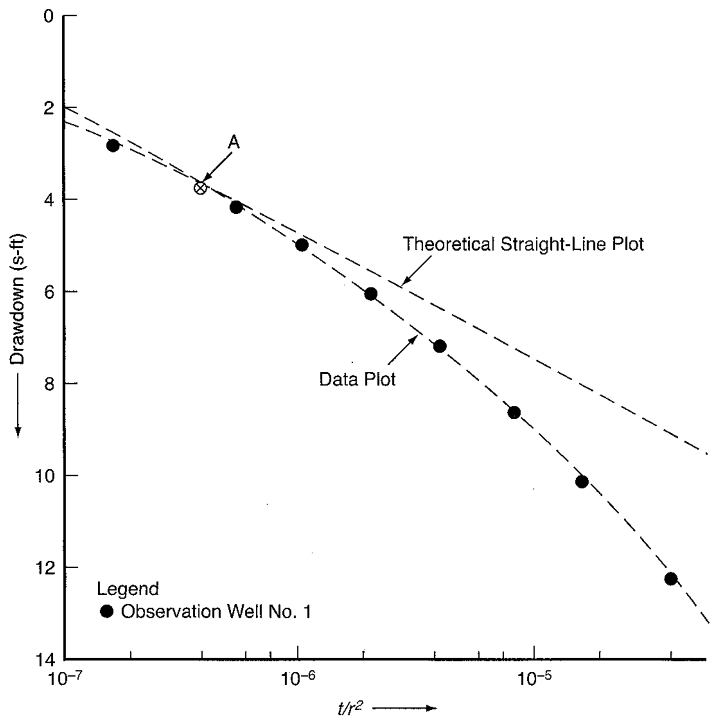
For the purposes of this text, the theoretical drawdown is calculated as the total (measured) drawdown minus the well loss in feet. The actual drawdown is the drawdown as measured in the well.

The term *well efficiency*, in this context, can be misleading because is does not indicate that the efficiency (productivity) is caused by both the well characteristics (well loss) and aquifer characteristics (theoretical drawdown). Therefore, wells with lower well efficiencies should not be thought of as necessarily inferior to wells with higher well efficiencies. Well efficiencies of greater than 100 percent indicate that the wells are developing.

Identification of Aquifer Boundaries

No aquifer is infinite, although for the purposes of calculation, aquifers that have extensive area may be assumed to be infinite. Most aquifers have, at some point, identifiable boundaries. Where the boundaries are close to the well, the drawdown test data will be plotted differently. While there are a number of potential boundary scenarios, there are two that are common: the impermeable barrier and the recharge barrier.

The effect of an impermeable barrier around an aquifer shows in the drawdown test when plotting in the manner previously outlined. The new graph, instead of

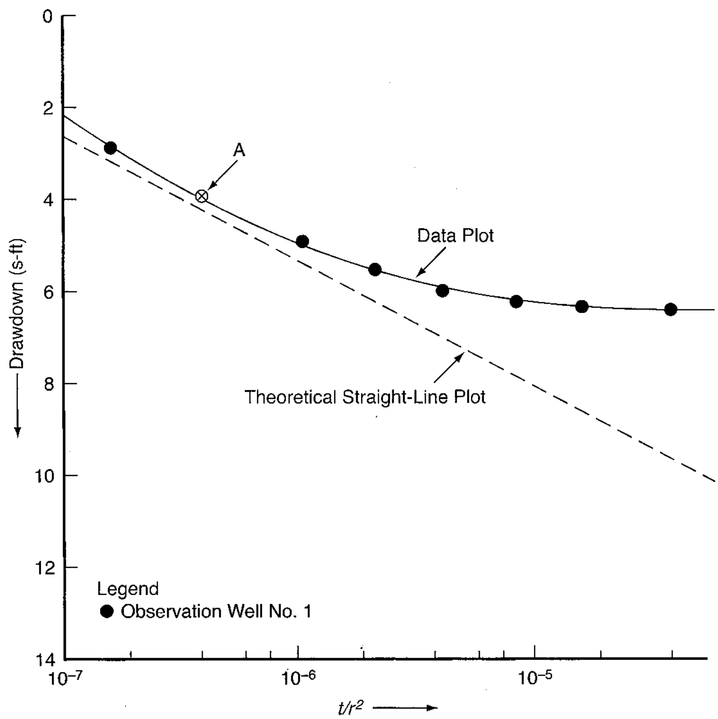


Source: AWWA, 2003

Figure 4-19 Example of drawdown response at impermeable boundary

staying on a straight line, now curves and eventually defines a new straight line having twice the slope of the original (see Figure 4-19). This phenomenon is known as *reflection*. The aquifer is cut off by an impermeable barrier caused by the rising side of a buried valley or intruded, impermeable formation. This situation is quite common in the northern, once-glaciated parts of the United States. The effect is the same as having a second well located across the barrier at the same distance from the barrier as the actual well, pumping at the same rate. Data gathered and plotted in this manner will indicate the presence, location (distance), and type of aquifer boundary with respect to the pumped well.

A recharge zone creates the opposite phenomena from an impermeable boundary. Instead of being cut off by an aquifer barrier, the aquifer is cut off by a recharging stream—a situation that is often found in the field. The data plot begins as expected, with a curved portion leading into a straight line. However, instead of continuing on the straight line, as the data theoretically should for an infinite aquifer, the plotted data curves above it and eventually defines a horizontal line



Source: AWWA, 2003

Figure 4-20 Example of drawdown response at recharge boundary

(see Figure 4-20). The rate of drawdown caused by the withdrawal well lessens because of the water contributed to the aquifer by the stream and gradually approaches a fixed value. The effect is the same as if a well, identical to the pumping well, is introducing water to the aquifer instead of withdrawing it. The reflective well is located at an equal distance from, and on the opposite side of, the recharge boundary from the withdrawal well.

Comparisons

To provide a baseline for testing the well design procedure, Nuzman (1989) developed some rule-of-thumb ratios between transmissivity and well specific capacity (AWWA, 2003):

Confined Aquifer $$Q/s = T/2,200 \quad \text{(Eq. 4-10)}$$

Semiconfined Aquifer $$Q/s = T/1,700 \quad \text{(Eq. 4-11)}$$

Unconfined Aquifer $$Q/s = T/1,200 \quad \text{(Eq. 4-12)}$$

These ratios were developed for a typical well radius of influence of 0.5 mi, and effective well diameter of 24 in., and assuming a storativity coefficient typical for the aquifer characteristics defined and the general assumptions of a theoretical aquifer (homogenous, isotropic, instant release from storage, infinite area extent, and no leakage or recharge). The equations are provided for purposes of comparison only and should not be used exclusive of good field testing. Once the geological data is secured, design information—size, materials, casing purpose—can be used to determine the appropriate depth of the casing and screening.

WATER QUALITY SAMPLING (from Bloetscher, et al., 2005)

Performance of groundwater monitoring and the development of periodic reports of such monitoring should be standard practice for all well systems. These analyses include the routine testing of the raw water quality of the proposed production zones. Water quality sampling is an integral part of proper maintenance of wells. Water quality samples should be analyzed by a licensed, state-certified, or USEPA-certified laboratory. The sampling period should be determined by the stability of the water quality results in the well; how often, if ever, the parameters change and the amount of the change; and in accordance with federal, state, and local regulations. Changes in water quality are usually an indicator of problems with wells and, if the changes are great, they may disrupt the water production process. In addition, certain changes in water quality can cause adverse environmental impacts.

ASTM standard D-4195-03 requires water analyses to be performed on raw water for the parameters in Table 4-8. It is recommended that for all water production programs, analyses be conducted for the same parameters. Standard sampling methods (ASTM, 2002) and chain-of-custody protocols should be used to collect and analyze the water samples. Temperature, pH, and silt density index (SDI) should be measured on-site at the time the sample is collected. Other chemical and physical parameters may require testing in certain regions based on specific groundwater quality of the area.

Geochemical considerations may impact the long-term viability of the groundwater program in some aquifer systems. One concern is the potential for fresh and saltwater interaction. Also, fractures or other head or boundary conditions that lie outside the zone of the aquifer testing program may be issues. These interactions may include ion exchange, which can occur where significant clays may be present.

Redox processes may cause carbonate precipitation (or formation dissolution), ion exchange, suspended solid clogging, and biofouling. Redox processes are caused by oxygen consumption in the aquifer, typically an indication of either chemical oxidation or microbiological activity that is using the oxygen. Chlorine oxidation is also common in potable water systems. Air binding, either dissolved oxygen or entrained air, will lead to clogging problems. Withdrawal velocities may cause

Table 4-8 Summary of parameters to be analyzed in water quality testing

Parameters	
Aluminum (Al) (total and dissolved)	Oxygen (O_2)
Barium (Ba)	pH
Bicarbonate (HCO_3^-)	Phosphate (PO_4^-) (total)
Calcium (Ca)	Potassium (K)
Carbon dioxide (CO_2)	Silica as silica dioxide ($SiO2-$) (total and dissolved)
Carbonate (CO_3^-)	Silt density index (SDI)
Chloride (Cl^-)	Sodium (Na)
Fluoride (F^-)	Strontium (Sr)
Free chlorine (Cl_2)	Sulfate (SO_4^-)
Hydrogen sulfide (H_2S)	Temperature
Iron (Fe) (totaled, dissolved, and ferrous)	Total dissolved solids (TDS)
Magnesium (Mg)	Total organic carbon (TOC)
Manganese (Mn) (total and dissolved)	Turbidity (nephelometric method)
Nitrate (NO_3^-)	

Source: ASTM D-4195-03

wearing and encrustration of excessive formation dissolution. Pressure differences between the formation and fluids may cause dissolution to occur or microfracturing. Temperature differences may also lead to dissolution problems.

SAND, SILT, AND COLLOIDS (from Bloetscher, et al., 2005)

Drilling methods and well development play a major role in identifying clogging potential. Proper selection of drilling equipment and performance of adequate pump tests, with optimal well development time, will indicate if sand, silt, or solids present an ongoing problem. The larger the pore size, the less potential there is for plugging, although filter theory indicates that particles 1/20th of the pore size may be effectively filtered out (i.e., may become part of the clogging matter). Inadequate well development is a frequent problem with new or refurbished wells.

Sand, silt, and colloids are relevant to measuring potential impacts to the aquifer formation, including plugging and fouling problems. Plugging and fouling problems are caused by a number of hydrogeologic, geologic, engineering, and construction related factors, including

- Hydrogeologic constraints that are not evaluated at the time of design and/or change over time, such as: sand, clay, or rock layers that are unstable and collapse into the well boreholes; naturally occurring and/or man-made fracturing/faulting; long-term water quality changes caused by changes to the hydraulic regime, such as dams; water hammer to the aquifer/formation; man-induced influences (mining the aquifer, introduction of chemicals and/or microorganisms); and naturally occurring phenomena (sinkholes, karst terrain features, and/or faulting);

- Poor well design and/or construction practices, including insufficient placement of grout, improper design of pumps, valves, and fittings; and excessive drawdown allowances;
- Poor operating and/or maintenance procedures;
- Mechanical failures, including failures of electrical motors and pumps, and failure of valves; and/or;
- Failure to develop the wells fully, or interfingered sand or silt layers that have not or cannot be sealed off from the borehole or corrected in well design.

Most of these issues can be mitigated to some extent in the field. Determining the amount of resulting problems can be found by video surveying of the wells; pump testing; and water quality testing for silt, sand, and colloidal material.

The purpose of sand testing is to determine the amount of sand being pumped from a well. This is important because sand, especially quartz sand, can adversely affect the longevity of pumps, motors, column pipes, and pipelines because of its ability to abrade steel. The abrasion has the ability to create points of potential corrosion by both electrolysis and bacteria. Sand testing should be performed on each production well on a yearly basis and should be performed in conjunction with step-drawdown testing. Two types of sand testing equipment can be used to perform sand testing. The first type is a Rossum sand tester, and the second type is a Lakos Laval sand separator.

Sand production is also an indicator that there may be structural concerns with the well and/or well screen. Continued sand production can cause catastrophic collapse of the formation around a well and is a serious concern. Under normal operating conditions, the concentration of sand produced by a water supply well should be less than the AWWA Standard for Water Wells A100-06 of 5.0 mg/L during a two-hr pumping cycle when pumping at the design rate. Any recommendations for limiting sediment concentration must take into account the water use, the method of treatment, the type of sediment, and the source of the sediment. Properly designed wells can meet 1.0 mg/L. The USEPA and the National Water Well Association (1975) have recommended the following limits:

- 1 mg/L—water to be used directly in contact with, or in the processing of, food and beverages.
- 5 mg/L—water for homes, institutions, municipalities, and industries.
- 10 mg/L—water for sprinkler irrigation systems, industrial evaporative cooling systems, and other uses where a moderate amount of sand is not especially harmful.

- 15 mg/L—water for flood-type irrigation and where the nature of the water-bearing formations and the overlying strata are such that pumping this amount of sand will not seriously shorten the useful life of the well.

The limits suggest reasonable goals that can be achieved if good well design, construction, and development practices are followed. In older wells or wells in problem aquifers, a well may pump unacceptable amounts of sediment. If the well cannot be redeveloped by conventional techniques, a special sand separator can be installed as a permanent part of the well system. Although sand separators are efficient, they may not remove all sediment and should not be used as a substitute for good well design and construction practices. In addition, if sufficient sand is removed, this removal could cause catastrophic collapse of the formation. The testing procedure for a Rossum sand separator is well documented in AWWA literature. While the Rossum sand tester is the method accepted by AWWA, the authors' experience has indicated that the use of a Lakos Laval sand separator provides a better method of quantifying sand produced from a well.

The amount of sand produced in milligrams per liter for each individual pumping rate is determined by the following equation (Witt and Andrews, 1993):

$$S = \frac{S_{wt}(1{,}000)}{3.785Qt} \qquad \text{(Eq. 4-13)}$$

Where:

S = sand content, mg/L
S_{wt} = weight of sand, g
1,000 = equation constant, mg/g
3.785 = equation constant
Q = rate through the sand separator, gpm
t = time, min

The well should be pumped at its design rate for 2 hr, and sand samples should be collected at 5, 30, 60, and 120 min without stopping the pumping. Sand samples are removed from the sand separator and analyzed. The amount of sand pumped during normal operation is reflected in the fourth (120 min) sand sample. This sample is a realistic figure for the quantity of sand that will be produced during normal well operations. 1.0 mg/L is the desired maximum. More sand, especially after proper development of the well, may indicate grouting problems or a sand vein in the production zone that may cause damage to the well and pumping equipment.

Large discrepancies in the amount of sand collected at the 5-min sample as compared to the amount of the 120-min sample are of concern and may be an indication of water hammer to the formation. Water hammer is a phenomenon whereby the turn-on or turn-off of the well causes large pressure fluctuations in the aquifer. Such fluctuations will dislodge sand and silt, and may cause damage to limestone and sandstone. Water hammer often indicates operational failure of the valves in a well and/or at the plant. It should be noted that the Lakos Laval sand separator only removes sand particles in the range of 74 µm with 98 percent efficiency. This means that particles less than 74 µm will pass through the sand separator.

Colloidal testing should be performed prior to well disinfection and after well disinfection. This procedure will allow evaluation of the effectiveness of the disinfection procedure. The filter pore spaces are 5.0 µm in size. This filter size allows for the capture of most clay- and silt-sized particles. Clay- and silt-sized particles can clog the gravel pack and well screens, causing increased drawdown, loss of production, and increased operating cost. Continued withdrawal of silts and clays can, like sand, cause sinkhole formation. The production of clays and silts may also be an indication of structural concerns with the well casing and the screen. A pressure gauge on each side (in-flow and out-flow) of the filter apparatus allows the measurement of the change in pressure across the filter cartridge. The following is an outline of the procedure to set up the cartridge filter:

1. Disinfect the filter holder with unscented Clorox® bleach and attach the colloidal test apparatus to the side of the discharge line.
2. Flush Clorox® out of the cartridge filter holder by opening the valve to the discharge line.
3. Insert the cartridge filters into the holder without touching the filter. (Open an end of the plastic bag and insert the filter, then remove plastic bag.)
4. Turn on water to run through the filter.
5. Check and note the discharge rate after 5 min; check and note the pressure in (P_{in}) and pressure out (P_{out}).
6. Check and note P_{in} and P_{out} at least once a day. Note any color changes in the filter and/or any growths on the filter. Once the pressure differential between P_{in} and P_{out} increases to more than 28 psi, remove the filter using plastic gloves.

The filter should be visually inspected and stored in a polyvinyl chloride (PVC) container and any odor noted. Culture swabs may be obtained and sent for microbiological analysis. The filters should be placed in PVC containers and sent for x-ray diffraction and microscopic analysis by a qualified professional.

SDI testing, as defined in ASTM Standard D-4189-94, is an empirical measurement to test for the potential of silt, colloidals, bacteria, colloidal silica, organic molecules, and/or corrosion products that foul well screens and gravel packs. The SDI test simply measures the decay in flow rate through a 47-mm diameter, 0.45-µm pore-size membrane. The 0.45-µm membrane is used because it is more susceptible to clogging from colloidal matter than from hard particles, such as sand and scale. Furthermore, the 0.45-µm size is smaller than the 5.0-µm size of the prefilter and therefore measures particles that would pass through the prefilter and clog the membrane. (The membrane is approximately 0.5 μm in size.) The measured decay in flow rate is converted to a number between 1 and 100.

The SDI number is a function of the rate at which the filter (membrane) clogs with colloidal material. The larger the SDI number, the greater the fouling tendency of the water. To perform the SDI test, a Millipore SDI or fouling index test kit or an equivalent is required. The SDI equipment includes the following: 47-mm filter holder, pressure regulator, pressure gauge, valves, fittings, tweezers, 0.45-μm membrane filter discs, a stop watch, and a 500-mL graduated cylinder.

To calculate the SDI of a given water, the following formula is used:

$$SDI = \left(1 - \frac{T_1}{T_F}\right) \times 100 \div T_T \qquad \text{(Eq. 4-14)}$$

Where:

SDI = silt density index (an empirical number between 1 and 100)
T_1 = the initial time to fill 500 mL, sec
T_F = the final time to fill 500 mL, sec
T_T = the total time test is performed, min

It is important to note the color of the filter because coloration is an indication of the clogging medium. If microorganisms are suspected, it is important to preserve the filter in a sterile container, such as a petri dish. This filter should be sent for microbiological analysis.

One method of controlling the SDI is through the regulation of the uphole velocity of water in the well. Decreasing the velocity will decrease the SDI of the water. For water supply wells, an uphole velocity of less than 5.0 ft/sec is recommended. Suspended solids create difficulty in the aquifer, generally causing well plugging and a reduction in aquifer permeability, especially if the aquifer has any chemical reaction with suspended solids or the ions among the solids. In many cases, suspended solids can bypass filtration tests, thereby creating a buildup within the wells that is unknown on the surface. To solve suspended solids problems, it is best to redevelop or pump the wells to remove the suspended solids.

MICROBIOLOGICAL ISSUES

Understanding the microbiological activity can help with understanding the chemical changes of the injected water. In stark contrast to public perception that aquifers are "pristine" environments, bacteria naturally exist in most aquifer systems; most aquifers with an organic content will have some degree of bacteriological activity. The typical agents for microbiological fouling include iron, sulfur-reducing and slime-producing organisms, although many others exist. As stated in chapter 2, some of these organisms are opportunistic pathogens, which is an additional concern. As a result, biological contamination is an ongoing problem often overlooked by engineers and hydrogeologists.

Microorganisms occur naturally in most aquifer systems, especially surficial systems. Most microorganisms require nutrients, such as organic carbon, nitrate, and phosphate, in order to grow and flourish, and to meet cell-building needs and general food source demands, all of which are available in abundance from surface activities. Casing and column pipe materials should be carefully considered because iron and certain other metals are required for healthy microbe populations. Of special concern from an operational perspective is one microbiological species that may impact human health or may cause biofilm growth that will clog the well screen or gravel pack. Certain of these species will aggressively attach to the ferrous metals often used for casings and column pipes. The organisms produce polysaccharide films that can cause microbiologically induced corrosion as they are generally acid-formers. Additional discussion on bacteria in wells is presented in chapter 7.

Iron bacteria, such as *Gallionella*, are common in aerobic environments where iron and oxygen are present in the groundwater, and where ferrous materials exist (such as steel or cast-iron wells). These bacteria attach themselves to the steel and create differentially charged points on the surface, which in turn create cathodic corrosion problems. The iron bacteria metabolize the iron that is solubilized in the process. Iron bacteria tend to be rust colored or cause rust-colored colonies on the pipe surfaces. Sulfur reducing bacteria are often responsible for the hydrogen sulfide smell released when raw water is aerated. These bacteria are common where sulfur naturally exists in the formation and will tend to form black colonies on pipe surfaces. While anaerobic, they will exist in environments where aerobic conditions can lead to symbiotic relationships with aerobic organisms.

The slime-producing bacteria are found in surface waters and in soil. Members of this genre are often used to protect farm crops from fungal growth and as a result are to be expected in groundwater that has organics. However, these bacteria are highly adaptive; research done several years ago indicated that the bacteria would grow in any environment into which they were introduced. The *Pseudomonas* genera are facultative anaerobes that can persist in oxygen-depleted environments by breaking down complex hydrocarbons for the oxygen. In some circumstances, they will use nitrogen in the absence of oxygen.

Pseudomonas bacteria can permanently affix themselves to laser-polished 316L stainless steel in a matter of hours, so attaching to steel or lower grades of stainless steel is easily accomplished. Given that the *Pseudomonas* sp. are adhering bacteria, they are capable of producing a polysaccharide matrix (biofilm) that can act as a barrier protecting the bacteria incorporated in the films from harmful substances such as disinfectants and, in some cases, oxygen. Biofilms also act to protect the bacteria from the shearing effect of turbulent flow and can provide an environment for other species. Periodic sloughing occurs when the biofilm gets too thick.

The microbiological accumulations or biofilms pose several significant concerns. First, the accumulations on the metallic surfaces create anodes and, in conjunction with reactions caused by dissimilar metals, can lead to a steady cathodic deterioration over time (with or without iron bacteria). Because the *Pseudomonads* are acid-formers, ferrous materials are particularly vulnerable to deterioration, especially in the presence of iron bacteria.

Because of the potential for microbiological problems, routine microbiological sampling of production wells is important. Biological agents can cause corrosion of the well casing, pumps, column pipes, and valves. Bacteria can clog gravel packs, well screens, and the formation, causing excessive operational costs by requiring higher pressures (heads) to obtain and treat water. Microbiological agents can circumvent treatment systems and can be released into the distribution system, causing clogging of irrigation systems and creating public health concerns. It is important to sample raw and finished water for microbiological contaminants.

There are two types of microbiological sampling. One should be routinely performed: each well should be sampled for fecal and nonfecal coliform bacteria and heterotrophic plate counts (HPCs) should be done on a monthly basis in the raw water. The presence of coliform bacteria is an indication that a well is biologically contaminated and may pose a threat to human health. If coliform bacteria is detected, the well should be retested. Should a second test show this presence, the well should be disinfected and should not be used until it clears a subsequent coliform test. It is not uncommon to have sampling errors in bacteriological sampling. Therefore, sampling protocol is important. Sampling jars should be dedicated to each well, and each jar should be sterilized before sampling.

The second type of microbiological sampling is speciation of the bacteria. Such sampling analysis is necessary to determine the presence and/or absence of microorganisms that could adversely impact treatment systems and/or could potentially threaten human health if adequate treatment of the recovered water is not provided. Organisms to be analyzed include growths of certain types of slime-forming bacteria, fungi, and algae. This process of microbiological growth is commonly referred to as *biofouling*. In many cases, the main source of biofouling organisms is feed water. The presence of these organisms will adversely impact the treatment process. In addition, some organisms, if not removed in pretreatment and posttreatment, may adversely impact the quality of the water.

METHODS FOR MONITORING GROUNDWATER QUALITY

Before developing a groundwater supply, the water quality must be currently acceptable and expected to remain so in the foreseeable future. Otherwise the investment is not warranted. After the initial water quality assessment is performed and groundwater development is assured, a system for monitoring water quality should be maintained, and a reassessment of up-gradient contamination risks should be performed periodically. Where contamination risks are significant, or where the water supply is critical, sentinel monitoring wells should be installed. Sentinel wells are located at various depths to define the initial groundwater assessment. In the future, sentinel wells can be used to detect changes in water quality and water elevations before they affect the water supply wells, serving as an early warning system.

The most common size for monitoring wells is 4 in. in diameter, constructed with PVC casings. However, the number of wells needed, and their locations, depths of completion, and construction details must be specified as part of an integrated wellfield monitoring plan. Increases in water usage may increase the contamination threat in the future, which may indicate a need for additional monitoring wells. This potential for development demonstrates the importance of continual evaluation of changes that might affect the groundwater supply. The wellfield monitoring plan should account for likely sources of contamination, local hydrogeology, and the hydraulic effects of the proposed groundwater development. For example, what was previously considered down-gradient from the well can become up-gradient either after pumping begins or as influenced by nearby surface water. These changes should be simulated with computer modeling to aid in designing a monitoring-well network.

Samples taken from monitoring wells should be analyzed for suspected contaminants that may impact the end use of the water. Historically, it has been the mineral quality of water that limited possible water uses. For instance, water containing high concentrations of sodium or boron will be unsuitable for irrigation. Today, biological issues and endocrine disruptors have been added to the carcinogens and minerals of the 1970s and 1980s as noted in chapter 2.

The sources of endocrine disruptors may appear benign (such as from agriculture). A wide variety of constituents, which can be harmful even in extremely low concentrations, have become a concern. Just as the concept that the biological quality of deeper groundwater usually has less surface impacts, testing for fecal bacteria and other microbiological indicators as well as emerging constituents should be performed periodically.

A list of the minimum required chemicals to be tested may be obtained from federal, state, and local regulatory officials. Indicator parameters, referred to as *priority pollutants*, often can be used to determine the likely presence or absence of chemicals that are a concern to groundwater development, but they are not guarantees of water quality. Fortunately, groundwater quality does not generally change rapidly as a result of slow movement as compared with surface water quality. Therefore, once water quality has been established, the frequency of groundwater sampling normally need not exceed quarterly or even semiannual checks, except for potable water sources or areas of suspected contamination.

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5

Well Design

All well projects go through a series of steps: predesign, field testing, regulatory criteria, design, construction, and testing and operations issues. The issues involved with predesign, field testing, and design include the required demands for water supply, measuring the impacts of competing users, and optimizing efficient and reliable operations that may limit groundwater opportunities. It should be noted that most testing occurs once some form of construction has begun—usually via a test well. Results from this testing provide engineers and hydrogeologists with the information needed to define the appropriate zones in the formation in which to place a casing and those to leave open.

PREDESIGN

Installing wells to provide water supplies are feasible from a technical perspective provided that certain subsurface conditions exist. These conditions include a formation that is areally extensive and porous enough to permit water flow to the well. Initial data to be collected at a potential well site was discussed in previous chapters.

After the initial investigation and confirmation of the presence of water-bearing materials, the amount of water that can be withdrawn must be determined. The basic aquifer parameters that must be evaluated are hydraulic conductivity/transmissivity and storage coefficient. In addition, drawdown, the extent of the cone of influence, flow, and specific yield must be defined. Aquifer testing provides data on the response of the aquifer to step-drawdown tests and other pump tests. Specific well design issues regarding up-hole velocity, screen size, well losses, casing burst strength, and other parameters must be determined so casings and screens can be properly placed.

The most significant aquifer parameters for predesign purposes are porosity, transmissivity, specific yield and specific retention, hydraulic head, and gradient. The first three describe the rock formation and quantities of water existing in the formation. Head and gradient determine how water moves through the formation and represent the mechanics of horizontal and vertical recharge to a well being pumped. Head and gradient are also used to analyze the transport of pollutants that may migrate to a well (AWWA, 2003). Hydraulic conductivity and transmissivity indicate how easily water will move in the formation. Hydraulic conductivity is the basic, three-dimensional parameter required for modeling purposes, but *transmissivity* is the most commonly used term by hydrogeologists.

Porosity

Porosity is the ratio of openings (voids) to the total volume of a soil or rock. Porosity is expressed either as a decimal fraction or as a percentage as follows:

$$n = \frac{V_t - V_s}{V_t} = \frac{V_v}{V_t} \qquad \text{(Eq. 5-1)}$$

Where:

n = porosity, as a decimal fraction
V_t = the total volume of a soil or rock sample
V_s = the volume of solids in the sample
V_v = the volume of openings (voids).

If the porosity determined using the above equation is multiplied by 100, the result is porosity expressed as a percentage.

Table 5-1 outlines the porosity of various formation materials. Soils are highly porous materials that are caused by loose soil particles, root holes, and animal burrows. The porosity of unconsolidated sand and gravel depends on the range in grain size, degree of sorting, and on the shape of the rock particles. Fine-grained materials tend to be better sorted and have the highest porosity values. Clay has a high percentage of voids, but because the voids are so small, clay transmits virtually no water.

Specific Yield and Specific Retention

Specific yield is the portion of water in a formation that will drain under the influence of gravity. Specific yield is important for determining the amount of water that can be withdrawn from a formation and should be checked on an ongoing basis throughout the life of the well. Specific yield is calculated as follows:

$$S_y = \frac{V_d}{V_t} \qquad \text{(Eq. 5-2)}$$

Where:

S_y = specific field
V_d = the volume of water that drains from a total volume of V_t
V_t = total volume of a soil or rock sample, and specific retention

Table 5-1 Values of porosity for various geologic materials

Material	Porosity (%)
Sedimentary	
Gravel, coarse	24–36
Gravel, fine	25–38
Sand, coarse	31–46
Sand, fine	26–53
Silt	34–61
Clay	34–60
Sedimentary rocks	
Sandstone	5–30
Siltstone	21–41
Limestone, dolomite	0–20
Karst limestone	5–50
Shale	0–10
Crystalline rocks	
Fractured crystalline rocks	0–10
Dense crystalline rocks	0–5
Basalt	3–35
Weathered granite	34–57
Weathered gabbro	42–45

Adapted from Davis, 1969; Johnson and Morris, 1962

Specific retention is the opposite of specific yield. Specific retention is the water that is retained as a film on rock surfaces and in very small openings that is not likely to be recovered in wells. The physical forces that control specific retention are the same forces controlling the thickness and moisture content of the capillary fringe, as expressed in the following equation:

$$S_r = \frac{V_r}{V_t} \qquad \text{(Eq. 5-3)}$$

Where:

S_r = specific retention

V_r = the volume of water retained in a total volume of V_t

V_t = total volume of a soil or rock sample.

Table 5-2 lists selected values of specific yield.

Hydraulic Head and Gradient

In an unconfined or water table aquifer, the depth to the water table affects the development of water supplies. Where the water table is shallow, the aquifer may fill

Table 5-2 Values of specific yield for various geologic materials

Material	Specific Yield in Percent (%)
Gravel, coarse	23
Gravel, medium	24
Gravel, fine	25
Sand, coarse	27
Sand, medium	28
Sand, fine	23
Silt	8
Clay	3
Sandstone, fine-grained	21
Sandstone, medium-grained	27
Limestone	14
Dune sand	38
Loess	18
Peat	44
Schist	26
Siltstone	12
Till, predominantly silt	6
Till, predominantly sand	16
Till, predominantly gravel	16
Tuff	21

Adapted from Johnson (1967)

to the surface during wet weather, making the area unsuitable for development without some form of drainage (as is commonly found in part of the southeastern US and particularly south Florida). Where the water table is at a great depth, the cost of constructing wells and pumping water for domestic needs may be prohibitively expensive.

Potentiometric head is the water surface in a confined aquifer. As noted in chapter 1, this is the point above the confining unit to which the water level rises. In either case, the highest head occurs where the aquifer is recharged. The change in head over the distance between the point of recharge and the point where a well is proposed to be installed is the gradient. These water levels are determined from a fixed measuring point. Typically, the referenced standard is the National Geodetic Vertical Datum (NGVD) of 1929, also commonly referred to as *sea level.*

The gradient between any two observation points is found as follows:

$$dh/dl = \Delta(z_1 - z_2)/\Delta l \qquad \text{(Eq. 5-4)}$$

Where:

z = elevation of the water table or the potentiometric head, whichever applies
l = distance between measuring points 1 and 2

The hydraulic gradient can be determined if the following data are available for three wells located in any triangular arrangement:

- Relative geographic position of the wells
- Distance between the wells
- Total head at each well

Total head is the sum of elevation head, pressure head, and velocity head. Because groundwater moves relatively slowly, velocity head can be ignored. Therefore, the total head at an observation well involves only two components: elevation head and pressure head. Groundwater moves in the direction of decreasing total head, which may or may not be in the direction of decreasing pressure head.

The equation for total head, h_t, is:

$$h_t = z + h_p \qquad \text{(Eq. 5-5)}$$

Where:

z = elevation head, the distance from the datum plane to the point where the pressure head, h_p, is determined.

Flow and Hydraulic Conductivity

The factors controlling groundwater movement are defined by Darcy's law as follows:

$$Q = KA\left(\frac{dh}{dl}\right) \qquad \text{(Eq. 5-6)}$$

Where:

Q = the quantity of water per unit of time
K = the hydraulic conductivity, which depends on the size and arrangement of the water-transmitting openings (pores and fractures) and on the dynamic characteristics of the fluid (water), such as kinematic viscosity, density, and the strength of the gravitational field (also referred to as the *coefficient of permeability*)
A = the cross-sectional area, at a right angle to the flow direction, through which the flow occurs
dh/dl = the hydraulic gradient

Unlike rivers and streams, groundwater tends to move slowly. As a result, unlike rivers and streams, groundwater flows under laminar conditions, which means that

Table 5-3 Typical values of hydraulic conductivity and permeability

$-\log_{10} K$(cm/sec)	−2	−1	0	1	2	3	4	5	6	7	8	9	10	11
Permeability	Pervious				Semipervious				Impervious					
Aquifer	Good					Poor				None				
Soils	Clean gravel	Clean sand or sand and gravels				Very fine sand, silt, loess, loam, solonetz								
					Peat		Stratified clay			Unweathered clay				
Rocks					Oil rocks			Sandstone		Good limestone dolomite			Breccia–granite	
$-\log_{10} k$(cm²)	3	4	5	6	7	8	9	10	11	12	13	14	15	16
$\log_{10} k$(md)	8	7	6	5	4	3	2	1	0	−1	−2	−3	−4	−5

Adapted from Bear, et at., 1969

the individual water particles tend to follow discrete streamlines and not to mix with particles in adjacent streamlines. As a result, the quantity of water, *Q*, is directly proportional to the hydraulic gradient, *dh/dl*.

If Equation 5-6 is rearranged to solve for *K*, the following is obtained:

$$K = \frac{Qdl}{Adh} = \frac{(m^3/d)(m)}{(m^2)(m)} = \frac{m}{d} \qquad \text{(Eq. 5-7)}$$

The units of hydraulic conductivity are those of velocity (or distance divided by time). However, the velocity units are less obvious in Darcy's law because the definition of hydraulic conductivity includes the volume of water, *Q*, that will move in a unit of time (gpd) assuming a unit hydraulic gradient (such as ft/mile) through a unit area (such as ft^2). Expressing hydraulic conductivity in terms of a unit gradient rather than an actual gradient at some place in an aquifer allows values of hydraulic conductivity for different rocks to be compared.

Table 5-3 outlines the ranges of hydraulic conductivity through 12 orders of magnitude. Hydraulic conductivity will vary by type of rock and likely will be different from place to place in the same rock (see Table 5-4). If the hydraulic conductivity is essentially the same throughout an area, the aquifer is considered to be homogeneous. If the hydraulic conductivity differs from one part of the aquifer to another, the aquifer is considered to be heterogeneous.

Water typically flows preferentially in one direction. As a result, the hydraulic conductivity may be different along different axes in an aquifer. If it varies by

Table 5-4 Ranges of hydraulic conductivity for various rock types

Material	Hydraulic Conductivity (m/sec)
Sedimentary	
Gravel	3×10^{-4} to 3×10^{-2}
Course sand	9×10^{-7} to 6×10^{-3}
Medium sand	9×10^{-7} to 5×10^{-4}
Fine sand	2×10^{-7} to 2×10^{-4}
Silt, loess	1×10^{-9} to 2×10^{-5}
Till	1×10^{-12} to 2×10^{-6}
Clay	1×10^{-11} to 5×10^{-9}
Unweathered marine clay	8×10^{-13} to 2×10^{-9}
Sedimentary rocks	
Karst and reef limestone	1×10^{-6} to 2×10^{-2}
Limestone, dolomite	1×10^{-9} to 6×10^{-6}
Sandstone	3×10^{-10} to 6×10^{-6}
Siltstone	1×10^{-11} to 1×10^{-8}
Salt	1×10^{-12} to 1×10^{-10}
Anhydrite	4×10^{-13} to 2×10^{-8}
Shale	1×10^{-13} to 2×10^{-9}
Crystalline rocks	
Permeable basalt	4×10^{-7} to 2×10^{-2}
Fractured igneous and metamorphic rock	8×10^{-9} to 3×10^{-4}
Weathered granite	3×10^{-6} to 5×10^{-5}
Weathered gabbro	6×10^{-7} to 4×10^{-6}
Basalt	2×10^{-11} to 4×10^{-7}
Unfractured igneous and metamorphic rocks	3×10^{-14} to 2×10^{-10}

Adapted from Domenico and Schwartz, 1990

direction, such as differences between conductivity in the vertical and horizontal directions, the aquifer is anisotropic. If the hydraulic conductivity is essentially the same in all directions, the aquifer is isotropic. While convenient to assume that aquifers are both homogeneous and isotropic, these aquifers are rare.

Transmissivity is related to hydraulic conductivity. Transmissivity is the capacity of an aquifer to transmit water. The transmissivity, T, of an aquifer is equal to the hydraulic conductivity of the aquifer multiplied by the saturated thickness of the aquifer as shown in the following equation:

$$T = Kb \quad \text{(Eq. 5-8)}$$

Where:

T = transmissivity
K = hydraulic conductivity
b = aquifer thickness

Table 5-5 Units of hydraulic parameters of aquifers

Porosity	Unit Cube of Material	Unit Prism of Aquifer
Transmissive capacity	Hydraulic conductivity (K)	Transmissivity (T)
Available storage	Specific Yield (S_y)	Storage coefficient (S)

As with hydraulic conductivity, transmissivity is also defined in terms of a unit hydraulic gradient.

Storage Coefficient

The storage coefficient is the ability of a formation to store and transmit water. These are the formation's most important hydraulic properties. These properties are given either in terms of a unit cube of the material or in terms of a unit prism of an aquifer, depending on the intended use. These abilities, as they relate to the two units of measurement, are shown in Table 5-5 (AWWA, 2003).

The storage coefficient, S, is defined as the volume of water an aquifer releases from or stores per unit surface area of the aquifer per unit change in head. The storage coefficient is a dimensionless unit, as the following equation shows, in which the units in the numerator and the denominator cancel:

$$S = \frac{\textit{volume of water}}{(\textit{unit area})(\textit{unit head change})} \qquad \text{(Eq. 5-9)}$$

The size of the storage coefficient depends on whether the aquifer is confined or unconfined. If the aquifer is confined, the water released from storage when the head declines comes from expansion of the water and from compression of the aquifer. In a confined aquifer having a porosity of 0.2 and containing water at a temperature of about 59°F (15°C), expansion of the water alone releases about 3×10^{-7} m^3 of water per cubic meter of aquifer per meter of decline in head. To determine the storage coefficient of an aquifer caused by expansion of the water, the aquifer thickness must be multiplied by 3×10^{-7}. If only the expansion of water is considered, the storage coefficient of an aquifer 300-ft (100-m) thick would be 3×10^{-5}. The storage coefficient of most confined aquifers ranges from about 10^{-3} to 10^{-5}. The difference between these values and the value caused by expansion of the water is attributed to compression of the aquifer (AWWA, 2003).

Capillarity and Unsaturated Flow

Most recharge of groundwater systems occurs during the percolation of water through the unsaturated zone of soil. This movement of water is controlled by both gravitational and capillary forces. The capillarity forces result from the mutual attraction (cohesion) between water molecules and the molecular attraction (adhesion) between water and different solid materials (AWWA, 2003). Because most pores in granular materials are of capillary size, water is pulled upward into a capillary fringe above the water table to a height, h_c, above the water level. In a steady- state condition or conditions in which the moisture content remains constant, flow of water in the unsaturated zone can be determined from a modified form of Darcy's law, as shown in the following equation:

$$Q = K_e A\left(\frac{h_c - z}{z}\right) \pm \left(\frac{dh}{dl}\right) \qquad \text{(Eq. 5-10)}$$

Where:

Q = the quantity of water
K_e = the hydraulic conductivity under the degree of saturation existing in the unsaturated zone
A = the cross-sectional area through which flow occurs
$(h_c - z)/z$ = the gradient caused by capillary (surface tension) forces
dh/dl = the gradient caused by gravity

The plus/minus sign accounts for the direction of movement: plus for downward and minus for upward. For movement in a vertical direction, either up or down, the gradient caused by gravity is 1. For lateral (horizontal) movement in the unsaturated zone, the gravitational gradient can be eliminated.

Because transmissivity depends on both K and b, its value differs between aquifers and from place to place in the same aquifer. Estimated values of transmissivity for principal aquifers the vs range from less than 1 gpd for some fractured sedimentary and igneous rocks to over 1,000,000 gpd for cavernous limestones and lava flows (AWWA, 2003).

In a related issue regarding transmissivity, Nuzman (1989) accepted that the field coefficient of permeability represents the limit of laminar flow through the formation at a given temperature and viscosity of the water (AWWA, 2003). The limit of laminar flow through the borehole wall is defined by the following equation:

$$Q = \pi dLk \qquad \text{(Eq. 5-11)}$$

This equation assumes uniform vertical flow that does not actually occur in wells. It has been found by field experience that the beginning of turbulent flow through the formation borehole was is approximately 2.35 times the laminar flow limit (AWWA, 2003). Williams (1985) defined the point where the flow transitions from predominately turbulent flow to predominately laminar flow, as

$$r_e = 0.9587\frac{(Q/L)d}{\theta} \qquad \text{(Eq. 5-12)}$$

Where:

r_e = critical radius (in.)
Q/L = specific aquifer discharge (gpm/ft)
Q = discharge rate (gpm)
L = length of screen (ft)
d = mean grain diameter (in.)
θ = effective porosity

It should be noted that Williams (1985) defined the Reynolds number at the point where the flow regime changes from laminar to turbulent as being 30.

Flow volumes can be derived for design purposes from monitoring wells and drawdown information for equilibrium conditions from one of two formulas developed by Theim. For water table aquifers

$$Q = \frac{K(H^2 - h^2)}{1{,}055 \log \frac{R}{r}} \qquad \text{(Eq. 5-13)}$$

Where:

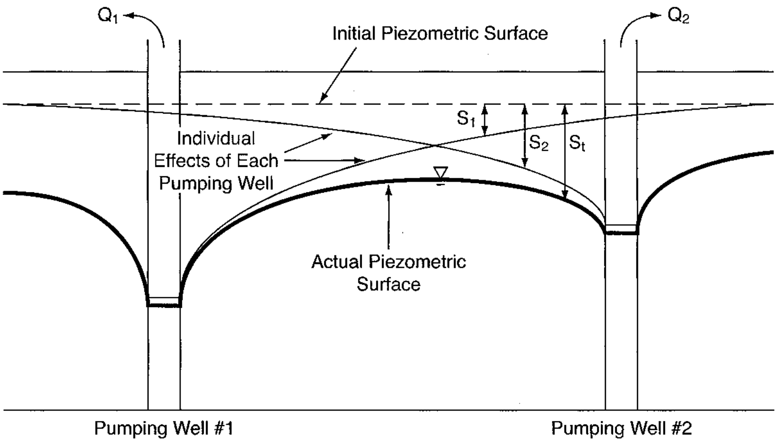
Q = discharge rate (gpm)
r = distance to observation well (ft)
R = borehole diameter (ft)
K = hydraulic conductivity (gpd/ft)
H = drawdown at the borehole
h = drawdown at observation well (ft)

For confined aquifers

$$Q = \frac{Kb(H - h)}{528 \log \frac{R}{r}} \qquad \text{(Eq. 5-14)}$$

Where:

Q = discharge rate (gpm)
r = distance to observation well (ft)
R = borehole diameter (ft)
K = hydraulic conductivity (gpd/ft)
b = formation thickness (ft)
H = drawdown at the borehole
h = drawdown at observation well (ft)



Source: AWWA 2003

Figure 5-1 Interfering drawdowns between wells

WELLFIELD DESIGN (from Bloetscher, et al., 2005)

The proper design of wells and wellfields is possible through measurable field data. A small-diameter test well is usually constructed to ascertain the depth and thickness of the aquifer, a pumping test conducted, and the data analyzed to determine the transmissivity and hydraulic conductivity and if the water quality can be satisfactorily treated. Once the aquifer parameters have been field tested and predesign assumptions resolved with the field findings, the most desirable spacing between wells in a wellfield, the effects of new wells on existing wells, and the optimum pumping rates and schedules can be made. The field tests will provide the parameters for thickness and extent of an aquifer, its transmissivity and storage coefficient, and the nature and location of boundaries. These parameters are very useful when making an overall appraisal of the groundwater resources of an area and the potential for future water supply development.

Wellfield Interference

Possible interference between wells should be determined before locating multiple wells in a well field. Determining interference between pumping wells will allow the design engineer and/or hydrogeologist to optimize spacing and pump capacity to determine the most efficient placement pattern and pumping rates. The total interference drawdowns estimated for various pumping rates are as shown in Figure 5-1.

Pumping Rates

When numerical values have been assigned to transmissivity and the storage coefficient, the drawdown effects of pumping can be determined. These effects are for any quantity of water at any reasonable distance from the pumping well. A graphic representation should be plotted of water levels against the logarithm of distance from the center of pumping for a given time period. A minimum continuous pumping period of 100 days is usually used as a conservative safety factor.

WELL DESIGN

Once the wellfield spacing and pumping rates are determined, the proper design of wells and specification of materials are made. Decisions regarding materials, screened interval length, screen openings, casing and column pipe diameter, and the need for sand or silt removal can be made once the field parameters are understood. A series of calculations must be made to ensure the proper size borehole, casing, screen, and screen spacing are designed. Typically, the client has a need for a specific water yield and well. The designer must bring these inputs together to design a cost effective and efficient well.

Up-hole Velocity

The maximum velocity criteria imposed on withdrawal wells is 10 ft/sec, which affects casing diameters. However, this velocity is too high for many wells because it tends to entrain sand and other particles if proper screening is not provided (see Entrance Velocity section). High velocity will also exert wear on the casing. Theoretical withdrawal velocities and pressures can be calculated for a maximum day flow rate using the following equation (Heald, 1994, p. 3-6):

$$V = \frac{0.4085 \text{x} (gpm)}{d^2} \qquad \text{(Eq. 5-15)}$$

Where:

V = velocity of flow, fps
d = inside diameter of the injection casing, in.
gpm = injection rate, gpm

Friction Loss (from Bloetscher, et al., 2005)

There are also pressure (head) limitations in a well. The total pressure head consists of three components: (1) friction loss (head loss) through the column pipe; (2) head caused by the formation; and (3) the pump driving pressure. The loss of pressure and upward buoyant forces decrease radially from the well. Therefore, the greater the distance from the well, the more the pressure remains in the formation.

Pressure (head) is friction loss through the pipe. Friction losses through a pipe are a function of the diameter of the pipe, the rate of flow through the pipe, and the roughness of the pipe referred to as the *friction factor* (or *coefficient of friction*). The head losses through the pipe are most commonly calculated using the Hazen–Williams formula, as follows (Heald, 1994, p. 3-7):

$$h_f = 0.002083 \times L \times \left(\frac{100}{C}\right)^{1.85} \times \left(\frac{gpm^{1.85}}{d^{4.8655}}\right) \qquad \text{(Eq. 5-16)}$$

Where:

hf = head loss due to friction (ft)
L = length of pipe
C = friction factor for Hazen–Williams (dimensionless)
gpm = flow (gpm)
d = inside diameter of the pipe (in.)

Density Differential (from Bloetscher, et al., 2005)

The density differential is calculated using a derivation of the Ghyben-Herzberg principle, which is stated as follows (Fetter, 1994, p. 370–371):

$$z_{(x,y)} = \frac{\rho_f}{\rho_s - \rho_f} h_{(x,y)} \qquad \text{(Eq. 5-17)}$$

Where:

$z(x,y)$ = depth to the saltwater interface below sea level at location (x,y) (ft)
ρ_f = density of fresh water (g/cm^3)
ρ_s = density of salt water (g/cm^3)
$h(x,y)$ = elevation of the water table above sea level at location (x,y) (ft)

This equation can be converted into the following, more practical, form:

$$h_d = \left(\frac{(\rho_s - \rho_f)}{\rho_f}\right) \times L \qquad \text{(Eq. 5-18)}$$

Where:

h_d = head due to density differential (ft)
ρ_s = density of salt water (g/cm^3)
ρ_f = density of fresh water (g/cm^3)
L = length of column of fresh/salt water (ft)

In this equation, L is comparable to z of the Ghyben-Herzberg equation.

Bottom-Hole Pressure (from Bloetscher, et al., 2005)

As the withdrawal rate increases, the bottom-hole driving pressure (head) from the injection zone decreases. The inverse is also true. The bottom-hole driving pressure (head) is defined as the change in pressure (head) in the formation caused by the withdrawal of the water. The bottom-hole driving pressure (head) is primarily a function of the pumping rate, assuming the following:

- Storage coefficient changes in the aquifer.
- Leakage changes in the aquifer.
- The transmissivity of the aquifer near the borehole is constant and does not change with time as a result of natural and/or man-made phenomena.

The hole-bottom driving pressure would be related to withdrawal rate as follows (Witt and Ameno, 1989, p. 8–10):

$$\frac{h_A}{Q_A} = \frac{h_B}{Q_B} \qquad \text{(Eq. 5-19)}$$

Where:

h_A = bottom-hole driving pressure at the injection rate
h_B = bottom-hole driving pressure at the injection rate of Q_B (psi)
Q_A = injection rate (gpm)
Q_B = injection rate, equation variable (gpm)

Total Dynamic Head (from Bloetscher, et al., 2005)

The total dynamic head (injection pressure) at the well head is calculated by as follows:

$$h_T = h_f + h_d + h_B \qquad \text{(Eq. 5-20)}$$

Where:

h_T = total dynamic head at well head (ft)
h_f = head friction loss (ft)
h_d = head density differential (ft)
h_B = head bottom-hole driving pressure (ft)

The three components were described in the previous 3 sections.

Head-to-Pressure Conversion (from Bloetscher, et al., 2005)

To convert feet of head into psi, the following formula is used (Heald, 1994, p. 2-14):

$$psi = \frac{h \times sp\,gr}{2.31} \qquad \text{(Eq. 5-21)}$$

Where:

psi = pressure (psi)
h = head (ft)
$sp\,gr$ = specific gravity of fluid (water is assumed 1.00)
h = head (ft)

Collapse Strength (from Bloetscher, et al., 2005)

In addition to the requirements of velocity and pressure, adequate surge or water hammer protection to the well must be addressed. The theoretical collapse strength of a well casing is calculated as follows (AWWA, 1964, p. 58):

$$P_a = \left(\frac{2E}{1-\mu^2}\right)\left(\frac{t}{d}\right)^3 \qquad \text{(Eq. 5-22)}$$

Where:

P_a = critical collapse pressure (psi)
E = modulus of elasticity for steel pipe (30,000,000)
μ = Poisson's ratio (usually taken as 0.30 for steel)
d = outside diameter of the pipe (in.)
t = wall thickness of the pipe (in.)

Table 5-6 outlines the collapse strength of steel pipe. Similar tables can be found for PVC and fiberglass.

Water Hammer Analysis (from Bloetscher, et al., 2005)

Adequate surge or water hammer protection must be incorporated into the design of the pumping system. Pressure surges associated with water hammer have been observed at several older and inadequately designed facilities. The potential for water hammer pressures resulting from instantaneous pumping stoppage at maximum rate should be analyzed. Water hammer is calculated using the following equation (AWWA, 1964, p. 62):

$$h = \frac{aV}{g} \qquad \text{(Eq. 5-23)}$$

Where a can be reduced to:

$$a = \frac{4,660}{\sqrt{1+\left(\frac{d}{100e}\right)}} \qquad \text{(Eq. 5-24)}$$

and:

a = wave velocity
h = pressure rise above normal (ft of water)
d = inside diameter of the pipe (in.)
e = thickness of pipe wall (in.)
e = velocity of flow (fps)
e = acceleration due to gravity (32 ft/sec)

Table 5-6 Collapse strength of steel well casing

Nominal Diameter		Wall Thickness			Outside Diameter		Inside Diameter		Weight		Collapsing Strength			
in.	(mm)	in.	in.	(mm)	in.	(mm)	in.	(mm)	lb/ft	(kg/m)	psi	ft water	(kg/cm^2)	(m water)
8	(203)	¼	0.250	(6.35)	8.625	(219.08)	8.125	(206.38)	22.36	(33.28)	755.54	1,745.29	(53.20)	(531.96)
8	(203)	5⁄16	0.3125	(7.94)			8.000	(203.20)	27.74	(41.29)	1,191.21	2,751.70	(83.87)	(838.72)
10	(254)	¼	0.250	(6.35)	10.750	(273.05)	10.250	(260.35)	28.04	(41.72)	461.08	1,065.10	(32.46)	(324.64)
10	(254)	5⁄16	0.3125	(7.94)			10.125	(257.18)	34.84	(51.84)	760.25	1,756.18	(53.53)	(535.28)
12	(304)	¼	0.250	(6.35)	12.750	(323.85)	12.250	(311.15)	33.38	(49.67)	306.09	707.06	(21.55)	(215.51)
12	(304)	5⁄16	0.3125	(7.94)			12.125	(307.98)	41.514	(61.78)	520.68	1,202.78	(36.66)	(366.61)
14	(355)	¼	0.250	(6.35)	14.00	(355.60)	13.500	(342.90)	36.71	(54.64)	242.43	560.02	(17.07)	(170.69)
14	(355)	5⁄16	0.3125	(7.94)			13.375	(339.73)	45.68	(67.98)	418.68	967.15	(29.48)	(294.79)
14	(355)	⅜	0.375	(9.53)			13.250	(336.55)	54.57	(81.21)	636.10	1,469.39	(44.79)	(447.87)
14	(355)	¼	0.250	(6.35)	14.50	(368.30)	14.000	(355.60)	38.05	(56.62)	221.82	512.41	(15.62)	(156.18)
14	(355)	5⁄16	0.3125	(7.94)			13.875	(352.43)	47.35	(70.47)	385.11	889.59	(27.11)	(271.15)
14	(355)	⅜	0.375	(9.53)			13.750	(349.25)	56.57	(84.19)	588.19	1,358.72	(41.41)	(414.14)
16	(406)	¼	0.250	(6.35)	16.00	(406.40)	15.500	(393.70)	42.05	(62.58)	172.25	397.90	(12.13)	(121.28)
16	(406)	5⁄16	0.3125	(7.94)			15.375	(390.53)	52.36	(77.92)	303.15	700.27	(21.34)	(213.44)
16	(406)	⅜	0.375	(9.53)			15.250	(387.35)	62.58	(93.13)	469.53	1,084.62	(33.06)	(330.59)
16	(406)	¼	0.250	(6.35)	16.625	(422.28)	16.125	(409.58)	43.72	(62.58)	155.89	360.11	(10.98)	(109.76)
16	(406)	5⁄16	0.3125	(7.94)			16.000	(406.40)	54.44	(81.02)	275.69	636.84	(19.41)	(194.11)
16	(406)	⅜	0.375	(9.53)			15.875	(403.23)	65.08	(96.85)	429.18	991.40	(30.22)	(302.18)

Table continued next page.

Table 5-6 Collapse strength of steel well casing (continued)

Nominal Diameter		Wall Thickness			Outside Diameter		Inside Diameter		Weight		Collapsing Strength			
in.	(mm)	in.	in.	(mm)	in.	(mm)	in.	(mm)	lb/ft	(kg/m)	psi	ft water	(kg/cm²)	(m water)
18	(457)	¼	0.250	(6.35)	18.00	(457.20)	17.500	(444.50)	47.39	(70.53)	126.48	292.16	(8.90)	(89.05)
18	(457)	5⁄16	0.3125	(7.94)			17.375	(441.33)	59.03	(87.85)	225.76	521.49	(15.90)	(158.95)
18	(457)	⅜	0.375	(9.53)			17.250	(438.15)	70.59	(105.05)	354.92	819.86	(24.99)	(249.89)
18	(457)	¼	0.250	(6.35)	18.625	(473.08)	18.125	(460.38)	49.06	(73.01)	115.51	266.84	(8.13)	(81.33)
18	(457)	5⁄16	0.3125	(7.94)			18.000	(457.20)	61.12	(90.96)	206.95	478.05	(14.57)	(145.71)
18	(457)	⅜	0.375	(9.53)			17.875	(454.03)	73.09	(108.77)	326.64	754.54	(23.00)	(229.98)
20	(508)	¼	0.250	(6.35)	20.00	(508.00)	19.500	(495.30)	52.73	(78.48)	95.46	220.52	(6.72)	(67.21)
20	(508)	5⁄16	0.3125	(7.94)			19.375	(442.13)	65.71	(97.79)	172.25	397.90	(12.13)	(121.28)
20	(508)	⅜	0.375	(9.53)			19.250	(488.95)	78.60	(116.97)	273.98	632.89	(19.29)	(192.90)
20	(508)	7⁄16	0.4375	(11.11)			19.125	(485.78)	91.41	(136.03)	399.05	921.82	(28.10)	(280.97)
20	(508)	¼	0.250	(6.35)	20.625	(523.88)	20.125	(511.18)	54.40	(80.96)	87.86	202.96	(6.19)	(61.86)
20	(508)	5⁄16	0.3125	(7.94)			20.000	(508.00)	67.79	(100.89)	159.00	367.28	(11.19)	(111.95)
20	(508)	⅜	0.375	(9.53)			19.875	(504.83)	81.10	(120.69)	253.68	586.00	(17.86)	178.61
20	(508)	7⁄16	0.4375	(11.11)			19.750	(501.65)	94.33	(140.38)	370.69	856.31	(26.10)	(261.00)
22	(559)	¼	0.250	(6.35)	22.00	(558.80)	21.500	(546.10)	58.07	(86.42)	73.75	170.37	(5.19)	(51.93)
22	(559)	5⁄16	0.3125	(7.94)			21.375	(542.93)	72.38	(107.72)	134.22	310.05	(9.45)	(94.50)
22	(559)	⅜	0.375	(9.53)			21.250	(539.75)	86.61	(128.89)	215.46	497.71	(15.17)	(151.70)
22	(559)	7⁄16	0.4375	(11.11)			21.125	(536.58)	100.75	(149.94)	316.88	732.00	(22.31)	(223.11)

Table continued next page.

Table 5-6 Collapse strength of steel well casing (continued)

Nominal Diameter		Wall Thickness			Outside Diameter		Inside Diameter		Weight		Collapsing Strength			
in.	(mm)	in.	in.	(mm)	in.	(mm)	in.	(mm)	lb/ft	(kg/m)	psi	ft water	(kg/cm^2)	(m water)
22	(559)	¼	0.250	(6.35)	22.50	(571.50)	22.000	(558.80)	59.41	(88.41)	69.37	160.25	(4.88)	(48.84)
22	(559)	5/16	0.3125	(7.94)			21.875	(555.63)	74.05	(110.20)	126.48	292.16	(8.90)	(89.05)
22	(559)	⅜	0.375	(9.53)			21.750	(552.45)	88.61	(131.87)	203.44	469.94	(14.32)	(143.24)
22	(559)	7/16	0.4375	(11.11)			21.625	(549.28)	103.09	(153.41)	299.84	692.62	(21.11)	(211.11)
24	(610)	¼	0.250	(6.35)	24.00	(609.60)	23.500	(596.90)	63.41	(94.37)	58.13	134.28	(4.09)	(40.93)
24	(610)	5/16	0.3125	(7.94)			23.375	(593.73)	79.06	(117.65)	106.51	246.04	(7.50)	(74.99)
24	(610)	⅜	0.375	(9.53)			23.250	(590.55)	94.62	(140.81)	172.25	397.90	(12.13)	(121.28)
24	(610)	7/16	0.4375	(11.11)			23.125	(587.38)	110.10	(163.84)	255.34	589.84	(17.98)	(179.78)
24	(610)	¼	0.250	(6.35)	24.50	(622.30)	24.000	(609.60)	64.75	(96.36)	54.92	126.88	(3.87)	(38.67)
24	(610)	5/16	0.3125	(7.94)			23.875	(606.43)	80.73	(120.14)	100.79	232.82	(7.10)	(70.96)
24	(610)	⅜	0.375	(9.53)			23.750	(603.25)	96.62	(143.79)	163.26	377.13	(11.49)	(114.95)
24	(610)	7/16	0.4375	(11.11)			23.625	(600.08)	112.43	(167.32)	242.43	560.02	(17.07)	(170.69)
26	(660)	¼	0.250	(6.35)	26.00	(660.40)	25.500	(647.70)	68.75	(102.32)	46.61	107.67	(3.28)	(32.82)
26	(660)	5/16	0.3125	(7.94)			25.375	(644.53)	85.73	(127.59)	85.88	198.38	(6.05)	(60.47)
26	(660)	⅜	0.375	(9.53)			25.250	(641.35)	102.63	(152.73)	139.73	322.78	(9.84)	(98.38)
26	(660)	7/16	0.4375	(11.11)			25.125	(638.18)	119.44	(177.75)	208.48	481.59	(14.68)	(146.79)
26	(660)	¼	0.250	(6.35)	26.50	(673.10)	26.000	(660.40)	70.09	(104.30)	44.21	102.13	(3.11)	(31.13)
26	(660)	5/16	0.3125	(7.94)			25.875	(657.23)	87.40	(130.07)	81.56	188.41	(5.74)	(57.43)
26	(660)	⅜	0.375	(9.53)			25.750	(654.05)	104.63	(155.71)	132.89	306.97	(9.36)	(93.56)
26	(660)	7/16	0.4375	(11.11)			25.625	(650.88)	121.78	(181.23)	198.55	458.66	(13.98)	(139.80)

Table continued next page.

Table 5-6 Collapse strength of steel well casing (continued)

Nominal Diameter		Wall Thickness			Outside Diameter		Inside Diameter		Weight		Collapsing Strength			
in.	(mm)	in.	in.	(mm)	in.	(mm)	in.	(mm)	lb/ft	(kg/m)	psi	ft water	(kg/cm²)	(m water)
28	(711)	¼	0.250	(6.35)	28.00	(711.20)	27.500	(698.50)	74.09	(110.26)	37.94	87.63	(2.67)	(26.71)
28	(711)	5/16	0.3125	(7.94)			27.375	(695.33)	92.41	(137.52)	70.22	162.21	(4.94)	(49.44)
28	(711)	⅜	0.375	(9.53)			27.250	(692.15)	110.64	(164.65)	114.83	265.25	(8.08)	(80.85)
28	(711)	7/16	0.4375	(11.11)			27.125	(688.98)	128.79	(191.66)	172.25	397.90	(12.13)	(121.28)
28	(711)	¼	0.250	(6.35)	28.50	(723.90)	28.000	(711.20)	75.43	(112.25)	36.11	83.41	(2.54)	(25.42)
28	(711)	5/16	0.3125	(7.94)			27.875	(708.03)	94.08	(140.00)	66.91	154.55	(4.71)	(47.11)
28	(711)	⅜	0.375	(9.53)			27.750	(704.85)	112.64	(167.63)	109.53	253.02	(7.71)	(77.12)
28	(711)	7/16	0.4375	(11.11)			27.625	(701.68)	131.12	(195.14)	164.51	380.01	(11.58)	(115.83)
30	(762)	¼	0.250	(6.35)	30.00	(762.00)	29.500	(749.30)	79.43	(118.21)	31.28	72.26	(2.20)	(22.02)
30	(762)	5/16	0.3125	(7.94)			29.375	(746.13)	99.08	(147.45)	58.13	134.28	(4.09)	(40.93)
30	(762)	⅜	0.375	(9.53)			29.250	(742.95)	118.65	(176.57)	95.46	220.52	(6.72)	(67.21)
30	(762)	7/16	0.4375	(11.11)			29.125	(739.78)	138.13	(205.57)	143.85	332.20	(10.13)	(101.28)
30	(762)	½	0.500	(12.70)			29.000	(736.60)	157.53	(234.44)	203.44	469.94	(14.32)	(143.24)
30	(762)	¼	0.250	(6.35)	30.50	(774.70)	30.000	(762.00)	80.77	(120.20)	29.86	68.99	(2.10)	(21.03)
30	(762)	5/16	0.3125	(7.94)			29.875	(758.83)	100.75	(149.94)	55.55	128.31	(3.91)	(39.11)
30	(762)	⅜	0.375	(9.53)			29.750	(755.65)	120.65	(179.55)	91.31	210.91	(6.43)	(64.29)
30	(762)	7/16	0.4375	(11.11)			29.625	(752.48)	140.47	(209.04)	137.73	318.15	(9.70)	(96.97)
30	(762)	½	0.500	(12.70)			29.500	(749.30)	160.20	(238.41)	194.99	450.43	(13.73)	(137.29)

Well Losses

Drawdown values obtained for a single pumping well using the Theim formulas represent only the head losses suffered by water movement through the formation under laminar flow conditions. The actual pumping level of a particular well cannot be calculated without considering high velocities and turbulence losses during pumping. At and near the well face, fluid velocities may become large enough that turbulent flow conditions exist. The magnitude of turbulence losses varies with each well because of differences in formation characteristics, screen slot sizes required, degree of well development, well diameter, and quantity of water being pumped. There are so many unknown quantities involved in the calculation of these individual factors that they are usually lumped together under the heading of *well losses*.

One method of approximating the well losses for a particular well is to use the step-drawdown equation as defined by Equation 4-5. The values of B and C (formation and well losses) may be calculated if proper test data are available. To collect such data, the finished well must be pumped at three to five increasing rates for equal periods of time and the drawdown measured for each pumping rate. When a full-scale aquifer performance test is not conducted, however, a step-drawdown test can differentiate the observed losses in the pumping well. Additionally, this test makes it possible to quickly compare the magnitude of well losses to determine when a well needs cleaning or other repair work. Irregular increasing well loss with increasing pumping rates indicates unsatisfactory development of a new well, or deteriorating aquifer or well conditions in an old well. Small regular increases in well loss or decrease in well specific capacity as a result of transition to turbulent flow in the aquifer are normal.

Entrance Velocity

Water entrance velocities through the screen openings should be between 0.1 and 0.2 ft/sec (0.03 and 0.06 m/sec). Such velocities will minimize head losses and chemical precipitation. For design of well screens installed in a radial collector well, an average velocity of about 0.033 ft/sec (0.01 m/sec) is used. Screen entrance velocities are computed by

$$V = Q/A \qquad \text{(Eq. 5-25)}$$

Where:

V = velocity, in ft/sec
Q = well capacity, in ft^3/sec ($1\ ft^3/sec = 449$ gpm)
A = effective area of screen, in ft^2

The effective screen area must be estimated carefully. It is standard practice to assume that 50 percent of the screen slots are plugged by particles after proper well development. The total open area required must be determined by adjusting either the length or diameter of the screen, because the slot size is not arbitrary.

A significant factor in well loss for sand and gravel wells is an open screen area when the percentage of open area is substantially less that the specific yield of the aquifer. Research by Williams (1985) has shown that when the open area of the screen is greater than the specific capacity of the formation, the actual head loss across the well screen is insignificant until the velocity through the screen exceeds 2 ft/sec (0.6 m/sec). In an attempt to limit turbulent flow losses around the well borehole, many regulatory agencies have prescribed screen velocities between 0.1 and 0.2 ft/sec (0.03 and 0.06 m/sec) and a minimum thickness of gravel pack resulting in large-diameter well construction. High velocity turbulent flow through the formation borehole results in higher pumping and maintenance costs. In this case, velocity is a function of quantity and area and is easily approximated in the design stage. For membrane applications where sand may become an operational problem, the velocity should be reduced.

BASIC DESIGN DECISIONS

Once the previous calculations have been made, the design engineer can evaluate the materials and sizing of the components. In choosing a supply well diameter, the minimum casing and screen diameter should be at least one pipe-size larger than the largest diameter of the pumping equipment to be installed. This gap allows adequate space for pump installation and removal, efficient pump operation, and good hydraulic efficiency of the well. If a shroud needs to be installed around a submersible pump and motor, appropriate allowance in diameter needs to be made. If additional equipment is to be installed, such as a transducer or water-level controls, then an increase of two pipe-size diameters may be needed.

Because the quantity of water to be pumped from a well, Q, is more correctly established using formation loss and well interference, the open area of screen is the basic parameter to consider. Screen slot size should be selected for accurate sampling and proper sieve analysis. Thus, the screen diameter and length are the two variables in design. Screen-length selection should incorporate more than a casual recollection of the aquifer thickness. The definition of transmissivity, T, incorporates flow through the total thickness of water-bearing material. If less than the total thickness is used, the value of T should be decreased. The Theis equation indicates that as T decreases, the formation drawdown will increase, although not in direct proportion. If the screened portion of the formation is significantly less than one half of the formation thickness (partial penetration), the additional drawdown suffered may be significant. Therefore, it is recommended that as much of the aquifer as practical should be screened to minimize reduction in yield.

If gravel pack construction is used, the borehole should meet minimum thickness requirements of 4 in. (16 mm) larger than the screen as specified in

AWWA Standard A100-06. If the average hydraulic conductivity, length of well screen and minimum borehole diameter, and the limit of borehole diameter are input, the limit of laminar flow can quickly be calculated. This value may appear to be very low. A flow yield of approximately 4 to 6 times the laminar flow rate may be cost effective. So some high-capacity wells may be operated in the turbulent flow range but may not be permitted by regulatory agencies. The gravel pack thickness can be increased to the available yield. Unfortunately, in low permeability aquifers, the maximum practical well borehole diameter will limit the water yield. Other limitations such as saturated thickness, available drawdown, and static water-level depths affect the available yield.

The well casing material and grout used in the construction of each newly drilled well must be designed for the life expectancy of the well. The type of pump installed should provide optimal service over a prescribed number of years, when pumping under specific conditions. Before selecting a pump, different types of pumping arrangements should be investigated to ensure the ultimate needs are met. For instance, vertical turbine pumps should not be used when the treatment involves membranes as the entrainment of oxygen at start-up may encourage fouling of the membranes.

There are a number of pumping options.

- Piston pumps are low capacity wells used for hand-pumped wells. They do not meet the needs of public water systems.
- Ejector pumps are small pumps widely used for private home wells. They do not have sufficient capacity to meet the needs of most public water systems.
- Suction pumps work on the principle of creating a vacuum and to pull the water up to the pump level. This type of pump can only be used with relatively shallow wells because the principles of physics limit suction to about 21 ft.
- Turbine well pumps are commonly used for water supply wells. They have a vertical shaft motor located at the ground surface and a long drive shaft extending down the well to operate the pump suspended below the water level. Turbine pumps are available in a wide variety of capacities, can be designed to produce almost any desired pressure, and the motor is easily accessible at the surface for maintenance and repair as well.
- Submersible pumps combine a turbine pump with a waterproof motor. Submersible pumps are located at the bottom of the column-pipe well down the borehole. The pumps require a discharge pipe, power wires, and a lifting cable. Submersible pumps are made in sizes ranging from small pumps used for private home wells to very large units for public water systems. These pumps are very common and provide long useful lives efficiently.

Throttling pumps to match flow demands will cause the systems to run at very low efficiency during low demand periods. To address the problem for continuous operation, a pressure-regulating valve or variable-speed drive is used that can match the pump output with the system demand. The overall cost of equipment and operation should be thoroughly analyzed before adopting such a system. Electric motors are usually selected according to National Electrical Manufacturers' Association standards, which include requirements for enclosures and cooling methods.

Pump selection should ensure that over-pumping of the aquifer, and damage to the casing, pump, formation, and column pipe is minimized. Pumps are available in steel, stainless steel, and bronze. Bronze pumps tend to be resistant to microbiological fouling, while stainless steel and steel may pose problems. Well and pump screens should be installed at the discretion of the hydrogeologist. Additionally, the well must be properly designed and developed before installing the production pump to minimize sand pumping. Often submersible pumps are used. Submersible pump usage requires

- Settings that prevent motor burial in sand or silt,
- Water temperature and flow past the motor to provide proper cooling,
- Use of cable and splices that meet the amperage and voltage requirements,
- Pipe tightening to prevent unscrewing by motor-starting torque,
- Clamping of cable to delivery pipe,
- Proper controls and protections,
- Necessary checks before, during, and after installation, and
- Adequate electrical power and backup.

A submersible pump is actually a turbine pump with its motors close-coupled beneath the bowls of the pumping unit and installed within the well under the minimum expected water-level point. This construction eliminates the need for the surface motor, long drive shaft, shaft bearings, and lubrication system of the conventional turbine pump. Submersible pump motors are cooled by water flowing vertically past the motor to the pump intake. The motor is usually longer and of smaller diameter than a surface motor of the same horsepower. When a large-capacity submersible pump is needed, the manufacturer should be consulted for specific design and installation recommendations.

The costs for a submersible pump depend on setting depth, required head and capacity, corrosion resistance, and other factors. Operating costs will depend on motor efficiency, column bearing, hydraulic losses, cable losses, setting depth, and similar factors. A thorough analysis of all factors should be performed to compare surface and submersible motor-driven deep-well pumps for a specific installation. Submersible pumps are especially useful for high-head, low-capacity applications, such as domestic water supply.

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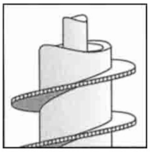


6

Well Construction and Development

The components common to most wells include well casings, cementing or grouting of wells, well screens, gravel packs, and sanitary seals. Considerations for these components include material specifications, sizing, and most important, the depth of the casing/screen to allow the appropriate water source into the well. Once the well is completed, it must be developed. Development may be the most overlooked issue in well construction, but good development practices will provide an efficient well with long life and low maintenance costs.

CASINGS

Purpose of Casings

There are two main purposes for the casing. The first is to provide structural reinforcement and stabilization for the borehole. Casings also serve to seal out contaminated water from the land surface and undesirable water from formations above the aquifer. A third benefit of the casing is to identify construction parameters (i.e., well diameter, screen length, etc.) that are used to establish baseline data for determining the optimum pumping rates given other aquifer parameters and logging results. This initial information is used to establish baseline conditions for future evaluation of pump and well performance.

Setting the Casing (from AWWA, 2003)

Setting the casing is related to the drilling method used to construct the borehole. There are five basic methods for setting the casing

1. Driving
2. Vibrating
3. Cable tool
4. Dual tube
5. Rotary

Table 6-1 Casing sizes for small wells based on yield

Yield*	Recommended Casing Diameter (in.)	Jet	Drilling Method Double Jet	Submersible
Less than 8 gpm	2	√	√	
	3	√	√	√
	4	√	√	√
	5		√	√
	6			√
8 to 16.5 gpm	2	√	√	
	3	√	√	√
	4	√	√	√
	5		√	√
	6			√
Greater than 16.5 gpm	3	√		
	4	√	√	√
	5		√	√
	6			√

*Yield at 50 ft of drawdown

Driving the casing has the benefit of not requiring grouting, but it is limited to softer rock and soil formations and limited depth. Jetted wells or well-points are such examples. When drilling a well using the cable-tool method, the casing should be driven when the ground formation could begin caving. A drive shoe, attached to the lower end of the casing, keeps the hole from collapsing. Drive shoes are threaded or machined to fit the pipe or casing, and the inside shoulder of the shoe butts against the end of the pipe. Drive shoes are forged of high-carbon steel, without welds, and are hardened at the cutting edge to withstand hard driving. Some regulatory agencies do not accept casings that are not cemented in place because they do not positively seal the borehole. Table 6-1 shows casing sizes and pump types for small wells.

Casings are driven using drilling tools, drive clamps, and a drive head. Where the well penetrates water-bearing rock underlying unconsolidated material, the casing is driven into the rock to obtain a good seal. Unfortunately, a tight seal that will prevent pollution or unconsolidated material from entering the well from above is not guaranteed, so a grouted seal is usually required. A length of casing is attached to the casing previously installed by threaded coupling or welding. A drive head is then attached to the upper end of the casing to protect it from the driving blows of the drive clamp, which is attached to the drill stem. When the drill is lowered into the length of casing and subsequently raised and lowered, the action of the dropping clamp on the drive head forces the casing into the drill hole. The concept is similar to drilling the well and uses the same drilling rigs. Additional protection can be gained by driving the casing down to stable rock and under-reaming the borehole beneath the casing to a diameter 2 in. (50 mm) larger than the outside diameter of the shoe for a depth of 10 ft (3 m) below the casing.

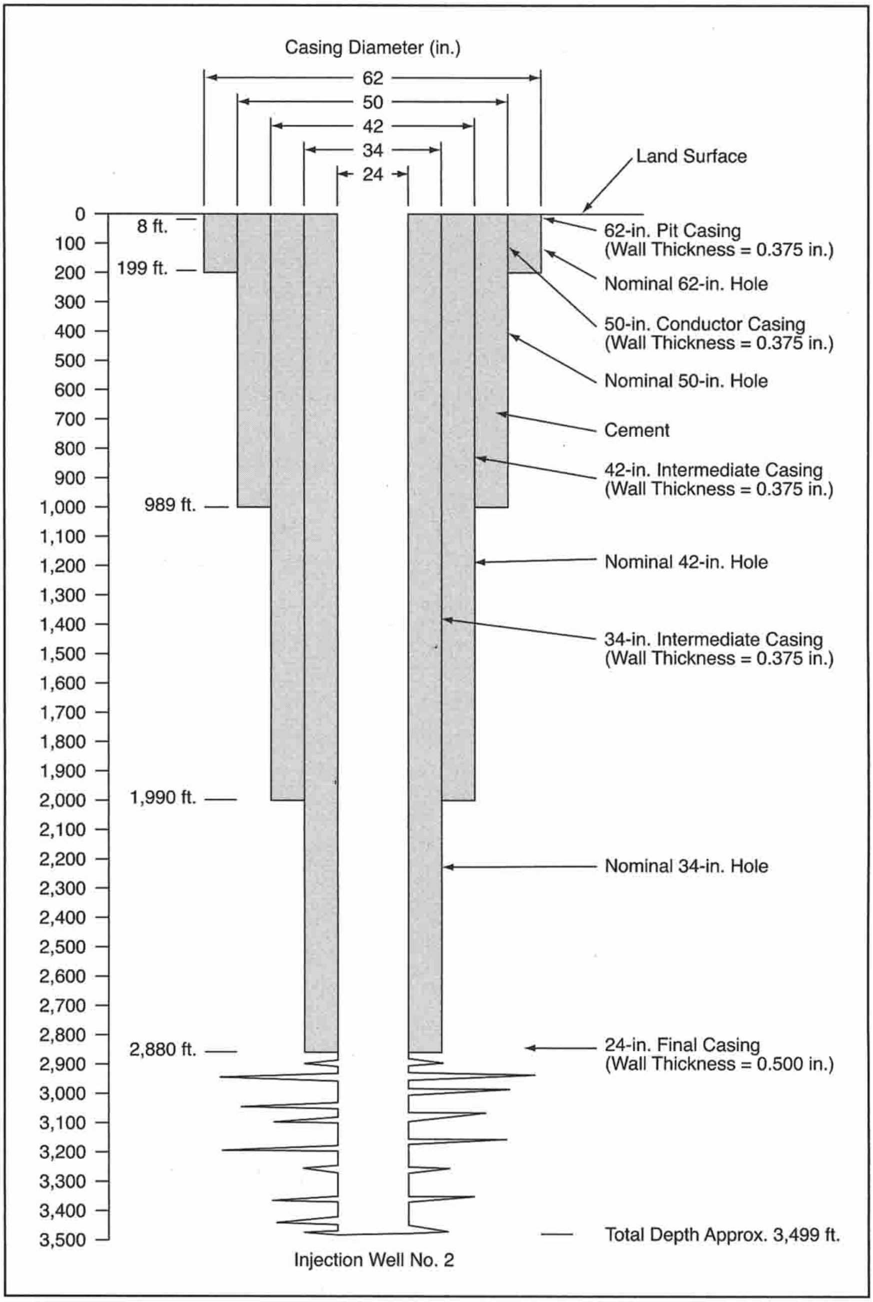
The under-reamed portion of the drill hole is filled with cement grout, and the casing driven to the bottom of the hole. Before drilling is resumed, the cement grout is allowed to set for several days, providing a good seal. Once drilling is restarted, the cement inside the casing is drilled out. An open, uncased hole is constructed in the water-bearing rock below this point. Vibrating the casing into the aquifer does not require cementing; however, the same limitations that apply to driven casings also apply to vibrating casings into place.

While cable-tool methods limit data collection on the formation because the casing is immediately installed, dual tube and rotary methods minimize disruption of the aquifer when setting the casing. For collection of geophysical data, rotary methods are the preferred method for setting the casing. Wells constructed using rotary methods are not usually cased until drilling is completed. Because the casing is smaller than the drilled hole, no driving is required. In some instances, a casing is installed concurrently with drilling, such as with the use of dual-rotary drilling methods.

Types of Casings

The well casing is a lining for the drilled hole that maintains the open hole from the land surface to the water-bearing formation. For the casing to be entirely effective, it must be constructed of suitable materials and be properly installed so as to be watertight for its entire depth. If the formation could likely cave over the full depth of the well, a single casing is usually sufficient. In these situations, the sand and gravel caves in around the outside of the casing and closes the space between the drill hole and the casing. However, single casings are usually restricted to smaller, surficial wells. In deeper wells, it is preferable to have multiple casings as this makes drilling easier in formations that may collapse. Likewise, using multiple casings may be desirable in aquifers that are corrosive or polluted.

If one or more outer casings are installed in a well, the annular space between the casings is filled with cement grout. With this type of installation, the outer casing may be either left in place or withdrawn completely. If withdrawn, the grout is placed as the temporary casing is removed. Each outer casing is generally one pipe-size larger in diameter than the outside diameter of the couplings of the protective casing. This type of grouted installation may also be used where the water-bearing formation underlies clay, hardpan, or other stable formations.



Source: Hazen and Sawyer, P.C., Boca Raton, Fla.

Figure 6-1 Telescoped well

There are several types of casing (pit, surface, intermediate, final, and tubing). A pit casing is the initial casing installed at the surface to prevent the introduction of contaminants from the surface and provide containment for the drilling operation at the surface. The pit casing should be steel and extend through the surface soils. The surface casing is the next casing installed. The surface casing typically seals the surficial formation from the rest of the well. The surface casing is not used for water table aquifers because the surface formation is the aquifer. A series of intermediate casings may be installed to seal off successive formations where the water is not desired or not available. Each successive casing is 6 in. smaller than the prior casing.

Figure 6-1 shows an example of a well with a series of casings. This concept is referred to as *telescoping*. The final casing string is the one that seals off all formations except the one where the water is desired. The final casing will be filled with the water to be withdrawn. The column pipe and pump is installed inside the final casing.

In fractured formations, care should be taken to identify where there are connections to poorer quality water sources than those desired for water supply or polluted water as a result of vugs and fractures in the formation. It is preferable to use these formations only where a competent layer of low-permeability rock overlays the aquifer. Under such circumstances, the well can be protected if it is watertight to a depth greater than that of the deepest existing well of questionable construction in the area and substantially below the lowest anticipated water level. The watertight construction is achieved by drilling the hole in the fractured rock 2 in. (50 mm) larger than the outside diameter of the casing couplings and filling the annular space between the drill hole and the outside of the casing with cement grout. In some areas, such construction may not be realistic because available water is cased-off. Other methods of assuring adequate water quality protection may be necessary.

Casing Materials

Casings are usually one of four materials: carbon steel, stainless steel, fiberglass, or PVC. Fiberglass and PVC have been used extensively in recent years for installations in shallow wells or where corrosion and/or bacteria may be an issue. Ingot iron is used in constructing gravel-wall wells or other large-diameter wells. In selecting a suitable material, the stress that the casing experiences during installation and the corrosiveness of the water and soil must be considered. All casings will provide satisfactory service given the correct groundwater and stress environment.

Many grades of casings are available, so specifying casings must include more than the nominal diameter of the casing. Tables 6-2 through 6-6 show examples of the standard casing sizes for steel, fiberglass, and PVC as outlined in AWWA Standard A100-06. Carbon and stainless steel are the most common casing materials (see Figure 6-2). Carbon steel has a number of benefits that make it useful:

Table 6-2 Wall thickness for steel casing

Nominal Size (in.)	Casing Diameter (in.) Wall Thickness (in.)		Wall Thickness (in.)	Weight (lb/ft)	
	External	Internal		Ends	Collars
2	2.375	2.067	0.154	3.560	3.710
2.5	2.875	2.469	0.203	5.790	5.880
3	3.500	3.068	0.216	7.580	7.670
3.5	4.000	3.548	0.226	9.110	9.270
4	4.500	4.026	0.237	10.790	11.010
5	5.563	5.047	0.250	14.620	14.900
6	6.625	6.065	0.250	18.970	19.330
8	8.625	8.071	0.250	27.700	25.400
10	10.750	10.192	0.279	31.200	32.200
12	13.750	12.090	0.330	43.770	45.400
14	14.000	13.250	0.375	54.570	55.800
16	16.000	15.250	0.375	62.580	64.080
18	18.000	17.250	0.375	70.590	72.370
20	20.000	19.250	0.375	78.600	80.700

Source: AWWA A100-06 Standard for Water Wells

Table 6-3 Steel well casings fabricated from standard plates

Diameter (in.)	Standard Plate		Well Casing Sheets	
	Thickness (in.)	Gauge	Thickness (in.)	Gauge
6	0.1046	12	0.1094	12
8	0.1046	12	0.1094	12
10	0.1046	12	0.1094	12
12	0.1345	10	0.1406	10
14	0.1644	10	0.1406	10
16	0.1644	8	0.1719	8
18	0.1644	8	0.1719	8
20	0.1644	8	0.1719	8
22	0.2500	—	—	10*
24	0.2500	—	—	10*
30	0.2500	—	—	8*

*Double Thick

ability tos weld, high yield and tensile strength, and high burst strength. Carbon steel provides the most amount of protection against borehole collapse because the strength of the material is greater than fiberglass and PVC. However, carbon steel is subject to corrosion from galvanic and microbial contamination. Therefore, careful consideration to the materials used in the well must occur to limit galvanic action.

Table 6-4 Fiberglass casing sizes

Nominal Size (in.)	Casing Diameter (in.)		Wall Thickness (in.)	Weight (lb/ft)	Pressure Rating—Internal (psi)
	External	Internal			
Future Pipe Industries, Inc., Red Box 1500					
4	3.75	3.33	0.21	2.3	1,500
5½	4.96	4.42	0.27	3.8	1,500
6⅝	6.10	5.43	0.34	5.7	1,500
7	6.97	6.21	0.38	6.9	1,500
10¾	9.94	8.85	0.54	15.3	1,500
13⅜	13.29	11.97	0.66	23.7	1,500
16	16.08	14.48	0.80	35.0	1,500
Burgess Well Company, Inc. "EON" Fiberglass Column Pipe					
4	5.00	4.50	0.250	4.5	400
6	6.625	6.00	0.310	5.8	400
8	8.625	8.00	0.310	7.8	300
10	12.75	10.00	0.375	10.5	250
12	12.75	12.00	0.375	12.6	225

Table 6-5 Small diameter PVC casing sizes—SCH 80

Nominal Size (in.)	Outside Diameter (in.)	Inside Diameter (in.)	Minimum Wall Thickness (in.)
1.5	1.900	1.720	0.090
2.0	2.375	2.149	0.113
2.5	2.875	2.601	0.137
3.0	3.500	3.166	0.177
4.0	4.500	4.072	0.214

Table 6-6 Large diameter PVC casing sizes—SCH 40

Nominal Size (in.)	Outside Diameter (in.)	Inside Diameter (in.)	Minimum Wall Thickness (in.)
5	5.563	5.047	0.258
6	6.625	6.065	0.280
8	8.625	7.981	0.322
10	10.750	10.020	0.365
12	12.750	11.938	0.406

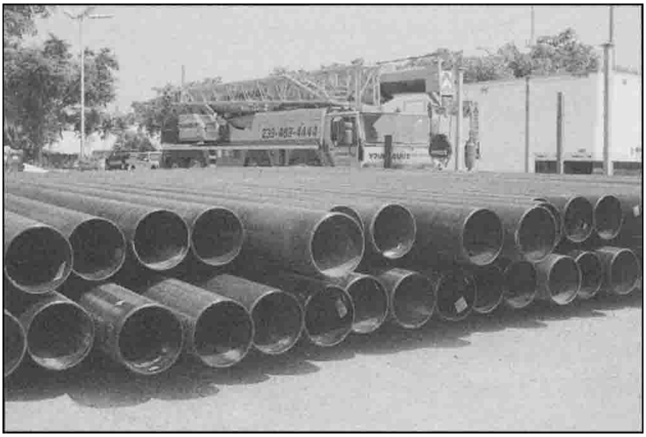


Figure 6-2 Steel casing materials

Aquifers with high microbial populations or high chlorides may not be appropriate for steel casings.

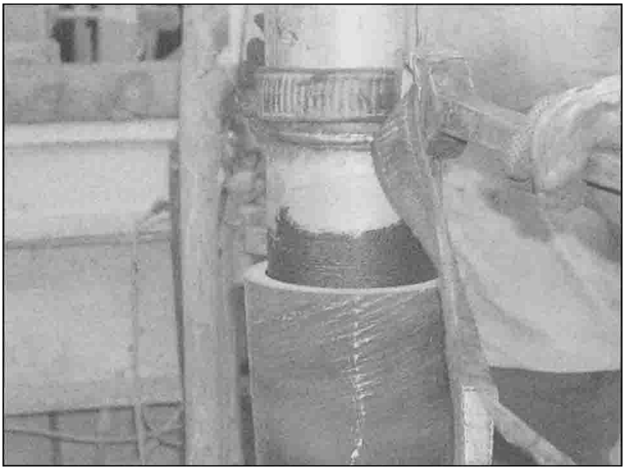
Stainless steel has the same benefits as carbon steel. Stainless steel is an upgrade that attempts to solve the corrosion problems but is still subject to both galvanic and microbial contamination. In some cases, the stainless steel may be more susceptible to microbial contamination. It is also significantly more expensive that the other options.

Fiberglass is lightweight and corrosion resistant (see Figure 6-3)—neither galvanic nor microbiological activity will damage it. Fiberglass is less expensive than steel. However, fiberglass has less burst, tensile, and yield strength than steel, so deeper wells are unlikely to use fiberglass casings (column pipes may also be fiberglass).

PVC is the least costly and lightest weight of the potential casing options (see Figure 6-4). Its use is becoming the more common in shallow wells as it is not subject to corrosion or microbiological attack. Galvanic activity is not a factor. PVC has less burst, tensile, or yield strength than steel or fiberglass. Care must be taken during construction of wells with PVC as the heat created during the grouting operation may buckle PVC casings.

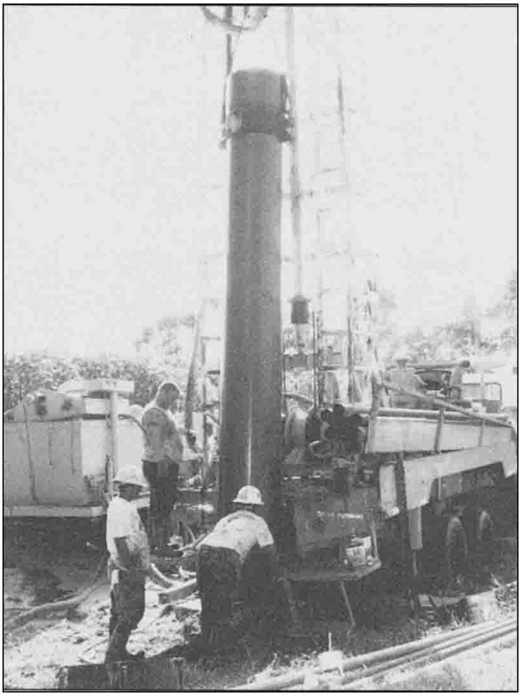
The lighter materials (PVC and fiberglass) may be used for test wells or temporary casings. Temporary casings may be used as forms when a grout seal is placed around the outside of the permanent casing. The temporary casing is withdrawn as the grout seal is placed.

Joints for permanent casings should have threaded couplings or should be welded (in the case of steel—see Figure 6-5) to ensure water-tightness from the



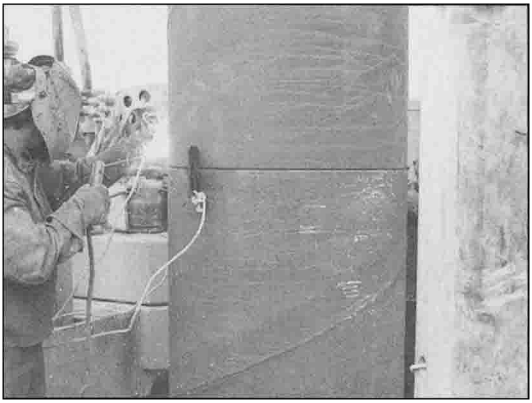
Source: John Largey

Figure 6-3 Fiberglass casing materials



Source: John Largey

Figure 6-4 PVC casing being installed



Source: John Largey

Figure 6-5 Welding a casing pipe

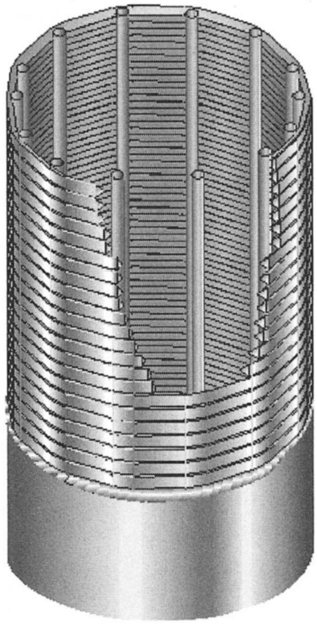
bottom of the casing to a point above grade. This precaution will prevent surface contamination or undesirable groundwater from entering the well from formations above the water-bearing formation through the casing.

SCREENS

Once the casing is placed and grouted in place, the column pipe and screen, if required, are placed. Screens are needed in most wells, especially where sand and fine materials may enter the borehole. The screen is designed to eliminate fine particulates that may damage downstream pumps and treatment equipment, while allowing the maximum amount of water from the aquifer to enter the well with a minimum of resistance. Generally, wells completed in unconsolidated formations, such as sands and gravels, are equipped with screens. In competent rock that will not release fines, such as limestone or granite, screens may not be required. Screens are sometimes installed in fractured formations that may collapse into the borehole and trap equipment.

Although a screen prevents sand from entering the well during pumping, a screen may allow fine formation particles to enter the well during the development process so they may be removed by bailing. At the same time, the large particles of sand are held back, forming a permeable, graded natural-gravel pack around the well screen itself. In this way, the hydraulic conductivity of the water-bearing formation around the well screen is greatly increased, resulting in lower velocity head loss and higher capacity per foot of drawdown.

Proper screen selection is extremely important in the design of a well drawing from unconsolidated aquifers. Selection is often a complicated matter that demands



Source: Variperm (Canada) Limited
Figure 6-6 Well screen

a highly specialized knowledge of well construction and operation. The size of screen openings, or the slot number, is usually expressed in thousandths of an inch. Screens have many sizes of openings, as shown in Figure 6-6. The proper screen slot size is determined through

- Collection and analysis of representative samples of the formation to be used for water production;
- Identification of the lithologic properties of the formation; and
- Laboratory analysis of grain-size gradation.

The width of the slot, or slot size, is best determined using a mechanical sieve analysis of a sample from the water-bearing formation. Representative samples of the formation must be selected for mechanical grain-size analyses. The largest slot opening practical is normally specified, subject to meeting the goals of maximizing the amount of water withdrawn while minimizing screen losses and the introduction of fines. Depending on the type of well construction, the slot size is selected to permit a percentage of the formation material to pass through it. For naturally developed wells, this amount usually ranges between 35 percent and 65 percent, depending on uniformity of the material and the overlying formation (AWWA, 2003).

The design criteria for water entering through the screen opening that has been adopted by many regulatory agencies for well construction is between 0.1 and 0.2 ft/sec (0.03 and 0.06 m/sec). The very low screen velocity criteria promoted the use of large-diameter well screens and more efficient well construction. However, research indicates that the actual head loss across the screen is minimized as long as the thickness of the well screen and the percentage of open area in the screen is equal to or greater than the specific yield of the aquifer, until the flow velocity through the screen exceeds 2 ft/sec (0.6 m/sec) (Williams, 1985). Therefore, the most important factor is the degree of turbulent flow that may be generated in the water flow through the formation and gravel-pack material surrounding the well screen.

Turbulent flow head losses around the borehole increase by the velocity squared. In laminar flow conditions, the head loss is linear with the velocity. In properly constructed and properly developed wells of high capacity, the well loss in head can be quite significant because of the turbulent flow in the well screen. Turbulent flow causes movement of sand particles, mechanical plugging of the gravel pack, as well as mechanical blockage and chemical precipitation of minerals around the outside of the well screen.

GRAVEL PACKS

All gravel-packed wells have screens. A gravel pack is included to act as a filter to permit the use of larger slot sizes in the well screen than would be possible if the area surrounding the screen were not gravel-packed. When a well screen is surrounded by an artificial gravel wall, the size of the openings is controlled by the size of gravel used and by the types of openings.

A gravel-wall well must be carefully designed. Table 6-7 outlines the typical grain sizes used in gravel packs. Selection of the gravel pack material is dependent on the aquifer formation. The material used in the gravel filter must be clean, washed gravel composed of well-rounded particles. Like the screen, the intent of the gravel pack is to prevent fines from plugging the screen or entering the borehole in large quantities. Gravel packs can consist of pea gravel, sand, or other rock. The filter size depends on the size of the natural formation and the intended slot openings of the well screen. Without proper gravel size, fine sand will not be prevented from entering the well, and the yield of the well will be reduced. The size of individual grains of gravel filter material should be four to six times larger than the median size of the natural material. At the same time, the uniformity coefficient of the gravel treatment should be similar to that of the formation material. The slot size for the screen should retain 90 percent of the pack material. An artificial gravel-pack filter can also be installed around the lateral well screens in a radial collector well to match finer-grained formation materials. Figure 6-7 shows a grain size curve for two materials Material A is much more uniform than Material B and preferable in a gravel pack.

Table 6-7 Various size grade scale in common use

Udden-Wentworth	Values	German Scale (after Atterberg)	USDA and Soil Science Society of America	USCOE and Bureau of Reclamation
Cobbles		200 mm	Cobbles	Boulders
64 mm	–6		80mm	10 in.
Pebbles		Gravel (kies)		Cobbles
				3 in.
4 mm	–2		Gravel	Gravel
				4 mesh
Granules				Coarse sand
2 mm	–1	2 mm	2 mm	10 mesh
Very coarse sand			Very coarse sand	
1 mm	0		1 mm	
Coarse sand			Coarse sand	Medium sand
0.5 mm	1	Sand	0.5 mm	
Medium sand			Medium sand	40 mesh
0.25 mm	2		0.25 mm	
Fine sand			Fine sand	Fine sand
0.125 mm	3		0.10 mm	
Very fine sand			Very fine sand	200 mesh
0.0625 mm	4	0.0625 mm	0.05 mm	
Silt		Silt	Silt	Fines
0.0039	8	0.002 mm	0.002 mm	
Clay		Clay	Clay	

The gravel pack is placed between the outside of the well screen and the borehole. After the outer casing is in place, the screen is lowered to the bottom of the well and centered. Selected gravel is added to the annular space between the screen and the casing through a small-diameter tremie pipe. The gravel is placed evenly around the screen in 2- to 4-ft (0.6- to 1.2-m) layers. As the gravel is added, the casing and tremie are slowly raised. The procedure continues until the entire screen is surrounded with gravel and the pack extends several feet (0.5 to 1 m) above the top of the screen. The outer casing is pulled back high enough to expose the entire screen section. As a rule, the screen is attached to an inner casing, extending to the land surface, into which the pump is placed. About 25 ft (8 m) of the outer casing is required to provide a seal against contamination by surface water. If the entire casing is removed, the gravel treatment must not extend to the land surface.

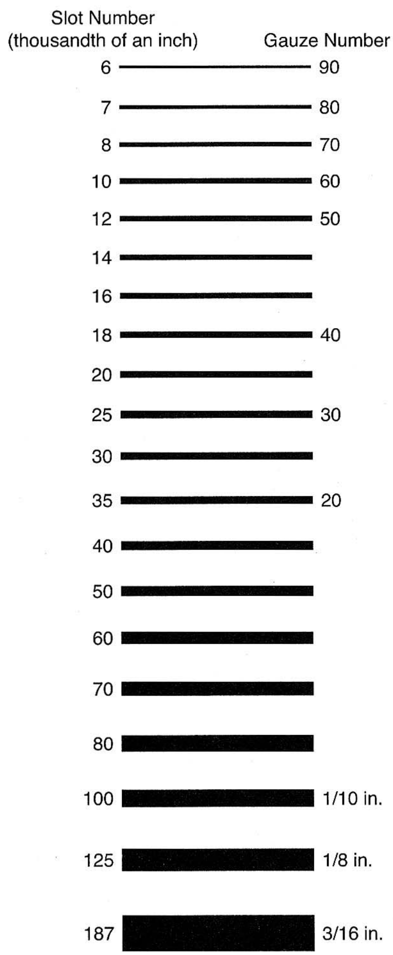
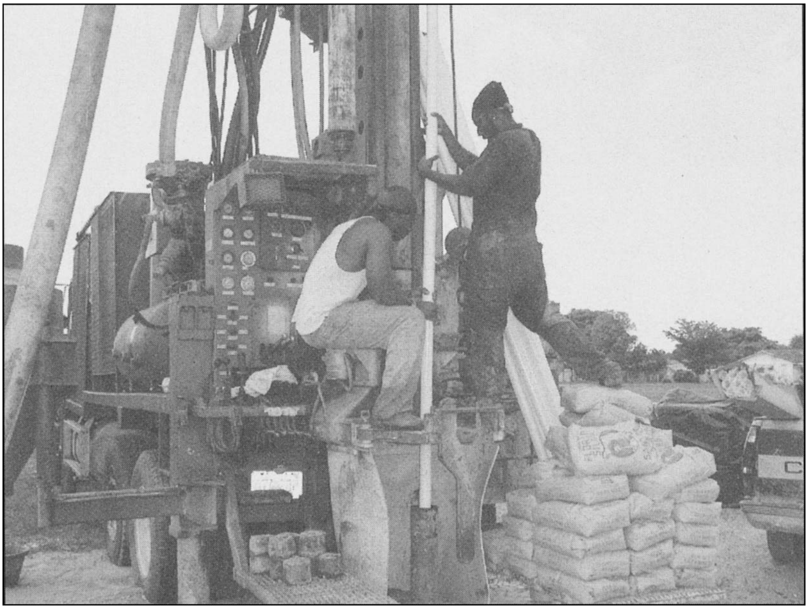


Figure 6-7 Well screen size chart (from AWWA M21, Groundwater)

The annular space between the working casing and undisturbed earth must be sealed with cement grout or puddled clay to prevent contamination from seeping into the formation. After the gravel filter has been placed, a pipe is often installed in the finished pump base or foundation to allow additional filter materials to be added if the gravel filter settles as a result of normal pumping operations, well development processes, or well rehabilitation procedures (AWWA, 2003).

Sealing the Well

Once the casing has been placed in the borehole, it must be sealed in place. Grouting provides structural reinforcement to the casing while sealing off the formation. The



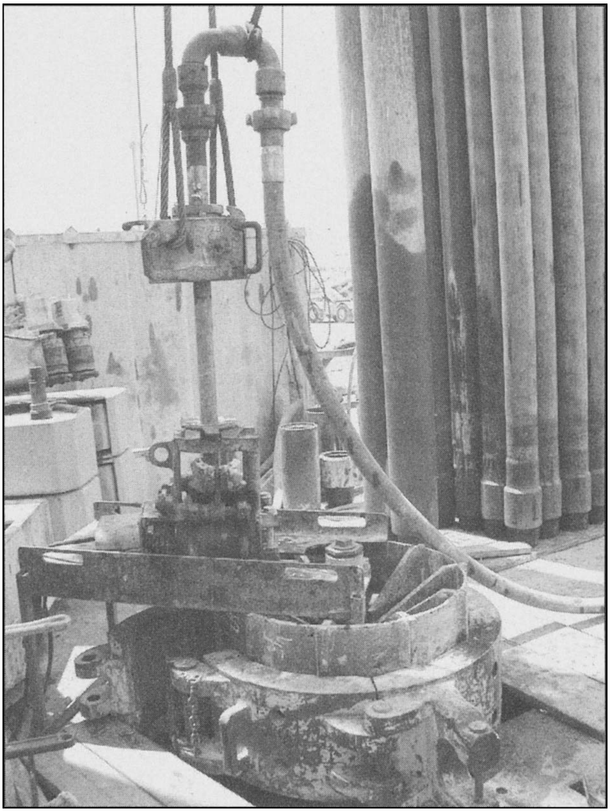
Source: John Largey

Figure 6-8 Dump methods for grouting

grout also provides some protection to the casing from potential deterioration from microbiological activity. Grout material should be placed uniformly into the annular space after water or drilling fluids have been circulated sufficiently to ensure any obstructions in the annular space have been cleared. In shallow wells, grout can be placed by dropping it from the surface (*rude and crude*—see Figure 6-8) or a bailer. The rude-and-crude methods should only be employed when the interval to be grouted can be seen from the surface. This generally limits usage of this method to intervals of less than 30 ft.

The dump-bailer method is perhaps the simplest method for grout placement. The cement grout is lowered in a dump bailer that discharges its load when it reaches the bottom of the hole. The bailer is placed in the annular space 1 ft above the bottom of the hole. After the grout is placed in the well, the casing is pulled up so that the shoe is above the grout. A plug is placed in the bottom of the casing, which is then driven to the bottom of the hole, displacing the grout into the annular space around the outside of the casing. Bailer methods permit the grout to be placed in stages. The elapsed time between dumps should not be more than 10 min.

However, in deeper wells, grouting the casing in place can be a challenge. If the annular space outside the casing is large enough to accommodate a grout (tremie) pipe, an air- or water-pressure drive is used. The tremie pipe should extend from the



Source: John Largey

Figure 6-9 Tremie pipe

surface to the bottom of the annular space. Grout is then pumped into the tremie pipe (see Figure 6-9). As the grout is placed, the pipe is slowly withdrawn to the surface, circulating around the casing to ensure a smooth and consistent pour all the way around the casing. The tremie pour should be continuous, and the tremie pipe discharge should be submerged in the grout at all times. The tremie method requires a minimum annular space of 3 in. (7.6 cm) between casings. The minimum tremie pipe diameter is generally 2 in. (5.1 cm), although concrete grout tremie pipes should be a minimum 3 in. (7.6 cm) to prevent clogging. Grout material placed using the tremie method should occur after water or drilling fluid have been circulated to clear obstructions.

A variety of pumping methods can be used but may be limited to site-specific applications. Pressure grouting involves forcing grout into the annular space. Grout pumping methods begin with the installation of a pipe inside the casing. The casing

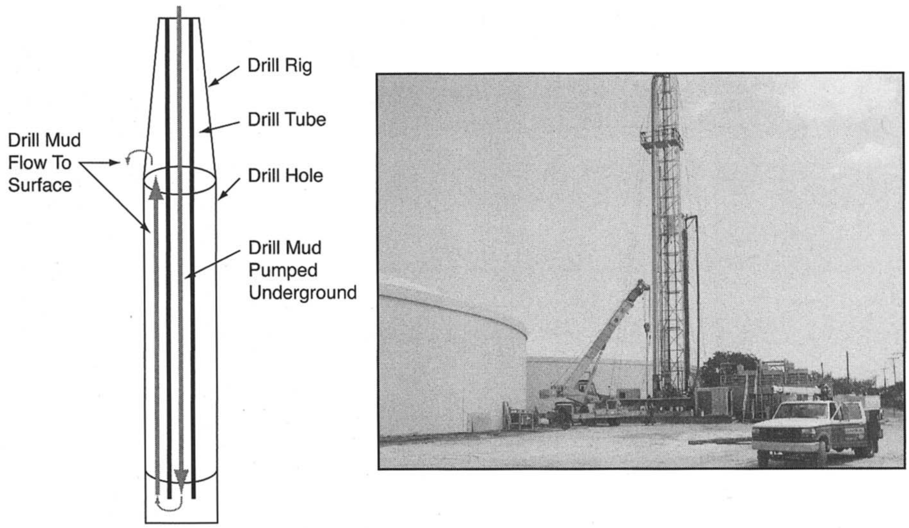


Figure 6-10 Pumping grout (above ground and below ground methods)

is suspended slightly above the bottom of the borehole, and a suitable packer connection is provided at the bottom of the casing. The packer allows removal of the grout pipe, and prevents grout leakage into the interior of the casing.

The continuous injection method requires the grout to be placed with a float shoe with a back-pressure valve. Tubing is run to a float shoe to carry the grout. When the annular space is deemed clean and free of obstructions, the grout is pumped down the tube into the bottom of the annular space (see Figure 6-10). When the space is filled, the grout pipe is removed. Work on the well is not resumed for at least 72 hr, after which time the packer connection and plug are drilled out (AWWA, 2003). Pumping should be continuous until the entire annular space is filled with grout. Concrete grout cannot be used with this method. As the tubing and shoe are not withdrawn, they must be drilled out, a complicating factor with this method. Pressure grout has the potential problem of exceeding the burst strength of the casing pipe if not monitored.

After grouting, an acoustic sonic log (i.e., cement bond log) should be run in the well to determine the competency of the cement bond to the casing and formation (or second casing, whichever is appropriate). The log should be run from the top of the casing to the bottom at least 72 hr after the grouting operation but before further construction commences.

CEMENT GROUTING

Water wells are cemented, or grouted, and sealed for the following reasons:

- To protect the water supply against pollution,
- To seal out water of an unsatisfactory chemical quality,
- To increase the life of the well by protecting the casing against exterior corrosion,
- To stabilize soil or rock formations of a caving nature, and
- To prevent entry of stormwater run-off around the casing.

As noted in previous sections, an annular space normally surrounds the casing. The annular space is the most likely source of contamination from the surface if not properly sealed. Unless this space is sealed, a channel exists for the downward movement of water. In loose caving formations, such as sand, the opening may be self-sealing, but in stable formations, this space must be cemented to prevent contamination from the land surface or porous formations connecting with the surface.

Three materials are commonly used for grouting: concrete, sand cement, and neat cement grout. Concrete grout is a mixture of portland cement (ASTM 15), sand, coarse aggregate, and water in the proportion of at least 5 bags of cement (94 lbs/cf) per cubic yard of concrete, and not more than 7 gal of water per sack of cement. Bentonite and other admixtures (ASTM C494) are commonly used to reduce shrinkage, increase viscosity, and reduce permeability (Lehr, et al., 1988). A minimum of 2 percent and a not-to-exceed maximum of 12 percent, by weight, of bentonite clay should be added to neat cement grout to compensate for shrinkage. Regardless of the materials used, cement, additives, and water must be mixed thoroughly.

Sand cement grout consists of sand, portland cement, and water. The sand to cement ratio is 2:1. Water content remains the same as do admixtures. Neat cement is made of only portland cement and water in the ratio of 7 gal of water per sack of cement (94 lbs/cf in each bag). Admixtures are similar to those used in concrete grout (Lehr, et al., 1988). Curing time before further construction is based on the type of portland cement used. Type I cement has a minimum curing time of 72 hr. Type II portland cement has a curing time of 36 hr and is preferred for many installations as a result.

When formations located below the depth of the protective casing are known to yield water of an unsatisfactory chemical quality, these formations may be sealed off with liners set in cement grout for their entire length, which may be several hundred feet deep. When a casing is extended to a consolidated formation lying below an unconsolidated formation, the most effective way to prevent sand or silt from entering the well at the bottom of the casing is cementing. The casing exterior is protected against corrosion by encasing it in cement grout, as described earlier in the section on casing installation. A minimum of a 2-in. (50-mm) thickness of grout is recommended; more may be required by some regulatory agencies.

The grout should be applied in one continuous operation if possible; however, it often must be placed in stages to ensure a satisfactory seal and be entirely in place. The grout must always be introduced at the bottom of the space to be grouted to avoid segregation of materials, inclusion of foreign materials, or bridging of the grout mixture, and if above the fluid level, to avoid leaving large packets of air in the annulus. An air pressure test (i.e., 7 to 10 psi) should be applied to the grout seal for a period not less than 1 hour to determine if any leakage exists. If the pressure drops during the 1-hour test, the necessary repairs and resealing of the grout should be made and the new seal retested.

WELL DEVELOPMENT

Well development may be the most important part of the well drilling process and is often underestimated with regard to the time required to properly develop the well. As a result, many wells suffer from incomplete development from the start, which makes them less efficient and less productive than they were designed to be. In the long-term, this causes additional client time and both capital and operating expense that are unnecessary.

The goals of well development are

- To clear fine materials from the face of the borehole;
- To clean and stabilize the formation by removing drilling mud, sand, and other foreign materials that are pushed into the formation by the drilling process (thereby improving porosity);
- To correct damage caused by the drilling process; and
- To improve ease of well disinfection.

The well development procedure includes all steps necessary to accomplish these goals, including subjecting the aquifer to high levels of energy and pressure to dislodge and remove materials that may clog the formation and reduce well efficiency. Not all wells are developed in exactly the same way. Gravel-pack wells and open-hole wells require different approaches, and the material moved in the open-hole well are far different than those of the gravel-pack. The rotary and cable-tool drilling methods have different impacts on the aquifer during construction.

Clear Fines From the Borehole

Removing fine-grained materials from the borehole involves removing the clay-sized particles that either naturally exist in the aquifer or are introduced or created as a result of the drilling process. The benefit is a reduction of wear on the mechanical parts of the well, as well as limiting future blockage of the screen and gravel pack.

Insufficient development will permit migration of near-borehole fines to the screen or gravel pack. For certain types of treatment process, such as membranes, the introduction of small particles may have adverse affects on the treatment process.

Clean and Stabilize the Formation

The intent of cleaning the formation is to create a zone of increased porosity adjacent to the borehole. If the near-borehole formation is cleared of fines, sand, and debris, the screens and gravel pack are less likely to clog. Less clogging will keep the specific capacity of the well high and limit potential mechanical damage on the system. Removing fines and debris will also stabilize the formation and prevent collapses from above. This assumes the proper seals are in place and that competent rock exists on top of the aquifer.

There are a number of things that can lead to a reduction in aquifer porosity and permeability near the well. Excessive pumping or pumping that removes substantial amounts of fines (because the screen size is incorrect) may cause the aquifer to compress, thereby narrowing flow paths, or possibly collapsing the borehole. In addition, in alluvial or sand formations, the compaction may occur because of reorientation of the grains as a result of pumping. Figure 6-11 shows a cube with a series of similar-sized grains in a cubic arrangement. The porosity of the cube exceeds 40 percent. However, the grains reorient in a rhombohedral fashion, which would reduce porosity to less than 25 percent (see Figure 6-12).

Sediments composed of well-sorted grain size will maintain initial porosity even if different layers have different grain sizes, but if the grain sizes vary, the porosity can drop to less than 10 percent. The well may subside at the surface as a result of formation collapse (see Figure 6-13). In all of these cases, if the voids in the formation are clogged during the drilling process, the permeability and efficiency of the aquifer will diminish.

Unconsolidated sediments, such as sand, gravel, and alluvial formations, have significant potential to have compaction, grain reorientation, and clogging through the movement of fines. If the materials are significantly compacted, the well may subside at the surface (Figure 6-13). Limestone, sandstone, and dolomite are unlikely to have grain reorientation but still may suffer from migration of fines into the aquifer and some compaction if over-pumped.

Correction of Damage Caused by the Drilling Process

For a well to function properly, the remnants of the drilling process must be removed from the borehole. Development of the well removes sand, drilling mud, and cuttings from the borehole and adjacent aquifer. Proper development will remove lost drilling mud from cavities and permeable formations, thereby restoring the initial aquifer condition and flow paths. Proper development provides the baseline efficiency for the well.

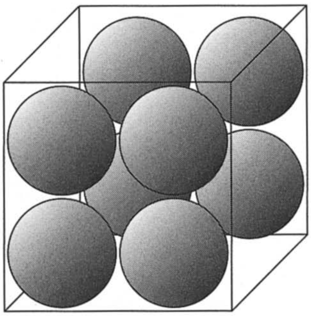


Figure 6-11 Cubic packing >40% porosity

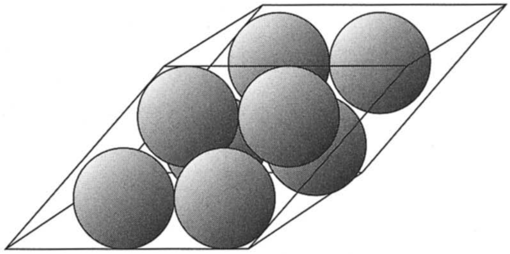


Figure 6-12 Rhombohedral packing >25% porosity

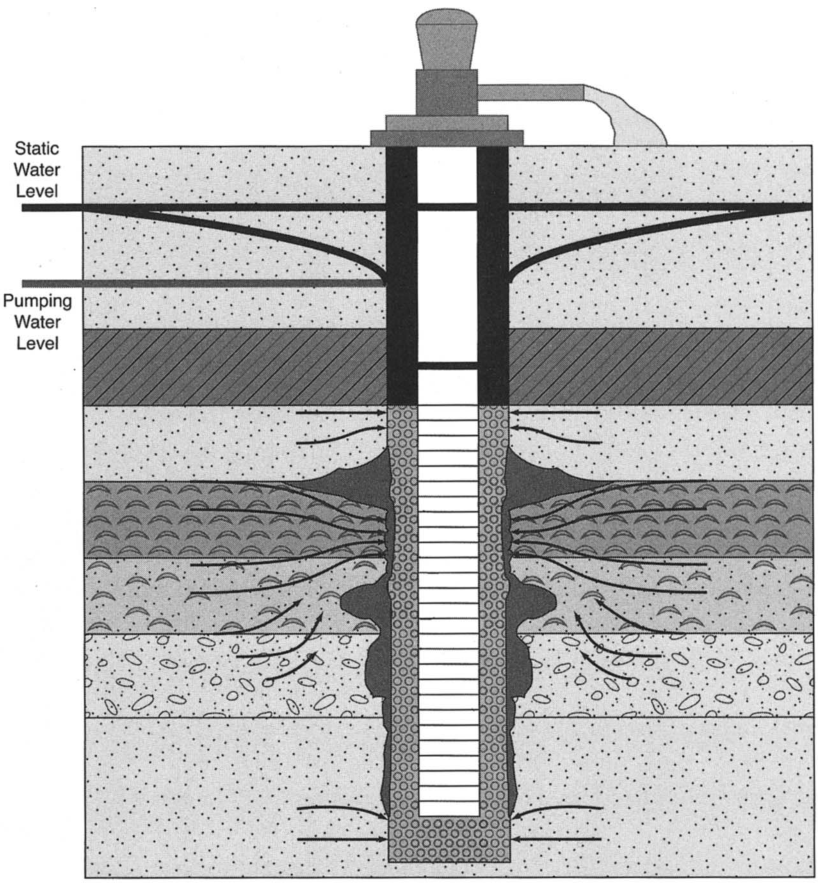


Figure 6-13 Formation collapse

Improve Disinfection

Clean boreholes will have a minimum amount of surface contamination and a limited amount of colonization of native or surface bacteria in the well. As a result, disinfection of the well can be accomplished more easily and more quickly than in wells that are not clean or that have not removed the biological component of the aquifer.

WELL DEVELOPMENT METHODS

Well development principles are designed to maximize the efficiency and specific capacity of the well efficiently. The well development protocol should be modified based on well type, aquifer type, grain size distribution, available equipment, well construction methods, and installed materials and equipment.

There are a variety of methods for well development.

- Over-pumping
- Raw-hiding
- Pump surging
- High-velocity jetting
- Air surging and pumping
- Mechanical surge blocks
- Double-flanged swabbing
- Chemical additives

Each method has its advantages and disadvantages. Over-pumping is the easiest method to use and may be satisfactory in many cases. This method pumps the water at much higher rates than the anticipated production rate to draw fines, drill cuttings, and other contaminants out of the formation. This takes time, especially when drilling mud is introduced into the production zone. Over-pumping has the tendency to preferentially develop the more permeable zones at the time of well development. For example, if a very permeable zone has been significantly intruded with drilling mud, the well may not be developed properly. However, there are risks to over-pumping in loose formations or where fine sands may exist. The fines may be removed, and the grains, in poorly consolidated formations, reoriented. In either case, there is a potential to damage the formation around the borehole, collapse the borehole, or cause bridging of the fines outside the screen, effectively sealing off the well. Over-pumping should be used with care in situations with unconsolidated formations and sand.

Raw-hiding is a variation of over-pumping that involves placement of the pump near the screen. The pump is turned on and run until the water is clear. The water is then reversed so it pushes into the formation, loosening adjacent particles. The process is repeated until no turbidity is found in the water. The method is inexact and not appropriate for most installations. It requires a deeper aquifer to get enough back-siphonage to dislodge formation materials.

Pump surging involves turning the pump on and off for short periods. This develops a mild water hammer in the well to dislodge the cuttings and other materials that need to be removed. Surging may also involve pumping water into the formation and then reversing the pump to draw it out. This method solves two problems with over-pumping—it breaks up the bridging of small particles and is less likely to pull sands and fines to the well. However, surging does create pressure and may damage friable formations, creating more fines and sediments that need to be removed. Fines will continue to migrate toward the well once pumping starts so development may be incomplete.

Air purging and mechanical block surging are essentially the same concept using different materials. With air purging, the air pumped into the borehole through a drop pipe or air line is replaced by water. With mechanical blocks, specific parts of the borehole are purged as opposed to the entire borehole. The same benefits and concerns apply to air purging and mechanical block surging as to pump surging.

High-velocity jetting is a means to scour the borehole and remove particles. The jetting occurs as the well is being pumped, so loose materials are moved to the surface. Jetting has advantages in hard formations where it may quickly remove materials on the borehole wall and screen. Soft formations should not be subjected to jetting because the formation could be damaged.

Double-flanged swabbing can be used to develop the well and to scrub the well to remove materials on the borehole wall. A typical swab consists of two rubber discs sandwiched between three wood or steel discs. The swab is constructed so that the outside diameter of the rubber disc is equal to the inside diameter of the screen, fitting closely to the inner surfaces of the well screen and casing. The swab is mechanically raised and lowered along the casing and well screen to draw drilling fluids and fines through the gravel pack and into the borehole. An air-lift may be used in conjunction with the swab to clear the borehole, or the swab may be fitted with a one-way valve allowing removal of development water and fines.

A variety of chemicals can be used to help in well development. Acidization is common to remove materials that cannot be swabbed or scoured off. Dispersing agents can also be used, but most chemical action is unnecessary for initial development. Chemical use is more appropriate for well maintenance (see chapter 7).

WELL DEVELOPMENT PROTOCOL (from Bloetscher et al., 2005)

Records of well development should be maintained. Establishing an efficient and timely protocol for development will ensure a smooth operation in the field. Such a protocol might be as follows:

1. Measure and record flow.
2. Measure and record pumping distance to water level.
3. Turn pump off and wait 5 min.
4. Record static water level.
5. Calculate drawdown (pumping water level minus static level).
6. Calculate specific capacity.
7. Develop the well by surging or air lifting.
8. Repeat steps 1–7.
9. If the well specific capacity increases significantly (at least 25 percent), disinfect the well and place it back into service. Otherwise keep repeating steps 1–7.

Any development effort, whether for plugging or not, will create a wastewater product that may contain chemicals, silt, sand, or other debris. The quality of this wastewater may require treatment. In each case, the waste stream characteristics must be identified, including

- pH of the water,
- Chloride level,
- Toxic substances,
- Silt,
- The quantity of the water to be discharged,
- The time element for which the discharge will occur (i.e., a relatively consistent flow over a period of time or surges),
- The new water quality of the wells, and
- The uptake of metals, SOCs, or VOCs that might violate air or water standards.

There may be a potential for environmental problems if chemicals are used in the redevelopment process. Otherwise, the major concern will be the potential for flooding areas near the well as the redevelopment water is discharged to the ground. This discharge will contain silt, sand, and other debris. If highly turbid, this water may require treatment. Regulatory agencies that may be involved in any discharge may include the USEPA, state agencies, and local environmental agencies. Discharges to a sanitary sewer system will involve local utilities.

Redevelopment

Periodically, the well will need to be redeveloped to remove accumulated precipitants in the screen, biological masses, and sediment buildup. Redevelopment will restore much of the initial aquifer efficiency. The same basic procedure is used to redevelop a well as was used to initially develop it. Further discussion is found in chapter 7.

SANITARY PROTECTION

Once the well has been constructed and developed fully, the final sanitary protection should be provided along with disinfection of the borehole, pump, casing, pipe, and fittings. Where the minimum depth for withdrawal varies with soil formations and surrounding conditions, the well casing should extend at least to the depth where protection from surface contaminants is anticipated. The screen should be set below that point. The sanitary seal prevents contamination from migrating downward to the screen from the surface.

The sanitary seal is usually constructed of neat cement. Every well casing should be grout sealed from land surface to the full depth. Many regulatory agencies require a minimum of a 6-ft-square concrete pad around the well casing, sloped at 1 in. per yard away from the well. Where a well is installed to a depth less than where protection can be assured, the well needs to be located in a wellhead protection zone as defined in chapter 2. It is suggested that in the immediate vicinity of the well, an impervious layer of well-compacted clay or neat cement at least 2-ft (0.6-m) deep should be placed on the land surface around the well. This barrier will minimize percolation from surface water to the withdrawal point.

Another means of protection is to submerge the well screen below the pumping level of water in the well. The pumping level of the well should never be allowed below the top of the screen as aeration of the well screen may promote aerobic bacteriological activity. The cascading water causes air entrainment and possible cavitation to the pump.

Disinfection (from AWWA, 2003; Bloetscher, et al., 2005)

During the process of well drilling and construction, the borehole is subject to contamination from the land surface. Contamination can also be introduced by tools, drilling mud (in the case of the rotary method), the casing and column pipes, and the screen. While extended pumping may rid the well of this contamination, disinfecting the well with chlorine is faster and provides more assurance. Most regulatory agencies will require disinfection of the well and a period of clearance testing from fecal coliforms prior to the well being put into use for water supply purposes.

Many disinfection methods are available although most involve chlorine in some form (typically, hypochlorite). Disinfection is achieved by pumping chlorine into the well casing and producing a mix by alternately starting and stopping the pump. As a general rule, a concentration of at least 50 mg/L of chlorine must be present in the well after introduction of the disinfection fluids. The disinfectant pumped into the well should be thoroughly mixed with the water in the well casing and must come in contact with the pump and discharge piping.

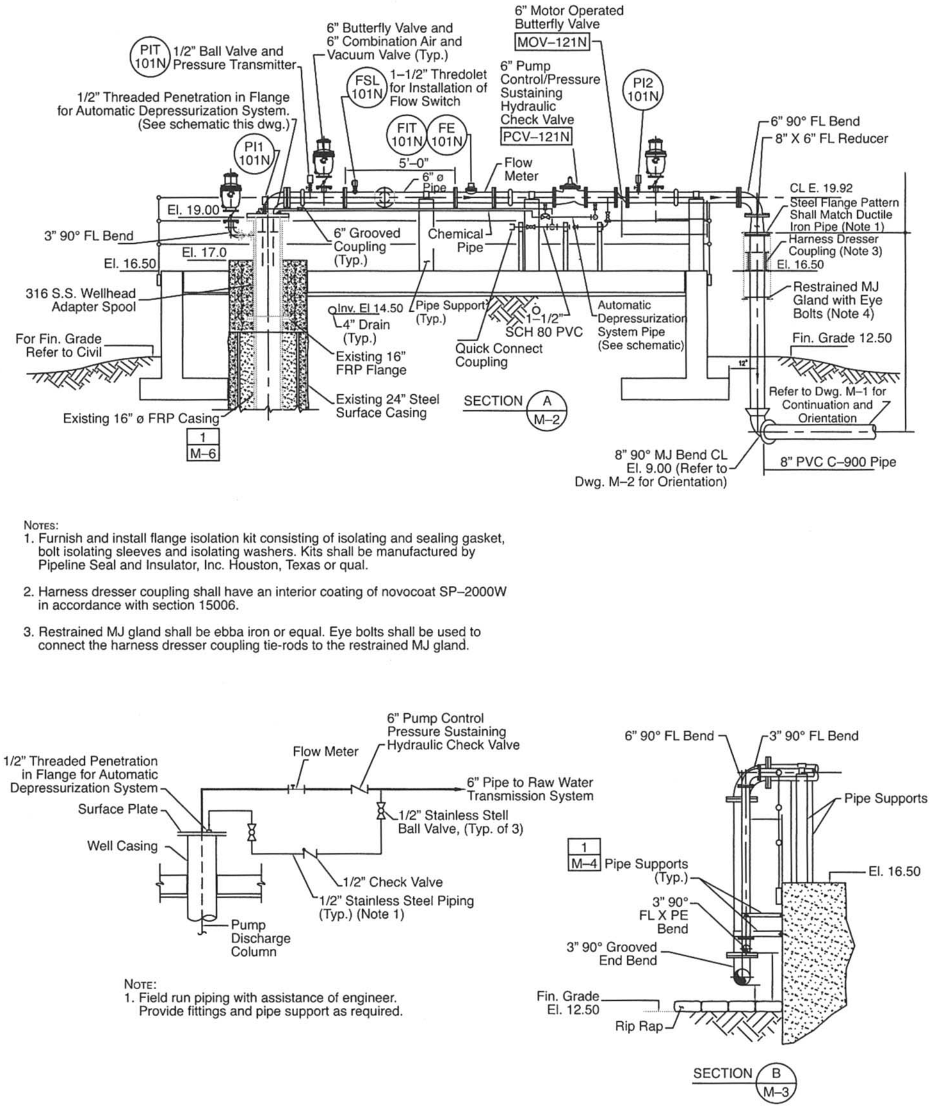
A gravel-pack well may prove difficult to disinfect. The material used for gravel treatment, even though washed and clean, still carries contamination. To resolve the problem, a tablet or powdered calcium hypochlorite can be occasionally added by hand to the gravel-filling tube as the gravel is placed.

Even with disinfection, the water pumped from a well may still show evidence of contamination. Under such circumstances, a chlorinator can be installed at the well to treat all the water discharged to the system. In time (perhaps as long as three or four months), normal pumping will usually rid the well of contamination. During this period, a free chlorine residual will make it possible to use the water. Additional information on disinfection is available in AWWA Standard A100-06.

SURFACE EQUIPMENT

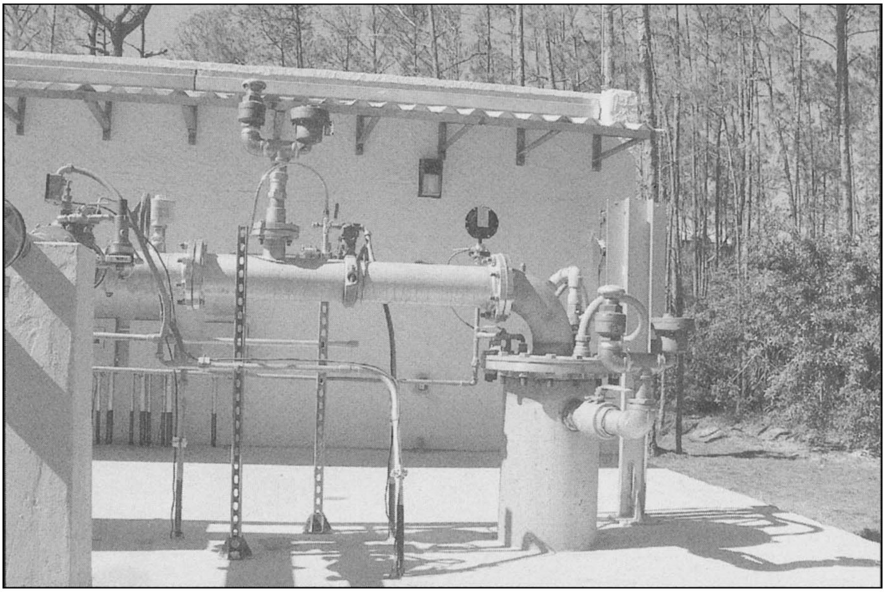
The final piece of well construction is the installation of the surface equipment. Surface equipment for wells is generally limited to some piping, a meter, and some sample taps or probes to monitor water quality. Figure 6-14 shows an engineering drawing for a wellhead that includes the well (top only), an air release valve, meter, butterfly valves for flow control, a check valve to prevent backflow, piping, and pipe supports. This installation is above ground and is shown in different perspectives. Figure 6-15 shows an example of an installed wellhead similar to the drawing shown in Figure 6-14. Surface equipment should be designed by a competent professional engineer. The design should include

- Lightning and transient voltage surges protection, including lightning arrestors, surge capacitors, or other similar protection devices, and phase protection;
- Access for repair and maintenance purposes that will not cause interrupted operation;
- Protection against surge and water hammer to protect the integrity of the well system;
- Operational reliability and flexibility in the event of damage to or failure of the pipeline or a well;
- Access to the well for geophysical logging without disruption of operations;
- Necessary screening for floatable solids prior to withdrawal to avoid plugging of the injection horizon; and
- Vandalism protection.



Source: Hazen and Sawyer, P.C., Boca Raton, Fla.

Figure 6-14 Drawing of wellhead



Source: Hazen and Sawyer, P.C., Boca Raton, Fla.

Figure 6-15 Photograph of wellhead

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7

Operation of Wells

WELL PERFORMANCE

Once the well is designed and constructed, two issues must be monitored on a regular basis: well performance and water quality. Well performance issues include the routine maintenance of pumps and motors and record-keeping of withdrawals. Water quality monitoring and record-keeping are generally straightforward and often dictated by regulatory agency requirements. However, ongoing issues with fouling and microbiological activity appear to be common with wells, so those topics will be covered in more detail.

Pump and Motor Maintenance (from Bloetscher, et al., 2005)

For each pump, issues to evaluate include the initial cost, cost of installation, cost of operation, cost of maintenance, and expected equipment life. Proper selection of system components can ensure system performance, but changing conditions sometimes justify altering or reselecting components to maintain economical operation. The range of expected operating conditions must be checked against the pump manufacturers' information to ensure reliable operation, including the ambient air and water temperature ranges, pressures, flow, corrosive and abrasive factors, power supply variation, duty cycle, and protective devices. The pump must be installed according to the manufacturer's instructions.

Continuous operation of a pump is generally preferable to intermittent operation, but varying water demand usually requires some combination of off- and on-time. For improved well performance and pump life, system components and storage capacity should be designed to minimize the number of pump starts and stops per day. At the same time, the pump must be sized and set so that it will never run for even a few minutes at "no delivery", as this will cause damage to the pump bearings by the overheating and failure of the submersible motor. If the well drawdown or the delivery system causes the pump to run at little or no delivery, protection should be provided to the pump. This protection could include a well-level switch that would shut off the pump or sound an alarm if the flow or water level dropped below a safe minimum level. Routine maintenance is often specified by the manufacturer and will include greasing bearings, polarity checks, and alignment checks.

Record-Keeping (from Bloetscher, et al., 2005)

As part of the proper operation of a groundwater system, gathering, compiling, and recording of a wide variety of data must be performed to document the operating history of the wells. These data are used to detect a loss of production efficiency and possibly the cause of a loss, to schedule maintenance at opportune times to avoid breakdowns, to evaluate the cost of water production, and to schedule capital improvements. The forms used for record-keeping are not critically important—the key is that the records must be collected and maintained in a logical fashion regardless of the form that is used. AWWA's Groundwater Manual (M-21) contains information recommended for data collection, including design, construction, and operational data. This information is summarized the following sections (AWWA, 2003). A log tracking the dates and time for work is essential.

The data collected and compiled relating to the well design should include

- Detailed individual well (geologic) logs,
- Well diameter,
- Proposed total depth,
- Position of the screens (or portion of the open hole if constructed in rock),
- Method of construction and materials,
- Pump design,
- Water-quality analyses,
- Static (nonpumping) water levels in the aquifer,
- Design pump discharge pressures, and
- Other data developed during the design phase.

When the production well has been constructed, "as-built" records of the well should be recorded. These records should include

- Method of construction used to drill the well,
- Driller's log of the materials encountered during drilling,
- Detailed individual well lithologic logs,
- Geophysical logs,
- Diameters (and materials of construction) of well casing and screens,
- Slot sizes of the screen,

- Gravel-pack material,
- The depths (settings) of the casing and screen, and
- The total depth of the well.

Pump data should include

- The type (and make) of the pump installed,
- The type and horsepower of the motor (driver),
- The pump setting (depth to the pump intake),
- The setting of the air line or other device for measuring the water level in the well,
- Notation for the point (and reference elevation) used for measurement of the water level, and
- All information provided by the pump and motor manufacturer, such as capacity and efficiency data.

The total pumpage for each well is generally required by permit to be recorded daily and reported monthly on operating reports. These numbers can be graphed to illustrate the seasonal and yearly production rates. This data can be used for future projection of water withdrawal rates and to monitor the actual volume of water produced from each well. Data can usually be recorded from a totalizer on flowmeters installed in the discharge piping for each well.

Records of water levels in the well during periods of nonuse (static) and during pumping should be recorded to provide a baseline for determining the amount of drawdown. The static levels can identify changes in the amount of water that may be available in the aquifer with time or at any given time.

Because temperature is often indicative of changes in flow regimes in aquifers, the groundwater temperature should be recorded and plotted. As the temperature of the groundwater varies, the capacity of the well fluctuates as a result of the viscosity of the water. In projects where recharge to the aquifer may come from infiltration of surface water, the temperature of the adjacent surface water body should also be recorded.

Operations personnel should evaluate any well failure or long-term decline in performance to determine if physical or mechanical problems are causing the decline. Specific capacity is a method to monitor well performance. As noted in chapter 5, specific capacity or the ratio of the yield of each well to its drawdown is used to plot the operational trend of each well. The specific capacity of a well should be calculated annually to identify the potential need for maintenance, plugging problems, or water supply concerns as outlined in chapter 4.

If specific capacity decreases, it may be the result of a drop in pumping water levels or a reduction in pumping yield caused by microbiological fouling, chemical precipitation, formation, well screen or gravel-pack plugging, pump corrosion, or biofouling. Water level declines can be caused by regional water level declines or reduced hydraulic efficiency in the well, most commonly plugging or incrustation of the borehole, screen, or gravel pack. Other specific yield problems may relate to

- Changes in the water-bearing zone,
- Insufficient development of the well at time of drilling,
- Pump wear; and
- Impeller detachment from the shaft.

Proper study and comparison of data enable the operator (or consultant) to anticipate maintenance and repair needs. Comparative data pertaining to the physical condition of the pump unit should also be collected. This data should include

- Water level measurements made before, during, and after the (drawdown) pumping test,
- A record of the pumping rate,
- Hydrographs generated during the test, and
- Any raw data collected (manual or computer generated).

Well maintenance activities should also be recorded. This data can be used to predict times when maintenance needs to be performed, identify possible causes of well decline, and plan for annual budgets for wellfield management when compared to the initial test data. These records should include

- Dates that maintenance was performed;
- Results of pre- and postmaintenance pumping tests;
- Methods (and materials) used in the maintenance procedures; and
- Other factors such as the coloration of the pumped water, amounts of sand removed, odors, and water quality analyses.

It is recommended that similar tests be rerun after any repair or maintenance work.

Design problems become evident from several operational conditions: over-pumping (which results in lowering of the water table), clogging or collapse of a screen or perforation of a screen section, corrosion, incrustation, and wear aggravated by excessive intake velocities. Other problems include poor selection of well materials (that lead to significant corrosion or collapse), incorrect specification of pumps and poor construction (casing damage, breaches in the grout, misplacement of screens and gravel pack, and misalignment).

Over-pumping can damage the well by reducing the storage and production capacity of a groundwater system as described in chapter 6. In granular formations, the water-bearing formation may consolidate. Where this occurs, it results in a lower water table, less water storage space, reduced yield from individual wells, and can collapse the well casing. Wear in the screens or pumps may be a result of entrance velocity, as water passes through the well screen (or the edge of the formation depending on the type of well). As the entrance velocity increases, sand, silt, and colloidal matter can enter the flow stream.

Other problems include suction breaks and electrical surges. No pump should operate at a rate at which it breaks suction as it may cause severe damage to both the pump and the aquifer as a result of water hammer (see chapter 5). Surging in the well may collapse the well if it was not properly stabilized. Surging can stimulate sand, silt, and colloidal activity or dislodge corrosion and precipitates. Air bubbles may be entrained into the wells, which can damage the distribution system piping by causing air pockets. The solution is to remove a bowl or slow the motor speed, not to close the valves to reduce pumping. Lightning strikes and poor grounding may cause electrical surges that damage motors and pumps. Appropriate lightning attenuation should be installed where required.

Well Abandonment

Regulatory agencies generally require utilities to abandon wells no longer in use. The well must be abandoned in accordance with the regulatory guidelines. The following is a general outline of a well abandonment plan. The plan is subject to modification based on the nature and cause of the abandonment.

- The head in the well will be suppressed by pumping a solution of sodium chloride (salt) and/or barium sulfide (barite) into the well (if required). Blow-out prevention equipment will be on site, should it be necessary for controlling the well.
- The well will be geophysically logged and television surveyed prior to abandonment. The nature and extent of the geophysical logging will depend on the value and cause of the well being abandoned. The following are logs that may be used:
  - Electric logs: single-point resistivity, long- and short-normal resistivity, and spontaneous potential,
  - Gamma ray,
  - Caliper,
  - Fluid conductivity,
  - Temperature,
  - Flowmeter,
  - Dual induction,
  - 3-D velocity log (sonic log), and
  - Cement bond log (if necessary).

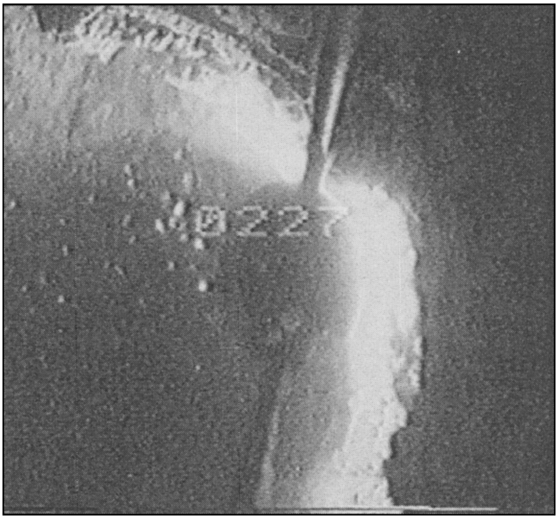
- All geophysical logs should be performed from the bottom of the borehole to land surface (for those logs that can be effectively performed in the cased portions of the well). All logs that can be performed only in open holes should be run from the bottom of the borehole to the bottom of the casing.
- The bottom of the borehole should be filled with clean, washed, and chlorinated (disinfected) gravel. The gravel should be tapped periodically to ensure proper placement. A bentonite/sand cap should be placed on top of the gravel 5 ft below the bottom of the casing. The hole is then filled with neat cement grout from the bentonite/sand cap to land surface.
- All fluid displaced during cementing must be contained and disposed of in an environmentally safe manner.
- A final well abandonment plan should be submitted to the appropriate regulatory agencies at the time of application for a well abandonment permit, subject to field modification based on logging and conditions encountered during the abandonment.

WATER QUALITY MONITORING (from Bloetscher et al., 2005)

As operations personnel review changes in static and drawdown levels to identify any trends, they should be cognizant of changes in specific capacity and water levels in the aquifer. Long-term reductions in water availability in the aquifer or limitations in specific capacity of the mechanical system caused by pump wear, clogged screens, or formation of bacterial fouling may be indicated. Repairs to correct mechanical problems should be scheduled before they become serious, but problems that are not mechanical may be more challenging.

Regulations require periodic monitoring of microbiological and chemical quality. As noted in chapter 4, intensive water quality monitoring should occur after the well has been completed to establish a baseline that can permit the water system operator to reduce the frequency of groundwater sampling and indicate if long-term changes in water quality are occurring. Fortunately, groundwater quality in many locations does not change significantly with time because the movement of groundwater is generally very slow compared with surface water. When changes do occur, potentially serious problems could be present.

Where contamination risks are high, sentinel monitor wells should be installed for this purpose. Sentinel wells, located at various depths, will provide definition for the initial groundwater assessment. Sentinel wells also serve as an early-warning system to detect changes in water quality and water elevations before they affect the water supply wells.



Source: John Largey

Figure 7-1 Sand entering a borehole

Particulate Plugging

Plugged screens increase the entrance velocity of the raw water, which can increase particle movement as well as drawdown. Sand, silt, and other particulates may clog the screen, providing less area to draw the water. When this happens, the capacity of the well decreases, the pumps become less efficient, and operations costs for electricity increase. Figure 7-1 shows a borehole with sand entering a pumping well. Sand will also increase wear on pumps and settle in large pipelines. Sand is problematic for membrane processes.

Removal of sand can be a delicate process because it is possible to damage the screen. Water samples from wells developed in sand aquifers should also be periodically inspected for the presence of sand. The presence of sand in a well may be an indication of eventual collapse of the well, collapse of the formation and, in extreme cases, sinkholes. These problems are generally repairable but require appropriate expertise to review the situation.

In most cases, particulate plugging is caused by poor well design or construction, including insufficient development of the well or inadequate formation sampling leading to poor screen selection and/or location. In some cases, the logging may not have been sensitive to thin layers of sand, silt, or colloidal matter that may be exposed with time. In wells with gravel packs, incomplete development or over-pumping may be indicated by plugging of the gravel pack and the screens.

Plugging by Iron and Manganese

At a pH less than 5, iron and manganese ions remain dissolved as Fe^{+3} and Mn^{+2} in the water supply. However, in the presence of 2 or 3 mg/L of dissolved oxygen or a higher pH shift, these metals can be precipitated around the well screen in an insoluble mass. Hard nodules will form from this precipitate, which collect additional ferric or manganese precipitates. Oxygen encourages iron precipitation. Acidic groundwater (pH less than 7) may dissolve calcium carbonate from the formation materials, causing migration to the well screen or increased turbidity.

Calcium Carbonate

One of the most common well problems is incrustation of the well screen or of the gravel pack around the screen. This may be caused by the release of dissolved minerals from the native water, geochemical reactions, or microbiological activity. Calcium carbonate forms a scale on the screen and cements together particles of sand and gravel. Calcium carbonate incrustation can usually be removed by a chemical process.

Corrosion

Three general types of corrosion involved in water wells are hydraulic, chemical, and galvanic. Hydraulic corrosion is caused by turbulent flow, hard particulates, and/or wearing flow velocities, which abrade well components. Hydraulic corrosion enlarges screens and opens holes in the casing that allow larger particles into the casing. As deterioration accelerates, the casing material diminishes and potentially collapses.

Hydraulic corrosion is generally caused by particulate matter from incomplete well development or fine material within the formation that is not screened out. Cavitation caused by turbulent flow will aggravate corrosion by flaking off pieces of metal. Pumping at rates higher than design flow is the primary cause of hydraulic corrosion.

Chemical corrosion is a problem in older wells because of materials used in the past. Chemical corrosion is caused by ionization of metallic elements, typically zinc or iron, through carbonation or oxidation reduction (redox) reactions. Chloride ions that exist in raw water can form weak acids that react with metallic ions or attack metals. Sulfide ions also create acids in certain environments that may attack metal surfaces. Oxidation and reduction reactions occur in groundwater environments and can accelerate corrosion in a well. The presence of high concentrations of dissolved oxygen may accelerate desiccation of brass or other pipe.

Galvanic corrosion is caused by the generation of electric currents in dissimilar metals. Galvanic corrosion is often a problem with stainless steel pumps that are connected to steel column pipes with bronze centralizers in a steel casing. Newer technologies and the use of stainless steel, bronze, and plastics over standard steel

Corroded End (Anode)

Magnesium
Magnesium Alloys
Zinc
Aluminum 25
Cadmium
Aluminum 17ST
Steel or Iron
Cast Iron
Chromium–Iron (active)
Niresist
18–8 Chromium–Nickel–Iron (active)
18–8–3 Chromium–Nickel–Molybdenum–Iron (active)
Lead–Tin Solders
Lead
Tin
Nickel (active)
Brasses
Copper
Bronzes
Copper–Nickel Alloys
Monel
Silver Solder
Nickel (passive)
18–8 Chromium–Nickel–Iron (passive)
18–8–3 Chromium–Nickel–Iron (passive)
Silver
Gold
Platinum

Protected End (Cathode)

Figure 7-2 Galvanic series

grades have reduced galvanic corrosion, although stainless steel grades may have some of the same inherent problems in high chloride waters (Bloetscher, et al., 2001, 2002a, 2002b). Figure 7-2 shows the galvanic series. The higher the conductance that exists between two metals, the greater the potential for galvanic action. This corrosion is typically found where casing screen is joined, where the submersible pumps are joined to the column pipes, or where bronze spiders exist. Poor pump alignment, stressed threads as a result of poor assembly, or poor welds may encourage this type of corrosion.

Microbiological Fouling (from Bloetscher, et al., 1998)

Microbiological fouling is generally interrelated with physical and chemical processes. Microorganisms can encrust or corrode the system enhancing physical and chemical well deterioration problems involving some microbiological fouling. The typical symptoms of microbiological fouling problems are

- Decrease in the water quality,
- Increased drawdowns,
- Reduced specific capacity,
- Change in the amount of iron or manganese in the water supply, and
- An apparent increase in microbiological densities, such as an observance of slimes or staining from the raw water.

Microbiological fouling encourages changes in the electrical potential and pattern of the well casing by using CO_2 on metallic surfaces to transfer ions. The bacteria attach to the steel pipe walls in the form of biofilms. As noted in chapter 2, a biofilm is an active ecosystem, providing an environment for survival to a variety of microorganisms by storing and transporting nutrients. As the bacteria in the biofilm absorb nutrients, they form tubercles and films that reduce the capacity of pumps and casings and may clog the well screen. Precipitates of iron, sulfur, and manganese can also exist within the biofilm. The biofilm also protects the bacteria cells from external reagents, such as chlorine, but traps iron, sulfur, manganese, and other nutrients.

It should be noted that certain microbiological activity is normal. Table 7-1 shows the bacteria found in several south Florida aquifers. Aquifers are not the pristine environments the public may believe. Bacteria find aquifers to be the ideal environments as there is tremendous surface area for colonization, the temperatures are relatively constant and moderate, the flow of water provides a consistent nutrient supply, and except for the immediate pumping zone, the water is not disturbed (Bloetscher, et al., 1998). All spaces within the aquifer formation are potential areas for colonization. Vugular formations and formations with air pockets are ideal for creating large biofilms within the aquifer, but never indicate severe plugging because of the size of the organisms in comparison to the vugs.

Monitoring bacteria population is important. Figure 7-3 is an example of a well in Venice, Fla. where sulfur-reducing bacteria (SRB), iron-reducing bacteria (IRB) and slime-forming bacteria (SFB) are monitored. When a biofouling problem has begun, little can be done to remove it. Control of the colonies is the best strategy.

Several steps should be followed to look for bacteria. A down-hole camera should be used to look for the colony seeds. Any equipment that is pulled out of the wells should be thoroughly cleaned so other wells are not contaminated. Operations personnel may need to obtain microbiological samples for analysis from nonwater sources (e.g., samples from the colloidal filter or from a slimy material growing on the pump or column pipe). For these analyses, swab samples should be collected. Sterile collection swabs for bacterial samples should be obtained by the operations staff and used to collect the specimen to be analyzed.

Table 7-1 Bacteria found in South Florida aquifiers

Bacteria	Isolated From Biscayne Wellfield	Isolated From South County Regional Wellfield	Isolated From Floridan Wellfield
Acinetobacter anitratus	√	√	√
Acinetobacter baumannii	√		√
Acinetobacter calcoaceticus	√	√	
Acinetobacter haemolyticus	√		
Acinetobacter 1woffii	√	√	
Actinomyces/Streptomyces sp.	√		
Aeromonas hydrophila	√	√	√
Alcaligenes faecalis	√	√	
Alcaligenes xylosoxidans	√	√	
Bacillus sp.	√	√	√
Burkholderia (pseudomonas) cepacia	√	√	√
Chryseomonas luteola	√	√	
Citrobacter diversus	√		
Citrobacter freundii	√	√	
Citrobacter perfringens	√		√
Citrobacter septicum	√		
Citrobacter sordellii	√		
Citrobacter sporogenes	√		
Clostridium bifermentans	√		
Corynebacterium sp.	√	√	
Crenothrix polyspora	√		
Desulfovibrio sp.	√		
Enterobacter aerogenes	√	√	
Enterobacter agglomerans	√	√	√
Enterobacter cloacae	√	√	
Escherichia coli	√		
Flavobacterium odoratum	√		
Flavobacterium sp.	√	√	
Gallionella ferruginea	√		
Klebsiella oxytoca	√		
Klebsiella pneumoniae	√		

Table continued next page.

Table 7-1 Bacteria found in South Florida aquifiers (continued)

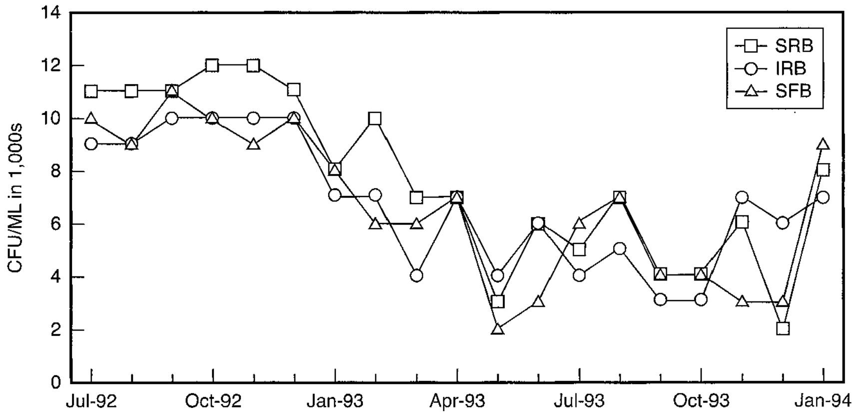
Bacteria	Isolated From Biscayne Wellfield	Isolated From South County Regional Wellfield	Isolated From Floridan Wellfield
Kluyvera sp.	√		
Micrococcus luteus	√		√
Micrococcus sp.	√	√	
Plesiomonas shigelloides	√		
Pseudomonas aeruginosa	√	√	√
Pseudomonas alcaligenes	√	√	√
Pseudomonas fluorescens	√	√	√
Pseudomonas pickettii	√		
Pseudomonas pseudoalcaligenes	√		
Pseudomonas putida	√		
Pseudomonas stutzeri	√	√	√
Rhodococcus equi	√		
Runyon Group IV mycobacterium	√		
Salmonella sp.	√		
Serratia marcescens	√	√	
Shewanella (pseudomonas) putrefaciens	√		
Sphaerotilus natans	√	√	
Sphingomonas paucimoblis	√		
Staphylococcus aureus	√		
Staph—coagulase negative	√	√	
Stenotrophomonas (xanthomonas) maltophilia	√	√	√

Source: Bloetscher, et al., 2000a

Water and swab samples should be sent to a microbiological laboratory. The conclusions based on the results of the microbiological analysis and the recommendations for control, if microorganisms are identified, should be performed by a qualified hydrogeologist with the assistance from a qualified microbiologist.

The following analyses should be performed on each water sample:

- Total coliform count



NOTE: CFU = colony forming units

Figure 7-3 Bacterial quantities in a well

- Fecal coliform count
- Heterotrophic plate count
- Bacterial identification
- Total fungal count
- Fungal identification
- Algal identification
- Protozoa

The following analyses should be performed on each swab sample: bacterial identification, fungal identification, and algal identification. *Cryptosporidium* sp. and *Giardia* sp. should be analyzed for evidence of surface water interaction or if the water supply is surface water. Biological Activity Reaction Test (BART®) tests are useful, but they are not conclusive for identifying biofouling problems. Speciation of bacteria is required because most environments yield a matrix of bacterial species. An individual BART® test only looks for limited species.

Resolving Operations Problems

Proper design will reduce potentially excessive entrance velocities or improper screen placement that can allow fine-grained particles to migrate into the wells. Proper materials, such as plastics or fiberglass, instead of steel or stainless steel should be used in water where microbial activity or high chlorides are present. Dissimilar metals should not be used in close proximity. Improper construction, poor grouting, excessive screen and casing damage, or the removal of protective sealants can lead to physical deterioration of the well. The improper application of certain chemical reagents, especially chlorine, and sequestering reagents or those used during redevelopment, may exacerbate deterioration. Overly aggressive pumping for redevelopment, over-pumping of the system, or the improper use of surging may cause structural damage to the well in the long term.

Many older wells were installed using methods and materials no longer in use and do not meet current standards. In these cases, the problems probably cannot be fully corrected. For many older wells, acidification, typically using sulfamic acid, can improve performance. Sulfamic acid solution will remove or loosen incrustation in the screens or the column pipe, although it will not remove much biofouling.

Physical agitation or surging is a method that often removes incrustation or reduces fine material entering the well screen or gravel pack. Tools are used that push water down into the well and pull it out, just as old hand-pumped well systems worked. Initially, the surge device is operated at less than 3 strokes per minute at 6 in. to 10 in. per stroke. Over time, the frequency and the stroke should be increased, which increases the surging. Care must be taken: if the casing or the formation is weak, or the screens damaged, the well structure can collapse during surging.

The addition of chemicals to the well is the most common treatment. Chlorine is used as a biocide for microbiological fouling, although in most cases it does not kill all the bacteria, it only serves to control the biofilm. A 12 percent sodium hypochlorite solution or commercial calcium hypochlorite provides the chemical strength needed for chlorination of the bacteria. In some cases hydrogen peroxide may be used to address biofouling problems, but certain bacteria, such as the *Pseudomonas* species, may be able to use the oxygen to their benefit, increasing rather than decreasing biological activity.

Another option is acidification, dropping the pH to less than 2. Hydrochloric, sulfuric, and nitric acid are used, but these chemicals must be used carefully. Sulfamic acid is preferred by some hydrogeologists for this reason. Deterioration of the well materials must be weighed against the removal of the biofilm or the incrustation. The addition of phosphates has been used, as it makes water "more slippery" and increases total well capability. However, phosphates provide a nutrient for biofilm. In all cases with chemical use, a plan for handling hazardous material and disposal must be made. None of these chemicals should be discharged to the ground; they must be hauled to an approved disposal site.

Another method, carbon dioxide injection (also hydraulic fracturing), uses gaseous carbon dioxide and liquid carbon dioxide under 100 psi of pressure. This technique causes the carbon dioxide to enter the formation, dropping the pH through a conversion of the CO_2 to carbonic acid. The water freezes, cracking and loosening incrustation. The formation may also crack and loosen, which can free the fractured zones or crack the bedrock formations and potentially increase yield. After the carbon dioxide is injected, the well is surged and redeveloped.

Sonar jetting is a relatively new method used to remove incrustations and may reduce biofilms. A sequence of small blasting caps is suspended and exploded, sending shock waves through the casing. Incrustations generally are blasted off the well screen, formation, and casing. After sonar jetting, surging and full redevelopment of the well must occur to remove all of the excess debris. Acidification improves the process to remove the encrustration to some extent. The problem with this process may be the inability to get permits to do the blasting, and the potential damage to the casing, cement seal, and/or the screens that may occur. Other methods that show some promise in certain specific cases are sectional flow control devices and inner sleeve installations within the casing, using entrained air to reduce fouling.

Owners and operators of wells that have increasing levels of contamination should immediately begin assessing their alternatives for correcting the problem. The major choices that may be considered in attempting to locate the source of contamination are to

- Determine if correction or removal of the source will allow the aquifer to return to normal;
- Determine whether the plume of contamination flowing toward the well can be blocked or intercepted;
- Determine if it is economically feasible to treat the water to remove the contamination;
- Investigate whether altering the well to draw water from a different aquifer is possible;
- Investigate the feasibility of drilling a replacement well at another location where there is no contamination;
- Investigate whether water from the contaminated well can be blended with water from an uncontaminated source to bring the finished water-level below the MCL;
- Investigate changing to a surface water source; or
- Investigate purchasing water from another water system.

Although groundwater quality does not vary much with time, certain quality features do gradually change.

WELL REDEVELOPMENT PROTOCOL

Even without plugging problems arising, wells should be redeveloped periodically to ensure efficient operation. Records of this redevelopment should be maintained. Establishing an efficient and timely protocol for redevelopment will save the utility money. A redevelopment protocol will be basically the same as the initial development protocol outlined in chapter 6.

1. Measure and record flow.
2. Measure and record pumping distance to water level.
3. Turn pump off and wait 5 min.
4. Record static water level.
5. Calculate drawdown (pumping water level minus static level).
6. Calculate specific capacity.
7. Redevelop the well by surging or air lifting.
8. Repeat steps 1–7.
9. If the well specific capacity increases significantly (at least 25 percent), disinfect the well and place it back into service. Otherwise keep repeating steps 1–7.

This protocol should be followed annually. As in the initial development process, the withdrawn water may contain chemicals, silt, sand, or other debris. The quality of this water may be such that it requires treatment. As a result, the following should be monitored in the withdrawn water during development:

- pH of the water,
- Chloride level,
- Toxic substances,
- Silt,
- The quantity of the water to be discharged,
- The time element for which the discharge will occur (i.e., a relatively consistent flow over a period of time or surges),
- The new water quality of the wells, and
- The uptake of metals, SOCs, or VOCs that might violate air or water standards.

There may be a potential for environmental problems if chemicals are used in the redevelopment process or if excessive silt, sand, and other debris are in the waste. The same procedures and regulatory limitations as in the development process must be adhered to. Caution should be taken to minimize the potential for flooding areas near the well as the redevelopment water is discharged to the ground.

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8

Summary

Groundwater is water that flows downward by gravity until it contacts a layer of rock or other impenetrable material, creating, an aquifer. This water may have entered the soil as a result of rainfall or snow melt, or it may be an ancient source found well below the surface. Groundwater moves downhill, taking the path of least resistance to the flow. Therefore, if underground conduits or channels (i.e., voids and/or fractures that lead to high permeability) are present, the water will tend to flow in these pathways. These formations may yield substantial quantities of water to wells.

Groundwater can have significant advantages over more traditional surface water uses. These advantages include:

- Less exposure to contamination (assuming not a surficial aquifer);
- Water quality is stable;
- Water temperature is stable;
- Water quality changes are slow to occur;
- Evapotranspiration losses are insignificant; and
- Less treatment typically is required.

However, groundwater sources have the following disadvantages:

- Difficult to clean up once contaminated;
- No early warning of contamination—unseen plumes of contaminants can migrate into a wellfield without warning unless sentinel wells are constructed;
- Competing uses from urban industrial, commercial, agricultural, irrigation, and ecosystem users in the same area;
- Determining the safe yields of material often is uncertain;
- Water levels are not obvious;

- Supplies are often limited in basins, which is why most large utility systems rely on surface supplies, not groundwater.

Well siting considerations include four issues: site availability, water supply, water quality, and wellhead protection limitations. Many small water systems also include land costs as a prime consideration when selecting sites for public water supply wells; however, this may overlook significant water quality or water quantity issues. Selecting suitable water quantity and quality are intertwined. The water system must balance factors including well depth, geology of the area, characteristics of the rock formations, and dissolved minerals in the aquifer.

The SDWA and its associated amendments are focused on protecting the public health from various contaminants in potable water supplies. This has impacts on groundwater use—the groundwater rules, wellhead protection programs, and water quality requirements all have impacts on the selection and treatment of groundwater supplies. Whether surface waters, groundwaters, or via operation and treatment, SDWA has basic requirements that must be met.

There are many drilling methods and many methods of well construction that have been developed for wells. The following are a variety of wells that serve many purposes:

- Water production (the focus of this document)
- Oil and gas wells
- Geothermal wells
- Injection/disposal wells
- Aquifer storage and recovery wells
- Environmental remediation wells

Environmental remediation wells are the shallowest of this group, often less than 10 ft deep, while oil and gas wells may be thousands of feet deep. Water supply wells fall somewhere in between. The following are the primary drilling methods for water supply wells:

- Cable tool
- Hollow stem auger
- Hydraulic rotary
- Mud rotary
- Reverse-air circulation
- Dual tube

All well projects go through a series of steps: predesign, regulatory criteria, design, construction and testing, and operations issues. Most testing occurs once some form of construction has begun—usually with a test well. Once the exploratory or test well is complete, geophysical logging can commence. Appropriate drilling, geologic, geophysical, and video logs and other tests, such as caliper and packer tests, must be conducted during the drilling and construction of new wells. Results for this testing permit engineers and hydrogeologists to define the appropriate zones in the formation to case, and those to leave open. When construction is complete, well development may be the most important part of the well drilling process and is often underestimated with regard to the time required to properly develop the well.

Once the well is designed and constructed, two issues must be monitored in a wellfield on a regular basis: well performance and water quality. Well performance issues include the routine maintenance items for pumps and motors and record-keeping of withdrawals. Groundwater withdrawal wells provide good service to most utilities for many years, but all wells are subject to fouling and other performance problems. These concerns include

- Mechanical failures, including failures of electrical motors and pumps, and failures of valves,
- Poor operating and maintenance procedures,
- Poor well design and construction practices, including insufficient placement of grout; improper design of pumps, valves, and fittings; and excessive drawdown allowances,
- Hydrogeologic constraints that cannot be evaluated at the time of design or change over time, such as:
  - sand, clay, or rock layers that are unstable and collapse into the borehole;
  - naturally occurring or induced fracturing and faulting;
  - long-term water quality changes caused by changes to the hydraulic regime, such as dams;
  - water hammer to the aquifer;
  - effects caused by mining of the water or introduction of chemicals and microorganisms; and
  - naturally occurring phenomena (such as sinkholes, karst terrain features, or faults).
- High silt or sand content caused by failure to develop the wells fully, or intercepting sand or silt layers that have not or cannot be sealed off in the borehole or corrected in well design.

All of these problems may exist in conjunction with, or as a result of, microbiological fouling problems in wells. As treatment technologies advance, the need to review and correct well performance problems, especially fouling concerns, has taken on greater significance.

All wells can plug or foul because of hydrogeologic, geologic, engineering, and construction factors. The problems are usually physical, mechanical, or environmental in nature. For example, performance problems are typically caused by fouling or sand and silt production in wells. These problems and their likely causes are outlined below.

- Water level decline in the well
  - reduced hydraulic efficiency in the well, most commonly plugging or incrustation of the borehole, screen, or gravel pack
  - regional water level declines
  - well interference or plugging of a gravel pack by sand, silt, or clay
- Lower specific capacity
  - drop in pumping water level
  - reduction in pumping yield caused by incrustation, formation plugging, pump corrosion, and biofouling
- Lower yield
  - dewatering or caving in of a major fracture or other water-bearing zone
  - insufficient development of the well
  - lack of connection to water-bearing fractures
  - pump wear
  - impeller detachment from shaft
  - incrustation, plugging, or corrosion and perforation of column pipe
- Sand/silt pumping
  - presence of sand or silt in fractures intercepted by well completed open-hole
  - leakage around casing bottom
  - inadequate screen and filter-pack selection or installation
  - screen corrosion
  - collapse of filter pack caused by excessive vertical velocity and wash-out
- Silt/clay infiltration
  - inadequate seal around the well casing or casing bottom
    infiltration through filter pack
  - mud seams in rock

Many of these performance problems can be traced to inadequate design and/or construction of the well. Several operational conditions that are warnings of design problems are over-pumping (which results in lowering of the water table), clogging or collapse of a screen or perforation of a section, and corrosion and incrustation aggravated by excessive intake velocities. Other design and construction errors include:

- Poor selection of materials that leads to significant corrosion or collapse of the well casing or screen;
- Poor construction—casing cracks or leaks, leaking or missing grout, misplacement of screens and gravel pack, misalignment (enhanced corrosion or collapse can result);
- Lack of well development—poor well yield, turbidity and sand pumping, biofouling, incrustation, and excessive drawdown can result.

Long-term maintenance of wells should include periodic redevelopment and specific capacity monitoring to ensure efficient operation. Records of this redevelopment should be maintained. Establishing an efficient and timely protocol for redevelopment will save the utility money and protect the well for the long-term.

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Dedication

Dr. Bloetscher dedicates this work to his parents, Frederick and Virginia Bloetscher in Tamarac, Fla. They are the initial (and continuing) proofreaders of all of the documents.

Mr. Muniz dedicates this work to his family, especially his wife, Dr. Lori S. Muniz, who has supported his efforts throughout his career, and to his children Natalie, Alberto (Tony), and Alexis.

Mr. Largey dedicates this work to his wife, Diane Mason-Largey, who has lovingly endured the many long days and nights in the life of a field geologist, and to Alice B. Largey, a true rock hound.

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