A LITERATURE SURVEY OF INFORMATION ON WELL INSTALLATION AND SAMPLE COLLECTION PROCEDURES USED IN INVESTIGATIONS OF GROUND-WATER CONTAMINATION BY ORGANIC COMPOUNDS

By D.H. Dumouchelle, E.A. Lynch, and T.R. Cummings

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MANUEL LUJAN, JR., Secretary

U.S. GEOLOGICAL SURVEY

Dallas L. Peck, Director

For additional information
write to:

District Chief
U.S. Geological Survey
6520 Mercantile Way, Suite 5
Lansing, MI 48911

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Inch-pound units can be converted to metric (International System) units as follows:

Multiply inch-pound unit	By	To obtain metric unit
foot (ft)	0.3048	meter (m)
inch (in.)	2.54	centimeter (cm)
mile (mi)	1.609	kilometer (km)
pound (lb)	453.6	gram (g)
gallon (gal)	3.063	liter (L)
gallons per minute (gal/min)	0.06308	liter per second (L/s)

Temperature

Degrees Fahrenheit (°F) can be converted to degrees Celsius (°C) by the following formula:

$$°C = (°F - 32)/1.8$$

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ABSTRACT

A survey of literature on well installation and water-quality sampling, particularly as they relate to investigations of ground-water contamination by organic compounds, has been conducted. Library card files and computerized data bases were searched to identify journal articles, conference proceedings, technical reports, books, and other publications. Pertinent information has been extracted from 105 references; each reference is listed in a bibliography. Material contained in the report is organized by topical categories that include drilling methods and equipment, well construction, well development, sampling materials and equipment, decontamination of equipment, and sampling techniques and procedures. Unpublished data of the U.S. Geological Survey on sample collection are briefly cited also.

INTRODUCTION

Ground-water-contamination problems throughout the country in recent years have led many investigators to explore appropriate techniques and procedures for accurately characterizing the nature and magnitude of these problems. Information collected during investigations of ground-water quality must reliably reflect the effect of contaminants on the ground-water system if decisions regarding remedial measures are to be effective. Opinions and recommendations based on individual research efforts differ, however, and no comprehensive guidelines exist. Neither is consensus likely in the immediate future on techniques and procedures. Much research in a variety of hydrologic and geologic settings remains to be done.

In recent years, the U.S. Geological Survey has conducted studies of ground-water contamination by organic compounds at sites throughout Michigan. Several of these studies have been made at the request of the U.S. Air Force. In 1986, as part of a general description of work to satisfy requirements of the Air Force's Installation Restoration Program, the Air Force requested a survey of literature pertaining to the collection of ground-water samples in areas where contamination was known or suspected. This report is the response to that request.

Purpose and Scope

This report summarizes literature related to well installation and the collection of ground-water samples for chemical analysis of organic compounds. Literature published during 1974-90 has been included. Evaluations of the relative merits of individual studies reviewed, or recommendations based on the literature survey, are beyond the scope of this report.

Approach

The literature survey began by searching files containing individual published papers in the U.S. Geological Survey's Water Resources Division Office, Lansing, Michigan. A search of the card catalog at Michigan State University's library was also made. The following data bases were searched to locate additional literature: WRSIC (Water Resources Scientific Information Center), NTIS (National Technical Information Service), GeoRef (Geologic Reference File), and Chemical Abstracts. Ground-water data bases of the National Water Well Association were queried for pertinent articles, and abstracts of proceedings of conferences were reviewed. In all, several thousand articles and abstracts were considered, and copies of the most pertinent articles were obtained. Subsequent detailed consideration of their contents reduced their number to the 105 discussed in this report, which are also listed in the bibliography.

At a few places in the report, unpublished information collected by the Water Resources Division of the U.S. Geological Survey in Michigan is cited and discussed. This information has been obtained in the course of investigations of ground-water contamination in an attempt to establish appropriate sampling procedures.

Acknowledgments

Janet Bix, Director of the National Ground Water Information Center in Columbus, Ohio, was particularly helpful in providing information. Her assistance at the National Water Well Association library was instrumental in making literature searches more thorough and complete than they otherwise might have been.

LITERATURE ON WELL INSTALLATION

A wide range of methods and techniques are used in the drilling, construction, and development of wells. The following discussions describe those most commonly used in investigations of ground-water contamination.

Drilling Methods and Equipment

In a review of ground-water sampling techniques, Barcelona, Gibb, Helfrich and Garske (1985, p. 25) note that the choice of a well-drilling method should be based on the geology, the well-depth requirements, and the need to minimize the disturbance of subsurface geochemical conditions. They emphasize that the availability and relative cost of drilling equipment should not be the primary selection criteria. Luhdorff and Scalmanini (1982, p. 359), in a discussion of the selection of drilling method, well design, and sampling equipment, cite nine objectives of a drilling program: (1) The physical penetration of all of the deposits at a site at a desired rate by a hole of desired diameter; (2) identification of lithologic units; (3) collection of water-quality samples during drilling prior to well construction; (4) collection of "undisturbed" samples of deposits; (5) geophysical logging; (6) adaption to special conditions, such as high pressure or the presence of toxic substances; (7) containment of drill cuttings and fluids; (8) conversion of the hole into a monitoring well during the initial construction process; and (9) completion of a monitoring well in the hole after a lapse in time to aid in interpretation of geologic and geophysical data. Gillham and others (1983, p. 36) call attention to the possibility that lubricants used on joints, moving parts, and surfaces to prevent corrosion can affect the quality of water in a well; they recommend that care be taken to clean lubricants or other organic compounds from equipment prior to drilling.

Cable-Tool Drilling

Cable-tool drilling has been used mainly for the installation of water-supply wells, but according to Keely and Boateng (1987, p. 302-303), the method may be advantageous for the installation of monitoring wells at hazardous waste sites. In cable-tool drilling, a hole is deepened by repeatedly lifting and dropping a heavy string of tools suspended by a cable. At the end of the string is a chisel-shaped bit that loosens unconsolidated material and breaks rock upon impact. A casing is temporarily installed to control caving and to minimize contaminant migration from one deposit to another. Above the saturated zone, it is sometimes necessary to add clean, uncontaminated water to the hole. The cuttings and water mix to form a slurry, which is periodically bailed from the hole. The well is constructed within the temporary casing, and a filter pack and grout are installed as the temporary casing is gradually withdrawn. An advantage to drilling wells with a cable tool, according to Keely and Boateng, is that little water is added and, when used, it is contained within the temporary casing. Thus, chances of altering ground-water quality are reduced. Another advantage cited is that disturbance of sediments is minimal because the smooth, temporary casing is slowly advanced. In addition, it is possible to drill a hole with a diameter large enough to install multiple monitoring wells within a single temporary casing. Keely and Boateng state that the major disadvantages of the method are the slow drilling rate and the cost.

According to Driscoll (1986, p. 276-277), cable-tool drilling may be the best, and in some cases the only, method to use in coarse glacial till, boulders, or rocks that are highly disturbed, broken, fissured, or cavernous. He states that cable-tool drilling is advantageous where aquifers are thin and yields are low because the method permits identification of zones that may be overlooked if other methods are used. Driscoll also cites other advantages: (1) Rigs are simple in design, require little sophisticated maintenance, and are relatively inexpensive; (2) drilling machines have low energy requirements; (3) the driller maintains intimate contact with the drilling process and the materials encountered by keeping a hand on the drilling cable; (4) because of their size, rigs can be operated in rugged terrain or in other areas where space is limited; and (5) wells can be drilled in deposits where loss of circulation is a problem. He cites the following disadvantages: (1) Casing costs are usually higher than for other drilling methods because heavier wall or larger diameter casing may be required, and (2) long strings of casing cannot easily be pulled from some deposits unless special equipment is available.

Scalf and others (1981, p. 25-26) believe that during cable-tool drilling excellent lithologic samples can be collected with the use of a sand-pump bailer. They state that information about water-bearing zones, such as their relative permeabilities and water quality, can be readily obtained. Cable tools can be used to drill in all materials; they are best when used in caving-prone gravel formations or where cavities occur above the water table. Disadvantages cited include a slow drilling rate, a minimum well diameter of 4 in. (inches), and the unavailability of rigs in some parts of the country. Scalf and others also state that the use of a temporary casing can complicate well completion and grouting.

The U.S. Environmental Protection Agency (USEPA) (1986, p. 74-75) states that, although cable-tool drilling is slow, the method has many advantages when installing wells in relatively shallow consolidated deposits and in unconsolidated deposits. The USEPA recommends that a temporary drive pipe having a minimum diameter of 6 in. be used to aid in the placement of well casing, screen, and gravel pack. The USEPA also states that a seal at least 5 ft (feet) long should be made prior to removal of the drive pipe, and that the drive pipe should be removed while the sealant is still fluid so the sealant can fill remaining annular space.

Direct Rotary Drilling

During direct rotary drilling, a fluid is pumped down a rotating pipe and returned to the surface through the annulus. The rotating drill pipe turns a bit that loosens unconsolidated materials and breaks up rocks. The drilling fluid cools the bit, removes cuttings, and creates a mud cake that prevents excess fluid loss and caving. Drilling fluids may be water, water and bentonite, or water and other additives. According to Barcelona and others (1983, p. 18), rotary equipment is capable of drilling monitoring wells in all deposits to almost any depth. Rigs are also available throughout the country.

Barcelona, Gibb, Helfrich, and Garske (1985, p. 28-29) believe that the use of drilling muds in direct rotary drilling makes the method inappropriate for constructing monitoring wells because muds contain organic matter that can affect water quality. They believe that the method also may cause circulation of contaminants.

Scalf and others (1981, p. 20) list advantages and disadvantages of direct rotary drilling. Advantages include the ability to drill without installing temporary casing, the ability to collect fairly reliable lithologic samples, and the relatively inexpensive cost. A disadvantage is that drilling fluid can mix with water in a deposit and thus be difficult to remove; bentonite or additives may also affect water quality. In addition, the top of the saturated zone is difficult to detect, and information regarding water-producing zones may not be obtained during drilling.

Keely and Boateng (1987, p. 301) state that direct rotary drilling is a popular method of drilling because it is fast and because geophysical logs may be run in the uncased hole. Despite advantages, they believe that the inability to develop a well adequately and to remove the mud residues restricts the use of direct rotary drilling. Mud that remains in surrounding deposits can reduce permeability and alter the chemical characteristics of the water. W.L. Bradford (U.S. Geological Survey, written commun., 1985, p. 5) states that the effect of bentonite muds on the chemical composition of water may be detected for a period of years after well development. Lubricant-sealers on drill stem joints also are recognized by Bradford as a potential source of contamination.

Gillham and others (1983, p. 39-40) state that, if contaminated zones are encountered in direct rotary drilling, drilling fluid may become contaminated and appropriate disposal after the completion of a well may be a problem. To alleviate some problems, they suggest drilling a hole to a depth several meters above the zone to be sampled, installing the casing, and circulating water to clean it. The remainder of the hole should be drilled with little or no drilling fluid.

If water is to be used as a fluid in direct rotary drilling, the U.S. Environmental Protection Agency (1986, p. 76-77) recommends analysis of the drilling water to ensure that contaminants are not present. According to the USEPA, one of the disadvantages of this drilling method is that it is difficult to recognize water-bearing zones because of the water used in drilling. Other disadvantages cited include the difficulty of maintaining an open hole when drilling in poorly consolidated deposits and the difficulty of maintaining water circulation in highly fractured terrains. The use of muds is cited as a benefit in direct rotary drilling because it stabilizes the hole as it is drilled. The USEPA recommends that consideration be given to the effect of mud on water quality, on samples of deposits, and on the operation of the well. Problems that can result from the use of bentonite mud are cited as (1) a reduction in the effective porosity of the deposits around the well, (2) a local change in the pH of ground water, and (3) the introduction of contaminants into the well from additives used to modulate viscosity and density of the mud.

Reverse-Circulation Rotary Drilling

According to Luhdorff and Scalmanini (1982, p. 360), reverse-circulation rotary drilling allows larger diameter holes to be installed than is possible by use of direct rotary drilling. In reverse-circulation rotary drilling the drilling fluid circulates up from the bit through the rotating drill pipe rather than down as in direct rotary drilling. The hydrostatic pressure of the fluid keeps the hole open, and there is less need than in direct rotary drilling for specialized mud; the length of time required for well development is also reduced. Keely and Boateng (1987, p. 301) note that the drilling fluid used in reverse-circulation rotary drilling is much less viscous than that used in direct rotary drilling; often the fluid is clear water. They say that cross-contamination is still possible, however, because of the large volume of water used. According to Schmidt (1982b, p. 121), reverse-circulation rotary drilling is more suited to drilling consolidated rock than are cable-tool or casing hammer methods; depths exceeding 2,000 ft have been reached. Barcelona, Gibb, Helfrich, and Garske (1985, p. 28) and Scalf and others (1981, p. 26) do not recommend reverse-circulation rotary drilling for monitoring wells, however, because of the large quantities of water required and because of the possibility that this water will enter the aquifer.

According to Driscoll (1986, p. 294-295), reverse-circulation rotary drilling is most successful in soft sedimentary rocks and unconsolidated sand and gravel where the static water level is 10 ft or more below land surface. He believes that the method is advantageous because the porosity and permeability of deposits near the hole are relatively unchanged during drilling, because casing is not required during well installation, because the method can be used in all but igneous and metamorphic rocks, and because the low velocity of the drilling fluid reduces washout. Driscoll notes, however, that reverse-circulation rotary drilling rigs are usually larger than other rigs, which precludes drilling in some areas.

Double-Wall Reverse-Circulation Rotary Drilling

Scalf and others (1981, p. 26) discuss a variation of reverse-circulation rotary drilling in which water or air circulates through a double-wall drill pipe by moving down the annulus between the pipes and up through the inner pipe. Some of the advantages of reverse-circulation rotary drilling cited are that water in deposits is not contaminated by drilling water, excellent lithologic samples can be obtained, and, if air rotary equipment is used, immediate information on water-bearing properties of deposits is available. Caving is also less of a problem than in air-rotary drilling. Scalf and others state, however, that grout placement can be difficult and that double-wall reverse-circulation equipment is expensive and not always readily available. Driscoll (1986, p. 303) adds, as advantages, that fast penetration rates are possible in coarse alluvial deposits and fissured rock, and that problems of lost circulation are either eliminated or substantially reduced.

Air Rotary Drilling

Luhdorff and Scalmanini (1982, p. 360) describe a modification of direct rotary drilling in which compressed air rather than water or drilling mud is used as a drilling fluid. The cuttings are removed by high-velocity air directed up the hole. Although foaming or misting agents are used to help clean the hole, the integrity of a deposit must be relied on to maintain an open hole because of an absence of hydrostatic pressure from drilling fluid.

Air-rotary drilling is thought to be the best drilling method in hard rock because mud is not used, according to Barcelona, Gibb, Helfrich, and Garske (1985, p. 27-28). They note that, in soft or unconsolidated material, a casing must be driven to prevent caving and, in highly creviced rocks, it can be difficult to maintain air circulation. In hard rocks overlain by a minimum of unconsolidated overburden, they consider air-rotary drilling to be a good method for constructing monitoring wells without adversely affecting water quality. If a well is drilled to monitor the concentration of organic substances in water, they suggest that air from the compressor must be filtered to prevent oil from entering the hole. They also note that foam is sometimes added to improve drilling, and that this foam commonly contains organic substances that can modify water quality. If drilling is in a highly contaminated deposit, they believe soil and water blown from the hole can create an exposure hazard.

An advantage to air rotary drilling, according to Scalf and others (1981, p. 22), is that the top of the saturated zone can be determined because water will be blown from the hole with the cuttings; field analyses of the water can be performed. Another advantage cited is that lithologic samples can be excellent if the deposits are hard and dry. A disadvantage is that water can flow from one unit to another that has a lower hydrostatic head until one of the units is cased and grouted.

The U.S. Environmental Protection Agency (1986, p. 75-76) concludes that air-rotary drilling is most appropriate where upper soil horizons are not contaminated and where sloughing of the hole wall would not contaminate the well. They also recommend that air from the compressor on the drilling rig be filtered to prevent contamination by oil from the compressor and that use of foam or joint compounds used on the drill rods be avoided.

Solid-Stem Auger

Solid-stem augers are most effective in shallow, unconsolidated materials, according to Scalf and others (1981, p. 26-29). A hole is drilled by rotating the solid-stem continuous-flight augers into the ground. The cuttings are brought to the surface on the rotating flights; no drilling fluids are needed as a result. When the desired depth has been reached, the augers are rotated, without advancing, to clean the hole. The augers are then removed, and the well is constructed. Scalf and others note that rigs are mobile and fast and, when drilling in unconsolidated material, inexpensive to use. Drilling depths, however, are restricted to about 150 ft. The following are cited disadvantages of solid-stem augers: (1) Lithologic samples returned by the augers may not be completely representative of the zone penetrated; (2) if the hole is deep, a determination of depth to the water table can be difficult; and (3) the augers cannot be used in hard rock. W.L. Bradford (U.S Geological Survey, written commun., 1985, p. 5) notes that, in caving sands or water-bearing zones, it is unlikely that the hole will remain open as the auger is removed. He states that, because augers create holes having enlarged and variable diameters, it is more difficult to assure a complete grout seal around the annulus than it is using some other drilling methods.

According to Gillham and others (1983, p. 37-38), solid-stem auger drilling can cause the least disturbance of all drilling methods in unconsolidated deposits. They state, however, that vertical mixing of water from different zones in a hole can prevent the collection of representative water samples. Gillham and others suggest that the problem can be avoided by augering through the contaminated layer with a large-diameter hollow-stem auger and then drilling to the desired depth with a smaller diameter auger.

The U.S. Environmental Protection Agency (1986, p. 74) states that solid-stem continuous-flight auger drilling is limited to consolidated sediments or fine-grained unconsolidated materials that will not slough when the auger is withdrawn. The difficulty of collecting soil or lithologic samples that permit accurate determination of site stratigraphy is also cited as a problem.

Hollow-Stem Auger

Drilling with hollow-stem augers is fast and relatively inexpensive in unconsolidated materials, according to Keely and Boateng (1987, p. 304). They conclude that the hollow-stem-auger method is preferable to other rotary methods because lithologic samples can be obtained with split-spoon samplers, no drilling fluids are needed, and well construction can begin inside the hollow auger flights after removal of the center plug when the desired depth is reached. However, hollow-stem augers cannot drill in hard rock or to depths much greater than about 100 ft. Keely and Boateng recommend use of a small-diameter tricone bit through the hollow stem to shatter large cobbles encountered. They suggest that clays and silts that are smeared into sand and gravel strata by the action of the auger can alter local permeability and the proportion of flow from each stratum to the well. They state that water quality in hollow-stem auger holes can be altered if water from an overlying stratum drains downward or if contaminated cuttings from a lower stratum come in contact with overlying materials. They note that the removal of the center plug in the auger can be accompanied by a rise of loose sediments in the lower auger flights that may complicate the collection of representative solid samples.

Hackett (1988, p. 60) states that, in cohesive materials, the auger column may be withdrawn to install the well casing and intake, filter pack, and annular seal. If, however, the hole will not remain open, he suggests that a well be installed by using the hollow stem as a temporary casing. He notes that, if working space between augers and well casing is too small, installing the filter pack and annular seal can be difficult. Hackett (1987, p. 54-60) states that cuttings from cohesive deposits may compact along the hole wall as they are brought to the surface. He states that the diameter of a hole in noncohesive deposits can be enlarged by caving of side walls. Reaming also can enlarge the hole beyond the outside diameter of the auger flights. Eccentric auger rotation can result in an uneven diameter of the hole. Hackett states the rise of sands can be overcome by use of clean water to maintain positive pressure inside the hollow stem. When shallow ground water has been contaminated and wells need to be installed to a greater depth, he suggests that a large-diameter surface casing be used to seal off the contaminated zone before continuing drilling with a smaller diameter auger.

According to Richter and Collentine (1983, p. 224), hollow-stem augers are useful for drilling in unconsolidated materials and soft bedrock, but are poor where large cobbles or boulders are present. Scalf and others (1981, p. 31) discuss the advantages of using a screened hollow-stem auger for drilling. They state that the depth to the water table can be determined accurately if a hollow-stem auger is used, and that water samples can be collected at any depth below the water surface during drilling without removing the auger or setting a casing or screen.

If a hollow-stem auger is used, the U.S. Environmental Protection Agency (1986, p. 73) recommends that the space between the inner diameter of the auger and the outer diameter of the well casing be at least 3 to 5 in. to permit effective placement of the filter pack and annular seal.

Hand Auger

Standard soil-sampling augers have been successfully used to install shallow wells when water samples at or just below the water table were required (Twenter and others, 1983, p. 8-9, and Cummings and Twenter, 1986, p. 62-83). By successive attachment of 4-foot extensions to the auger heads, wells have been installed to depths of 30 ft in unconsolidated material. Auger heads having a diameter of 3 1/4 in. are convenient for installing 2-inch wells in studies of ground-water contamination by fuel substances, which are normally trapped in the capillary fringe at a spill site. The low cost and speed of installation allow detailed examination of small areas.

Bucket Auger

Bucket augers are commonly used to construct large-diameter shallow wells. According to Barcelona, Gibb, Helfrich, and Garske (1985, p. 29), use of bucket augers is limited to fine-grained deposits in which holes will remain open. Scalf and others (1981, p. 31-33) describe a large (8-inch minimum diameter by 2-foot-long) bucket with a cutting edge that is slowly rotated into the ground. When the bucket fills with cuttings, it is brought to the surface and emptied. They state that no drilling fluids are needed, lithologic samples are excellent, and casing and screen installation and grout placement are easy unless a small-diameter casing is used. Below the water table caving is cited as a problem. Scalf and others state that bucket augering is restricted to unconsolidated deposits and to depths of less than about 50 ft; they also note that drilling rigs are not widely available.

Driscoll (1986, p. 310-311) states that bucket augering is most suitable in areas where clay deposits prevent caving during drilling and installation of casing. Although augering in sand below the water table is difficult, he believes that it is possible if the hole is kept full of water or drilling fluid. However, he notes that highly permeable sand deposits may require a large supply of water at a drilling site. Further, cobbles and boulders can cause problems because they must be removed from the bottom of the hole individually.

Casing Hammer

According to Keely and Boateng (1987, p. 305), casing-hammer drilling combines some of the desirable features of the auger, rotary, and cable-tool methods. In casing-hammer drilling, an auger or mud-rotary drill is used through the center of a temporary casing, which is driven into the hole with a casing hammer. The hole is drilled 1 to 2 ft, and casing is driven to the drilled depth. The process is repeated until the desired hole depth is reached. Richter and Collentine (1983, p. 224) consider the method applicable in unconsolidated deposits and soft rock, but it is not generally applicable in hard rock or where boulders are present. Advantages of the method cited are: (1) Temporary casing tends to seal off contaminated intervals, thereby preventing vertical movement of contaminants; (2) screens can be precisely placed; and (3) completion of wells within the temporary casing is easy. However, Richter and Collentine state that removal of the temporary casing without damaging the permanent casing can be difficult; drilling rigs also are expensive and not readily available. According to Woessner (1988, p. 72), an advantage of casing-hammer drilling is the easy collection of lithologic and water-quality samples at discrete depths. Although holes less than 6 in. in diameter cannot be constructed, small-diameter wells can be installed within a driven casing. Gandl and Webb (1985, p. 148-149) describe the use of Shelby tubes[1] for the collection of soil samples as a casing-hammer hole is deepened.

Diamond Drilling

Gillham and others (1983, p. 40-41) discuss diamond drilling, a method commonly used in crystalline rocks to obtain cores and to drill wells. Diamond teeth are set in a bit attached to a core barrel. Water circulates through the bit to cool the cutting surface. A disadvantage of diamond drilling cited is that, in permeable zones, drilling water can enter the rocks and modify water quality.

Jetting

According to Scalf and others (1981, p. 33-34), jetting is fast and inexpensive. Water or mud is pumped down through a small-diameter pipe fitted with a chisel bit or special jetting screen. The bit and jetting action of the water dislodge material, which is forced to the surface through the annulus. Scalf and others state that, without special equipment, jetting can be used only in very soft deposits and when installing wells 30 ft or less in depth. They note that only a small amount of equipment is necessary when jetting; thus, wells can be installed in locations that are difficult to reach with a large drilling rig. The diameter of casing is generally limited to 2 in., which restricts the type of sampling equipment that can be used. The large amount of water needed and possible grouting difficulties are considered disadvantages.

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[1] A thin-walled soil sampler, 12 to 30 in. long.

Driscoll (1986, p. 307-308) discusses two additional drilling methods in which jetting is used. In one, the jet-percussion method, water is forced down a hollow drill rod, out through the ports on the bit, and back to the surface with cuttings through the casing. During drilling, the bit is raised and lowered to loosen the deposit. Driscoll states that wells 3 to 4 in. in diameter can be drilled to depths of about 200 ft with this method. In a second method discussed, hydraulic percussion, the drill rod is lifted and dropped in a casing filled with water. A check valve in the bit permits water and cuttings to be forced to the surface through the drill rod as the bit moves up and down. According to Driscoll, this method is restricted to small-diameter wells drilled through sands and clays that are relatively free of cobbles and boulders.

Driven Well Points

Richter and Collentine (1983, p. 225) consider driven well points to be a rapid and inexpensive way to obtain water-level and chemical-quality data. Well points are considered applicable in areas where unconsolidated deposits are present and where the water table is shallow. A drilling rig is generally not required because the well point is driven by a hand- or trailer-mounted hammer. A disadvantage cited is that no lithologic samples can be collected.

Backhoe

According to Richter and Collentine (1983, p. 225), backhoes can be used to excavate shallow pits or to install casing of very large diameter. They state that backhoes are fast, mobile, and readily available, and permit collection of representative lithologic samples. However, use of backhoes is not recommended when water-quality samples are needed because the potential for contamination between lithologic units is extremely high.

Construction Considerations

The type of materials used in the construction of wells installed in investigations of ground-water contamination, particularly contamination by organic compounds, can have a major effect on the quality of water in a well. The diameter of the well, because it affects collection of representative samples, also needs to be considered. Other important considerations are the nature of the annular seal and drilling fluids.

Well Casings, Screens, and Joints

Materials used in the construction of wells can modify the chemical characteristics of ground water. According to Morrison (1983, p. 70-72), the choice of construction materials should depend on the type of chemical analysis required. PVC (polyvinyl chloride) is cited as the most widely used material and, of the plastic casings, probably has the least effect on samples collected for the analysis of volatile organic compounds. Morrison states that, because of the high cost of Teflon[2] casings and screens, many wells are installed with Teflon below, and PVC above, the water table. He also believes that plastic casing should be smooth inside and outside to provide clearance for downhole equipment. Use of casings with threads machined directly into the pipe, which have a flush joint between the inner and outer diameters, eliminate problems associated with solvents used to weld the pipe, according to Morrison.

W.L. Bradford (U.S. Geological Survey, written commun., 1985, p. 13-14) ranks casing materials based on their chemical reactivity. Glass is considered the most unreactive, followed by Teflon, stainless steel, galvanized steel, PVC, black iron, and fiberglass, in order of increasing reactivity. The use of black iron, galvanized steel, and stainless steel pipe is recommended for casing if volatile organic compounds are the major contaminant of interest, if trace metals are not of interest, and if the pH of the ground water is greater than 5.0. Bradford states that new Teflon and other plastics should be washed with detergent and flushed with water for several hours to remove any leachates.

Driscoll (1986, p. 720-721) discusses advantages and disadvantages of PVC, polypropylene, Teflon, Kynar[3], low-carbon steel, and stainless steel as casing and screen materials. He states that PVC has excellent chemical resistance to weak alkalies, alcohols, aliphatic hydrocarbons, and oils, and that it has good chemical resistance to strong mineral acids, concentrated oxidizing acids, and strong alkalies. However, he states that PVC is weaker, less rigid, and more temperature sensitive than are metallic materials, and that it has poor chemical resistance to ketones, esters, and aromatic hydrocarbons. Driscoll believes that polypropylene has excellent chemical resistance to mineral acids, good to excellent chemical resistance to alkalies, alcohols, ketones, and esters, and good chemical resistance to oils, but less satisfactory chemical resistance to concentrated oxidizing acids, aliphatic hydrocarbons, and aromatic hydrocarbons. Polypropylene is also cited as having poor machinability because it tends to melt rather than cut when slotted. Teflon is cited as having outstanding resistance to chemical attack and as being insoluble in all but a few fluorinated solvents. According to Driscoll, Kynar has greater strength and water resistance than Teflon, is resistant to most chemicals and solvents, and costs less than Teflon. He notes that Kynar is not readily available, however, and its chemical resistance to ketones and acetones is poor. He cites other disadvantages of Kynar: (1) It is heavier than other plastics, (2) it may react with and sorb some constituents, and (3) it is not as chemically resistant as stainless steel. Driscoll cites advantages of low-carbon steel as: (1) It is strong and rigid, (2) it is not temperature sensitive, (3) it is readily available, and (4) its cost is low compared to the cost of stainless steel and Teflon. He considers the strength of stainless steel through a wide

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[2] Teflon is a trademark for resins made of tetrafluoroethylene polymers or of fluorinated ethylene-propylene copolymers.

[3] Kynar is a trademark for polyvinylidene fluoride.

range of temperatures, its excellent resistance to corrosion and oxidation, its ready availability, and the moderate cost of casing to be advantages. Driscoll cites the following disadvantages: (1) It is heavier than plastics, (2) it may act as a catalyst in some organic reactions, and (3) the cost of stainless-steel screens is greater than the cost of plastic screens.

Sosebee and others (1982, p. 43-45) studied contamination of ground water by PVC adhesives and PVC primers in the laboratory and in the field. Tetrahydrofuran, methylethylketone, methylisobutylketone, and cyclohexanone, major constituents of the adhesives and primers, were found in water surrounding bonded joints. Sosebee and others state that the presence of these compounds in water can mask the presence of other hazardous contaminants when chromatographic analyses are made. Such tests indicate, however, that successive washes with water decrease the amount of these compounds in water.

Barcelona and others (1983, p. 37-39) studied the effects of contaminated water on materials used in well construction and in sampling. Rigid well-casing materials were ranked from best to worst: Teflon, stainless steel 316, stainless steel 304, PVC 1, low-carbon steel, galvanized steel, and carbon steel. They state a properly constructed well with a Teflon casing can be expected to perform consistently better than a well with other casing materials. Further, Teflon has not been reported to contribute organic or inorganic contaminants to aqueous solutions. Teflon is considered chemically inert, with poor sorptive properties and low potential for leaching. Stainless steel is considered best when a durable corrosion-resistant material is needed. Stainless steel 316 also is cited as being less susceptible to pitting from organic acids or halide solutions than is stainless steel 304. Barcelona and others believe that, after removing the residues of manufacturing, stainless steel can be expected to function nearly as well as Teflon. They note that carbon and copper steel casings can corrode, and that galvanized steel is generally more resistant to corrosion than is conventional steel.

Barcelona and others (1983, p. 39-44) state that schedule 80 PVC is durable enough for most well-construction applications and will outperform ferrous materials in acidic environments of high ionic strength. PVC is considered chemically resistant to all compounds except low-molecular weight ketones, aldehydes, and chlorinated solvents. Barcelona and others believe that problems may occur, however, if PVC is in contact with aqueous mixtures of organic compounds under conditions that encourage leaching of the polymer matrix. Rigid PVC materials, if they have passed a National Sanitation Foundation leach test, are virtually free of plasticizers. Failure of the test, according to Barcelona and others, is defined as exceeding the maximum contaminant levels set by the U.S. Environmental Protection Agency's drinking-water regulations. They state, however, that rigid PVC contains several types of additives and therefore has the potential to contaminate ground-water samples. Barcelona and others believe the occurrence of significant contamination depends on site conditions and the specific PVC formula used. They note that PVC may be coated with natural or synthetic waxes, fatty acids, or fatty acid esters, and thus it should be washed with detergent and rinsed with water before use. They state small amounts of solvent cements also can affect samples for months; threaded joints are thus preferred to cemented joints. Manufactured screens rather than hand-sawn slots are recommended to avoid exposing fresh surfaces. Paired wells, one being PVC and the other a nonpolymeric material, are suggested if environmental conditions are unknown or if high levels of organic compounds are present. They believe that the use of two different well casing materials should reveal any contamination resulting from the PVC.

Houghton and Berger (1984, p. 206) conducted a field study of PVC, acrylonitrile-butadiene-styrene copolymer, and steel well casings to test their effects on water quality. Results of the study indicated that acrylonitrile-butadiene-styrene copolymers may be more susceptible to leaching and adsorption than is PVC. Compared to water from wells with steel casings, water from the wells cased with acrylonitrile-butadiene-styrene copolymers and PVC was enriched in dissolved and total organic carbon.

Reynolds and Gillham (1986, p. 125-131) conducted a study that indicated absorption by polymer well casings could significantly modify the quality of water standing in a well. Tetrachloroethylene, bromoform, hexachloroethane, 1,1,1-trichloroethane, and 1,1,2,2-tetrachloroethane in water solution were used in tests. Concentrations ranged from about 20 to about 45 µg/L (micrograms per liter). Some materials absorbed these compounds so fast that significant absorption occurred during the recovery and sampling period. They believe that absorption by PVC occurred slowly enough that, if development and sampling take place on the same day, modification of water quality should not be significant. Results were similar with well casings made of polytetrafluoroethylene, except when tetrachloroethylene was the contaminant in water. Tetrachloroethylene was rapidly absorbed after only minutes of exposure. PVC casing is considered to be better than polytetrafluoroethylene for collecting samples containing tetrachloroethylene. Further, the absorption capacity of the polymer is not reduced by surface saturation because diffusion of compounds into the polymer matrix continues to make surface-adsorption sites available. Reynolds and Gillham note that it is possible for contaminants to diffuse through the casing, and for absorbed compounds to diffuse out of the polymer matrix and contaminate ground water.

Berens (1985, p. 64) observed that PVC may be permeated by organic compounds in a matter of days or weeks in the presence of strong, nearly pure, swelling agents or solvents; however, in the absence of extremely high levels of environmental contamination, permeation of PVC pipe is calculated to be virtually zero for many centuries.

Barcelona and Helfrich (1986, p. 1182-1183) observed systematic differences in the concentrations of chlorinated hydrocarbons in water collected from wells that have casings made of stainless steel, PVC, or polytetrafluoroethylene. Differences were attributed to sorptive effects of polymeric casings. Although Barcelona and Helfrich noted a significant effect of well-casing materials on concentrations of chlorinated hydrocarbons in water, they concluded that the effect was unpredictable.

In a study of five city water systems that use PVC pipes, Dressman and McFarren (1978, p. 30) found that the highest concentration of vinyl choride (1.4 µg/L) was in water from a system less than 1 year old; the lowest concentration (0.03 µg/L) was in water from a system 9 years old. Although results of tests are considered valid by Dressman and McFarren, they state that interpretation of the data is difficult because the vinyl chloride content of the PVC was unknown.

Curran and Tomson (1983, p. 70) studied the leaching of trace organics from five plastics: polypropylene, polyethylene, Teflon, Tygon[4], and PVC. Two water solutions, one containing 0.5 µg/L 1,4-dichlorobenzene and the other containing 0.05 µg/L naphthalene, were pumped through tubing made from each plastic. Analyses of the water indicated that Teflon yielded less of these compounds than the other plastics. On the basis of their tests, Curran and Tomson believe that rigid PVC, if washed and rinsed with room temperature water prior to installation, is an acceptable alternative to Teflon for monitoring wells. Polyethylene and polypropylene are believed to be satisfactory casing materials if trace amounts of organic compounds are not significant in an investigation.

Miller (1982, p. 237-244) tested schedule 40 PVC 1120, low-density polyethylene, and polypropylene casings in the laboratory. The casings were exposed to water solutions containing trichlorofluoromethane, 1,1,1-trichloroethane, trichloroethylene, 1,1,2-trichloroethane, bromoform, and tetrachloroethylene. The results of the study indicated that schedule 40 PVC 1120 was superior to polyethylene and polypropylene. PVC well casing did not adsorb or release five of the six organic compounds tested. Among the compounds tested, only tetrachloroethylene was adsorbed on PVC. The amount adsorbed was 25 to 50 percent greater than in control experiments. Tetrachloroethylene was totally adsorbed by both polyethylene and polypropylene casings. With respect to control experiments, 50 to 75 percent of the other contaminants were adsorbed on polyethylene. Adsorption of 1,1,1-trichloroethane on polypropylene was greater than that on PVC, but less than that on polyethylene. The remaining four contaminants tested adsorbed on polypropylene in amounts ranging from 25 to 50 percent with respect to controls. Virtually no subsequent desorption of tetrachloroethylene by any of the casings was detected. Polyethylene and polypropylene released 50 to 100 percent of the bromoform and about 25 percent of the other contaminants. With regard to rates of adsorption and desorption, PVC was found to have the slowest rates for both processes. Adsorption on polyethylene was most rapid, but adsorption was complete after 1 week.

Parker and others (1990, 146-155) studied the effect of four casing materials on the sorption or desorption of organic contaminants in ground water. Casings made of PVC, polytetrafluoroethylene, stainless steel 304, and stainless steel 316 were used in tests. Casings were cut into sections ranging in length from 11 to 14 mm (millimeters), and the sections were cut into quarters. Using water from a well, 2 mg/L (milligrams per liter) solutions of the following compounds were prepared: trichloroethylene, cis 1,2-dichloroethylene, trans 1,2-dichloroethylene, chlorobenzene, o-dichlorobenzene, p-dichlorobenzene, and m-dichlorobenzene, m-nitrotoluene, 1,3,5-trinitrobenzene, and hexahydro 1,3,5-trinitro-1,3,5-triazine. Sections of the casings were placed in the solutions of these compounds and left for periods of 1, 8, 24, 72, 168, and 1,000 hours. Results of tests indicated that the stainless steel casings did not sorb the compounds. Significant losses of the organic compounds from solution were observed with the two

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[4] Tygon is a trademark for a series of vinyl compounds.

plastic casings. Although the rate of loss differed for each compound, losses were always greater with polytetrafluoroethylene than with PVC. Neither plastic, however, sorbed hexahydro 1,3,5-trinitro-1,3,5-triazine or 1,3,5-trinitrobenzene even after 1,000 hours of immersion in the test solutions. On the basis of their tests, Parker and others conclude that PVC casing is superior to polytetrafluoroethylene casing if water is to be analyzed for organic compounds. Parker and others also conducted experiments to determine if the sorption of organic compounds was reversible. Sections of PVC and polytetrafluoroethylene casing that had been immersed in test solutions for 1,000 hours were rinsed and placed in fresh well water for three days. Measurements indicated that the amount desorbed was generally equivalent to the amount sorbed. Trichloroethylene and trans 1,2-dichloroethylene were desorbed most readily. Parker and others suggest that diffusion from the polymers may be more rapid because of the relatively small size of these two molecules.

Sara (1986, p. 332-336) discusses materials used in monitoring well construction. Based on experience with almost 3,000 monitoring wells, he concludes, after a brief review of work by other investigators, that rigid PVC well casing performs as well as, if not better than, Teflon or stainless steel. He recommends the use of threaded joints to eliminate the possibility of contamination of samples by solvent-cemented joints. Driscoll (1986) states that joints can be made watertight by wrapping them with Teflon tape or by placing a Teflon or Viton[5] O-ring in the joint.

Sykes and others (1986, p. 47) conducted a study to determine if differences in the adsorption of methylene chloride, 1,2-dichloroethane, trans 1,2-dichloroethylene, trichloroethylene, toluene, and chlorobenzene were significant between PVC, polytetrafluoroethylene, and stainless-steel 316 casings. No statistically significant differences were observed in the amount absorbed on each casing when exposed to water containing approximately 100 parts per billion of these organic compounds for periods of 1 hour, 24 hours, and 7 days.

According to the U.S. Environmental Protection Agency (1986, p. 78-83), many of the materials used for casings and screens in monitoring wells may modify the quality of ground water. Also, many materials may not have the long-term structural characteristics required of Resource Conservation and Recovery Act (RCRA) monitoring wells. In selection of well casings and screens, the USEPA recommends that the anticipated lifetime of the monitoring program, well depth, chemical constituents to be monitored, geochemical environment, and other site-specific factors be considered. Examples of the effects of certain environments on specific types of casings are cited. The USEPA states that (1) steel casing deteriorates in corrosive environments; (2) PVC deteriorates when in contact with ketones, esters, and aromatic hydrocarbons; (3) polyethylene deteriorates when in contact with aromatic and halogenated hydrocarbons; and (4) polypropylene deteriorates when in contact

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[5] Viton is a trademark for fluoroelastomers based on a copolymer of vinylidene fluoride and hexafluoropropylene.

with oxidizing acids, aliphatic hydrocarbons, and aromatic hydrocarbons. Steel, PVC, polyethylene, and polypropylene also can modify water quality by releasing or adsorbing constituents to or from ground water. The USEPA also states that fluorocarbon resins or stainless steel should be specified for use in the saturated zone if the concentrations of volatile organic compounds are to be monitored for a 30-year period. If a highly corrosive environment is expected, fluorocarbon resins are preferable to stainless steel. Where nonvolatile organic compounds are in water, PVC well casings and screens approved by the National Sanitation Foundation or the American Society for Testing and Materials may be appropriate. In the unsaturated zone, casing constructed with stainless steel, fluorocarbon resins, or PVC is considered appropriate. The USEPA recommends that the suitability of other casing and screen materials be evaluated on a site-specific basis. They also state that plastic pipe sections must be flush threaded or be connected by other mechanical methods that does not introduce contaminants into the well. Monitoring wells should be structurally sound in order to withstand vigorous well-development techniques. Steam cleaning of well casings and screens prior to installation is recommended to ensure that all oils, greases, and waxes have been removed. Casings and screens constructed of fluorocarbon resins should be washed with detergent prior to use rather than steam cleaned because such materials are soft.

If less-than-optimal materials are to be used for a well casing, an identically constructed well should be installed in an uncontaminated part of the aquifer as a source of control samples (Pettyjohn and others, 1981, p. 182; Scalf and others, 1981, p. 19; Seanor and Brannaka, 1983, p. 42).

Driscoll (1986, p. 719) recommends that (1) a screen be constructed from material that is inert in the water, (2) the open area of a screen be large enough to facilitate rapid sampling, (3) the slot size be small enough to prevent the filter pack or surrounding deposit from entering but be large enough for well development, and (4) the slot openings be nonplugging in design.

Well Diameters

Schalla and Oberlander (1983, p. 56-57) discuss several advantages and disadvantages of small- (2-inch), medium- (4-inch), and large- (6-inch or greater) diameter wells. Installation of small-diameter wells normally costs less than installation of large-diameter wells. According to Schalla and Oberlander, more accurate data concerning the elevation of the water table, the transmissivity and porosity of deposits, and the areal extent of a plume can be obtained at acceptable costs by using several small-diameter wells rather than one large well. They believe that, if the aquifer has a high transmissivity, large-diameter wells are preferable. If transmissivity is low, small-diameter wells are believed preferable. They note, however, that all development techniques may be used, with some modification, if 4-inch wells are installed. Wells 4 in. in diameter provide a larger volume of water and yield water from a larger part of the aquifer than do smaller diameter wells. Schalla and Oberlander suggest that installation of a sufficient number of sampling points to define the extent of a plume may not be economically feasible if only large-diameter wells are used. They also believe that pumping of a large-diameter well may disrupt a plume and that samples of water collected may not be representative of conditions.

Rinaldo-Lee (1983, p. 73) believes that, if transmissivity of a deposit is low, small-diameter wells recover faster than large-diameter wells; thus less pumping time prior to sampling is required to purge stagnant water from small-diameter wells than from large-diameter wells. She notes that in areas where the water table is very deep, small-diameter wells may be difficult to construct and sample, and the probability of well-casing failure increases. Nacht (1983, p. 25) states that a small-diameter well installed in fine-grained material may not yield enough water for chemical analysis.

Schmidt (1982a,b, p. 28-29, p. 121-122) states that many small-diameter wells have inadequate gravel packs and annular seals. Small-diameter wells permit the withdrawal of only small volumes of water; thus, only water near the well screen is obtained. Schmidt considers 4-inch-diameter wells to be marginal for water-quality monitoring because the casing can be easily damaged if a portable pump is used. If a permanent pump is installed, accurate water levels are difficult to obtain. Six-inch-diameter wells are recommended for several reasons: (1) A proper gravel pack and annular seal can be constructed, (2) a large diameter allows proper development of the well, (3) a permanent pump or water-level recorder can be installed, and (4) a greater part of the aquifer can be sampled. Schmidt believes that 6-inch-diameter wells may provide information equivalent to that obtained from five to ten 2-inch-diameter wells.

According to Gibb (1983, p. 74), large-diameter wells installed in deposits having very low permeabilities can result in erroneously low water levels for days or months after pumping. Sampling of large-diameter wells is also more time consuming because the large volume of standing water in the well must be removed prior to sampling.

The U.S. Environmental Protection Agency (1986, p. 83) recommends the use of well casings of 2- or 4-inch inside diameter. The USEPA also believes that larger diameters may be necessary where dedicated purging or sampling equipment is used or where the well is screened in a deep deposit.

Annular Seal

Gibb and Barcelona (1984, p. 50) and Gibb (1983, p. 75) discuss the importance of properly backfilling the annular space in a monitoring well to prevent migration of water from surface or subsurface deposits and to provide support for the casing. They suggest that the diameter of a hole be at least 2 in. larger than the casing to allow room for the annular seal. Materials used for the annular seal must be chosen carefully to ensure that grouting does not modify water quality. Hole cuttings containing clay-size materials, bentonite, and cement grout are common annular sealants. Limitations of these sealants include difficulty in compacting hole cuttings during placement, reduction in the swelling properties of bentonite when in contact with highly mineralized water, and the tendency for cement to shrink and crack during curing. They state that expanding cements or cement-bentonite mixes are preferable.

Gibb (1986, p. 343-345) states that organic compounds in ground water, if in contact with bentonite clay, can indirectly increase the permeability of the clay seal. The volume of bentonite clay can increase 10 to 15 times after wetting with deionized water. Maximum swelling volumes can be reduced by 75 percent, depending on the quality of water. Solution channels can form in clay or cement seals because of compaction or subsidence, freezing and thawing at the surface, and presence of strong solvents. Regardless of the choice of sealants used above the gravel pack, Gibb suggests that the upper 5 to 10 ft of the hole should be sealed with expanding neat cement. He also suggests that the risk of contamination of water by cement can be reduced by placing a 1-foot-thick layer of fine Ottawa or silica sand above the gravel pack and covering the sand with 1 to 2 ft of bentonite pellets. The cement is then placed above the bentonite. Either neat cement or slurried bentonite, if installed under high pressures, can be forced into the underlying gravel pack and affect the quality of water. Gibb also notes that bentonite has considerable ion-exchange capacity that can affect the quality of water if the seal is close to the well screen.

Morrison (1983, p. 70) states that backfilling entirely with an impermeable seal seems to promote channeling along the casing-seal interface. He believes that grout is especially susceptible to channeling, and that bentonite or admixtures of it are also susceptible to this problem. He states that, of the bentonite clays, calcium bentonite may be preferable if ground water contains organic compounds or metals because calcium bentonite is less affected by these substances. Morrison (1986, p. 23) believes that sealant materials should be one to two orders of magnitude less permeable than the surrounding deposits. A mixture of fine sand and powdered bentonite (2 to 7 percent bentonite by volume) is thought to cause fewer shrink-swell or cracking problems than do pure bentonite or cement grouts. The mixture also provides a seal of known permeability. Similar sand-bentonite mixtures are preferred to drill cuttings, pure bentonite, or grout for backfilling above the seal.

According to Jennings (1986, p. 348-350), bentonite may not provide an adequate seal if improperly installed, and may affect the quality of water in or near the well. If grout is poured into the annular space rather than emplaced from the bottom with a tremie pipe, the grout can bridge or prematurely hydrate before completely filling the annular space. When coarse-grit sodium bentonite is used in deep wells penetrating an extensive saturated zone, the problem of premature hydration is believed to be greater. Pellets expose less surface area than coarse-grit particles do, and hydration is slower; bentonite pellets are thus more likely to penetrate a saturated interval to the desired depth. In the unsaturated zone, however, bentonite pellets may not completely hydrate, and an inadequate annular seal can result. In metal-rich calcic soils, calcium bentonite, instead of sodium bentonite, may be preferable. If sodium bentonite is used in calcic deposits, cation exchange may permit contaminants to infiltrate the grout. Jennings states that grout that penetrates the deposit or gravel pack can raise the pH of water and cause precipitation of insoluble metal hydroxides. He also states that additives in grouting and sealant materials can yield contaminants to ground water.

Senger and Perpich (1983, p. 231-233) describe a gasket that could replace bentonite as a sealant in highly mineralized water. Because bentonite does not swell readily in such water, a ring gasket that swells three to four times its original volume in highly mineralized water was developed. The gasket can be placed directly above the well screen before it is installed; thus, there is no doubt of its location within the hole. Although the gasket can be manufactured in any size or shape, it may not work well in holes that have a highly irregular shape. Also, the gasket material contains soluble and insoluble organic and inorganic contaminants, and its use in wells must therefore be evaluated on a case-by-case basis.

Nakamoto and others (1986, p. 54-55) found that the hydration of cement grout can produce long-term increases in the pH of water. In one laboratory test, the pH of water exposed to curing cement for 24 hours increased from 7.5 to 12.7. The pH remained high for more than 60 days even though the water was changed daily. For the first 30 days the pH of the water continued to increase to between 12.0 and 12.7. From 30 to 60 days the pH was always as great as 10.4; after 60 days the pH was always as great as 9.0. Nakamoto and others suggest that a sand-bentonite mixture instead of cement may eliminate the problem. Dunbar and others (1985, p. 72-73) found that the pH of water from monitoring wells at a hazardous-waste facility has remained high for more than 2 1/2 years, despite repeated well development. They believe the high pH is the result of contact between the ground water and cement grout used as a seal from the sand pack to the surface.

According to Johnson (1983, p. 76-78), multiple-completion wells, which consist of several pipes with short seals between screens or intakes in each zone, are suitable for monitoring. It is difficult, however, to ensure that the seals of multiple-completion wells are intact. Nakamoto and others (1986, p. 54) verify the integrity of well seals in multiple-completion wells by measuring hydraulic head and water quality in each zone. If hydraulic head differs substantially, they consider the seals to be intact. Furthermore, if water in a zone has a dissolved constituent not found in zones of lower head, then flow through the well seal is considered improbable.

The U.S. Environmental Protection Agency (1986, p. 83-85) describes the required properties of the annular seal in a RCRA monitoring well. The USEPA states that the annular seal (1) must prevent migration of contaminants from the surface or intermediate zones to the sampling zone, and (2) prevent cross-contamination between strata. Further, the materials used should be chemically inert to ensure that chemical reactions with the water do not affect the integrity of the seal or modify the chemical characteristics of water collected for analysis. The USEPA believes that the permeability of the seal should be one to two orders of magnitude less than that of the surrounding deposits. Certified sodium bentonite pellets are suggested as the most appropriate compound for use in the saturated zone because the pellets will penetrate the column of water to create an effective seal. A cement and bentonite mixture, bentonite chips, or antishrink cement mixtures should be used in the unsaturated zone and extend below the frost line. From just below the frost line the cap should be composed of concrete and should blend into a 4-inch thick apron extending 3 ft or more from the outer edge of the hole. The USEPA suggests that calcium bentonite may be more appropriate for use in calcic sediments or soils because its cation exchange capacity is lower than that of sodium bentonite.

Drilling Fluids

Rotary drilling techniques require the circulation of fluids through a hole to stabilize deposits, lubricate the drill bit, and remove cuttings. These fluids and their additives can affect the quality of water in a well for months after drilling has ceased.

According to Claassen (1982, p. 11), the degree to which drilling fluids penetrate deposits is dependent on their viscosity and the applied pressure. Low-viscosity fluids may penetrate the deposits farther, but they are easier to remove during well development. High-viscosity fluids will not penetrate deposits significantly, but they may be almost impossible to remove by circulating water. If drilling fluids plug pore spaces along a significant part of the hole, well development will be difficult, some producing zones may remain plugged, and samples may not be representative of the ground water.

The use of drilling fluids is also discussed by Fetter (1983, p. 61). He recommends that minimal amounts of drilling fluid be used, and that the use of organic-polymer-based drilling additives be avoided. The organic materials in these additives break down in ground water and can increase the chemical oxygen demand, biochemical oxygen demand, and total organic carbon concentration. Fetter also states that water from wells drilled with fluids containing bentonite can have a high chemical oxygen demand.

Brobst and Buszka (1986, p. 67-70) examined how water in three wells drilled using fluids containing guar bean, guar bean with a breakdown additive, or bentonite was affected by each. They found that the water quality of all of the wells was modified; however, the duration of the effects varied. The concentrations of chloride and sulfate and the chemical oxygen demand in water were higher in the three wells than in surrounding ground water. Despite well development and pumping, the chemical oxygen demand remained high for 50 days where guar bean with an additive had been used, for 140 days where bentonite had been used, and for 320 days where guar bean only had been used. The high chemical oxygen demand was attributed to organic carbon in the guar-bean fluids and polyacrylate polymer in the bentonite. Chloride and sulfate concentrations decreased with time. Brobst and Buszka concluded that the chloride was probably in the chlorinated city water supply used during drilling and development. The additive used in the guar-bean fluid contained ammonium persulfate and ferrous sulfate, both of which are highly soluble in water and thus may be responsible for the high sulfate concentrations. The gypsum in the bentonite was believed to be the likely source of sulfate in water from that well. The well drilled using guar-bean fluid alone was the only well that did not have a high sulfate concentration.

Jennings (1986, p. 350-353) discusses how drilling-fluid additives can impair water quality. Additives are used to control a variety of fluid properties such as viscosity, density, and lubricating ability. The types of additives discussed include lubricants, surfactants, viscosifiers, and weighting materials. According to Jennings, petroleum-based oils, graphite, and soaps are used as extreme-pressure lubricants to increase drilling efficiency and reduce the likelihood of shearing the drill stem. He states that increases in concentrations of total organic carbon, total organic halogen, or other organic constituents in ground water may be observed if petroleum products are introduced into the hole. Soaps and surfactants are cited as difficult to clean from the hole. Bentonite, sodium carboxymethycellulose, attapulgite clays, or sub-bentonite clays are cited as viscosifiers commonly used to thicken drilling fluids. If the volume of fluid needed is overestimated, the fluid may invade the deposits and alter ground-water quality. Bentonite, Jennings believes, can raise the pH of water. A high pH can persist because deposits adjacent to the well are difficult to clean during development. Weighting materials, such as barite lead compounds and iron oxides, are used to control pressure, prevent caving, and facilitate the pulling of dry casing. These additives can introduce barium, mercury, cadmium, lead, and iron into the hole. Surfactants are used to reduce interfacial tension between contacting surfaces. These additives may contain sodium, potassium, ammonium soaps, fatty-acid esters, salts of fatty alcohol sulfates, dialkyl dimethyl ammonium compounds, and alkyl ethoxylates.

Ericson and others (1985, p. 30-33) found that some organic fluids can clog narrow screen slots and remain in water from the well, even after several hours of well cleaning. They recommend that, where possible, air or potable water from wells be used as the drilling fluid. Bentonite-rich drilling fluid, anionic polymer emulsion products (or equivalents that are not self-destructing), and synthetic biodegradable surfactants should not be used in or near water-bearing zones that are to be screened or sampled. They believe that these materials can be used in conjunction with a temporary casing that is flushed prior to drilling. Organic, self-destructing, biodegradable guar-gum-based fluids can be used in water-bearing zones. The time required for the fluid to break down depends on water temperature.

Dunbar and others (1985, p. 73-74) found that sodium hypochlorite, used to degrade organic drilling fluid, can produce trihalomethanes. In their study, trihalomethane compounds detected in water from wells were attributed to the addition of sodium hypochlorite without sufficient well development.

Well Development

Scalf and others (1981, p. 36-38) discuss four methods of well development: surge block, air lift, bailer, and surging by pumping. A surge block is a plunger with pliable edges that will not catch on the well screen. Moving the block within the well forces water in and out of the screen. The surge-block method is most commonly used with cable-tool drilling rigs; it is not easily used with other types of rigs. In air-lift development, compressed air is pumped down a pipe in the well. In the first step the water is raised within the well, but it is not blown out. It is allowed to fall back, causing a back-washing action. In the second step the water is blown out of the well to remove fine material. Scalf and others state that care must be taken to avoid injecting air through the screen because air can become trapped and alter the chemical characteristics of water. In the development of a well with a bailer, the bailer is allowed to sink quickly. The agitating action caused by raising and lowering the bailer is similar to that of surge blocks. Each time the bailer is lifted to the surface, fine materials are removed. Bailers can be made for small-diameter wells and used by hand in shallow wells. Surging by pumping consists of repeatedly starting and stopping a pump to move water through the screen. Periodically, the well is pumped to remove the fine material produced during development.

Keely and Boateng (1987, p. 306-307) discuss the use of surge blocks or surge plungers to develop wells. Surging can cause channeling of the filter pack near the screen as well as displacement of native fluids. Channeling can reduce the filtering capacity of the material. Keely and Boateng also note that fine material outside of the well may not be removed during air-lift development. Overpumping, another method of well development, is described by Keely and Boateng. Overpumping involves repeatedly pumping the well dry and allowing it to recover. Sediment-free water is not always obtained during the first attempt. If not, Keely and Boateng recommend that the well be pumped again after a day or so; sediment-free water is usually obtained during the second pumping.

According to Barcelona, Gibb, Helfrich, and Garske (1985, p. 37-41), a well must be properly developed in order to obtain representative samples of water from an aquifer. Fine material is forced into deposits during drilling, forms a mud cake, and reduces the hydraulic conductivity of materials near a well. Development will break down the mud cake and also enhance the yield of a well; more importantly, development will ensure that water free of suspended solids is obtained when sampling. In well development, water is forced through the screen and gravel pack at alternating high and low velocities. The alternating flow breaks up the mud cake and loosens fine materials within the deposits. Pumping removes the loosened materials, and the procedure is repeated until the water is visually free of sediment. Although well development takes time, sediment-free water requires less time to filter than does water containing sediment, and samples are more representative of ground water in the deposit. Barcelona, Gibb, Helfrich, and Garske recommend that, during air-lift development, air from the compressor be filtered to ensure that oil is not introduced into a well. They also say that air-lift development can affect the oxidation-reduction potential of deposits, and can thus affect the chemical characteristics of water.

Barcelona and others (1983, p. 20-21) discuss problems that could be encountered during well development. They state that tight-fitting surge blocks may damage 2-inch-diameter PVC wells. When developing a well with a pump, a well is alternately pumped and left idle. In most instances, no outward movement of water from a well is achieved and blockage of water moving toward the well by fine material limits the effectiveness of the technique. Barcelona and others also caution that field personnel may be exposed to hazardous materials in badly contaminated ground water during air development. If deposits are relatively unproductive, only a few development methods can be used. Surging is difficult because of the low hydraulic conductivity of the materials. Recovery from pumping is too slow to adequately remove fine material from the well and gravel pack. Prior to grouting, circulating clean water down the casing, out through the screen and gravel pack, and up the open hole will break down and remove the mud cake. Little water will be forced into deposits because of their low hydraulic conductivity. Barcelona and others state that the well should be sealed immediately after development and then pumped.

Paul and others (1988, p. 78) found that well development by bailing produced the best results where wells were installed in fine-grained glacial tills. When wells were surged, the turbidity of water was much greater than when wells were only bailed. In one test, the turbidity of water in surged wells had not decreased when a second sample was collected about 4 months later, whereas the turbidity of second samples from the bailed wells had decreased by almost fourfold.

W.L. Bradford (U.S. Geological Survey, written commun., 1985, p. 8) states that the introduction of any foreign material into a well can affect the chemical quality of water. If mineral acids are added to loosen bentonite, the well should be pumped and the pH and specific conductance of the water should be measured until the acid has been removed. If water must be added in the initial surging, deionized or uncontaminated water from the same aquifer with similar concentrations of major dissolved ions should be used. The well should be pumped until the effect of added water is eliminated.

Johnson (1983, p. 77) notes that a small-diameter casing limits the type of equipment and the well-development technique that can be used. Gibb (1986, p. 341) adds that the water velocities needed to break down the mud cake also remove the drilling fluids, and that removal of colloidal-size particles is difficult. Nakamoto and others (1986, p. 52-53) describe the development of a multiple-zone monitoring well. Prior to gravel-pack installation, as much of the mud cake is removed as possible. Each screened zone is usually developed three times by air-lift methods during construction. The first step is a gentle surge to settle the gravel pack. Once the gravel, sand, and grout have been placed in the hole, water is gently pumped to test for grout migration into the gravel pack. If grout is observed in the water, water is pumped vigorously until grout no longer appears. Surging several times verifies that grout is no longer present in the water. After a sanitary seal has been installed and allowed to set for 12 hours, each screened zone is developed by an air-lift method until the water is free of sediments.

Palmer and others (1987, p. 41-44) state that the sand pack will achieve chemical equilibrium with ground water near the well if a well is extensively developed by pumping. If an insufficient amount of water has been moved through the sand pack, chemical analyses of water may not accurately reflect ground-water quality. If the well is surged, the same water moves repeatedly through the pack and equilibrium may not be reached.

The U.S. Environmental Protection Agency (1986, p. 87-88) suggests that, for well development to be effective, reversals or surges in flow are required to prevent fine particles from reducing flow to the well. Surge blocks, bailers, or pumps can be used to create flow reversals or surges. The USEPA recommends that water from the deposit be used for the surging, although water from another source may be necessary in developing low-yield water-bearing deposits. If water from another source must be used, the USEPA suggests that a chemical analysis of the water be made. Decontamination of equipment used in development is also recommended.

LITERATURE ON COLLECTION OF WATER SAMPLES

A wide range of methods are used to collect samples of ground water for chemical analysis. To ensure that samples of water are not modified by materials used in sampler construction, or by the pumps or bailers used, consideration must be given to the specific requirements of each investigation. Decontamination of sampling equipment is required, particularly if trace amounts of organic compounds are of interest. Well purging and pumping rates must also be considered.

Sampling Materials and Equipment

Materials

Barcelona and others (1983, p. 48-49) describe characteristics of materials suitable for use in sampling equipment. They conclude that materials should be durable, reliable, easy to clean and repair, and unlikely to add foreign compounds to water collected for analysis. Seanor and Brannaka (1983, p. 42) suggest that sampling equipment be constructed from relatively inert materials to reduce the possibility of organic compounds leaching from or adsorbing on sampling materials. When collecting water samples for the analysis of organic compounds, equipment that permits water to contact metal, rubber, or lubricants should be avoided.

Nacht (1983, p. 26) suggests that contamination of ground water by the materials used in a sampling device or well casing may become significant if the concentrations of organic compounds are in the parts per billion range. He believes that parts of the sampling device and well casing that come into contact with water should be constructed from Teflon, stainless steel, or glass. Nacht discusses problems associated with each of these materials, including the expense of Teflon and stainless steel and the fragility of glass. He concludes that PVC is suitable for well casings if the well is adequately flushed prior to sample collection.

Barcelona, Gibb, Helfrich, and Garske (1985, p. 53-57) recommend rigid Teflon as well as flexible Teflon for use in sampling equipment. Teflon, which is easy to clean, is thought to be the material least likely to contaminate water samples. Stainless steel 316 is also considered an acceptable rigid material, particularly if organic compounds are the contaminates of interest. Stainless steel 304 is considered to be an acceptable rigid material, although it may corrode in acidic waters containing a high dissolved-solids concentration. Other steels (low carbon, galvanized, and carbon) may be more suitable than PVC if organic compounds are present. Steel, however, must be cleaned well to remove any manufacturing residues. Polypropylene and polyethylene follow Teflon in a ranking of flexible sampling materials by Barcelona, Gibb, Helfrich, and Garske. These plastics are recommended for sampling corrosive waters having high dissolved-solids concentrations. Flexible PVC is not recommended for collection of samples for the analysis of organic compounds. Plasticizers and stabilizers, which make PVC flexible, can modify the chemical characteristics of water. Viton, silicone (medical-grade), and neoprene are not thought suitable under some sampling conditions. These materials are recommended for use only if other materials are unavailable.

According to Barcelona and others (1983, p. 49), Teflon is an excellent material for sampling applications; it is, however, considered difficult to machine, and threaded components are damaged easily. They state that most tubing materials, with the exception of Teflon, contain numerous additives. True polymers, such as polyethylene and polypropylene, contain fewer additives than do other plastics, and thus are recommended for sampling equipment when the use of Teflon is not possible. If silicone rubber tubing is a necessary component of a sampling device, medical-grade rather than laboratory-grade tubing is recommended. Some laboratory grades may contaminate water with metals. Other elastomeric materials, such as latex and neoprene, are not recommended for transfer lines or surfaces that contact water samples.

According to Gillham and others (1983, p. 48-49), metallic equipment has the advantage of being strong, rigid, and insensitive to normal temperature variations that occur in the field. However, oxidation and corrosion of metallic equipment can contaminate water with metals. In addition, oil and lubricant residues from manufacturing can contaminate water. Plastics are weaker, less rigid, and more temperature sensitive than metals. Although most plastics will not corrode and can withstand chemical attack by inorganic compounds, they are susceptible to attack by organic compounds. Plastics can yield numerous contaminating substances or adsorb existing contaminants; either process can modify water quality. Of the most commonly used plastics, Gillham and others consider polyethylene to have the greatest potential for modifying water quality; Teflon is thought to have the least potential. In addition to metals and plastics, glass may be used in sampling equipment. Glass is relatively inert and less expensive than other materials; however, glass can adsorb some dissolved substances.

Junk and others (1974, p. 1100) found that contamination of water by organic compounds, ranging from 1 to 5,000 parts per billion, occurred when water flowed through various plastic tubes (polyethylene, polypropylene, black latex, a plastic garden hose, and six types of PVC). Barcelona, Helfrich, and Garske (1985, p. 57) tested Teflon, polyethylene, polypropylene, PVC, and silicone rubber. All of the tubing sorbed some of the test compounds (trichloroethylene, trichloroethane, tetrachloroethylene, and chloroform) within minutes. Tests indicated that sorption was 2 to 5 times more rapid in the first 5 to 10 minutes than in the following 15 to 60 minutes. In subsequent desorption tests, the bulk of the sorbed material remained in the tubing when leached with water for a comparable time period. From 5 to 15 percent of the sorbed material could not be leached with either distilled water or bicarbonate solution. According to Barcelona, Helfrich, and Garske, the tests show that sorption of chlorinated hydrocarbons occurs by absorption into the polymer matrix. Of the materials tested, sorption and leaching were less when Teflon was used.

Reynolds and others (1990, p. 135, 140-141) conducted laboratory experiments to evaluate 10 materials used in the construction of ground-water monitors. Borosilicate glass, stainless steel 316 tubing, aluminum tubing, galvanized steel sheet, rigid PVC rod, polytetrafluoroethylene tubing, Teflon, nylon, polypropylene tubing, low-density polyethylene tubing, and latex rubber tubing were used in tests. Each of these materials were placed in water containing 1,1,1-trichloroethane, 1,1,2,2-tetrachloroethane, hexachloroethane, bromoform, and tetrachloroethylene for periods as long as 5 weeks. Concentrations ranged from 2.5 to 100 µg/L. Borosilicate glass was the only material that did not cause a decrease in the concentration of the halocarbon compounds. All six of the synthetic polymers absorbed the compounds at rates dependent on the flexibility of the polymer, water solubility of the compound, the ratio of the water volume to polymer surface area, and the temperature.

The three metals also reduced the concentrations of the compounds. The reduction was believed to have been caused by reactions with metal surfaces or metal ions released from the surfaces.

Devlin (1986, p. 503) conducted leaching and adsorption studies with Teflon and polyethylene tubing using 15 volatile aliphatic, chlorinated, and aromatic organic compounds in concentrations ranging from about 65 to about 210 µg/L. Neither tubing contaminated organic-free deionized water significantly. The adsorption studies indicated that polyethylene adsorbs substantially more volatile organic compounds than does Teflon. However, uncontaminated water samples were obtained when polyethylene tubing was flushed before sampling. A short length of silicone tubing was also tested. When properly flushed prior to sampling, silicone tubing did not modify water quality. For nondedicated systems, Devlin believes that Teflon is the best material because less flushing is needed to clean tubing.

Holm and others (1988, p. 88) state that diffusion of volatile hydrocarbons in water through the walls of fluorinated ethylene-propylene copolymer tubing can cause underestimation of contaminant concentrations. They recommend that the tubing length be minimized and the flow rate be maximized to reduce gas transfer. They also believe that tubing having the maximum wall thickness available should be used in sampling.

Scalf and others (1981, p. 44) suggest that careful consideration be given to the equipment used for sampling. When samples are collected for the analysis of trace organic chemicals, pumps should not be lubricated with oils or be made of Tygon or rubber tubing. Scalf and others also believe that, ideally, sampling equipment should be economical to manufacture, completely inert, easily cleaned, able to operate at remote sites without an external power source, and capable of delivering continuous but variable flow rates.

To minimize contamination of samples, the U.S. Environmental Protection Agency (1986, p. 104-107) recommends use of fluorocarbon resin or stainless steel sampling devices and dedicated samplers. If a dedicated sampler cannot be used, the sampler should be thoroughly cleaned between sampling events. The following devices are considered suitable for sampling: gas-operated, fluorocarbon resin or stainless steel squeeze pumps; fluorocarbon resin or stainless steel bailers with double check valves and bottom-emptying device; syringe bailers constructed of stainless steel or fluorocarbon resin; and fluorocarbon resin or stainless steel bailers with single check valves. Sampling equipment with neoprene fittings, Tygon tubing, silicon rubber bladders, neoprene impellers, polyethylene, and Viton, and PVC bailers are not recommended. The USEPA also states that (1) positive gas-displacement bladder pumps should be operated continuously so that they do not produce pulsating samples that are aerated in the return tube or upon discharge, (2) check valves should be designed and inspected to ensure that fouling does not reduce delivery capabilities or result in aeration of the sample, (3) sampling equipment should not be dropped into the well because the impact may cause degassing of the water, and (4) clean sampling equipment should not be placed directly on the ground or on contaminated surfaces prior to insertion into the well. The USEPA also states that Teflon-coated wires, single-strand stainless steel wire and monofilament lines or cords are relatively easy to clean, and should be used instead of braided cables, polyethylene cords, and nylon cords to raise and lower bailers.

Although materials used to construct well casings and screens are important in studies of ground-water contamination, screen length also has been cited as potentially significant. Reilly and others (1989, p. 272-275) considered the vertical flow of water in well screens 50 ft or more in length. Using a numerical model, they concluded that samples from such wells, when collected in studies of ground-water contamination, are not likely to be representative of water in the aquifer at the depth at which they are collected. Experiments indicated that significant vertical flow occurs within a long screen, even if the head difference between the top and the bottom of the screen is less than 0.01 ft. One simulation of flow in a 60-foot screen indicated that about 60 percent of the total inflow to the well occurred in the upper 10 ft; about 56 percent of the total outflow from the well occurred in the lower 10 ft.

Pumps and Bailers

Schalla and others (1988, p. 90) suggest that different sampling systems may produce different results because of pressure changes within devices, aeration of samples, and adsorption or release of contaminants onto or from sampling equipment. Nielsen and Yeates (1985, p. 86) describe the characteristics of an "ideal" sampler as one that (1) easily fits within the well casing, (2) is easily transported and operated in the field, (3) is constructed of inert materials or materials that are nonreactive with substances of interest, (4) is able to deliver a sample without altering it, (5) is (if a pump) able to produce water at variable rates, (6) is capable of sampling at the required depths, (7) is easily cleaned and maintained in the field, (8) is compatible with the degree of analytical sensitivity required, and (9) is durable, reliable, and economical.

Fetter (1983, p. 63-64), Emenhiser and Singh (1984, p. 36), and Houghton and Berger (1984, p. 213) recommend that air-lift, submersible, and peristaltic pumps be avoided if collecting samples for the analysis of volatile organic compounds or other compounds subject to degassing. Instead, bailers made of glass and Teflon are recommended by Fetter, and Teflon or stainless steel bailers are recommended by Emenhiser and Singh. Fetter also recommends positive-displacement pumps made of glass and Teflon; Houghton and Berger recommend a gas squeeze pump for sampling organic compounds. Imbrigiotta and others (1986, p. 12-13) describe an ideal sampler for volatile organic compounds as one that subjects the sample to a minimum of turbulence, does not heat the sample, and is constructed of nonreactive materials such as stainless steel, Teflon, Viton, or glass.

Barker and Dickhout (1988, p. 118-119) evaluated a bladder pump, an inertial-lift pump, and a peristaltic pump for the collection of samples of ground water containing volatile organic compounds. In field tests, the bladder and inertial pumps gave essentially the same results for all organic compounds tested and, except for benzene, concentrations were significantly lower when a peristaltic pump was used. In laboratory tests, the inertial-lift pump consistently produced the highest concentrations of volatile organic compounds. The bladder pump produced concentrations 13 to 20 percent lower; the peristaltic pump produced concentrations 23 to 33 percent lower. Barker and Dickhout believe these results reflect differences in losses due to volatilization. They conclude that significant losses are possible if bladder and peristaltic pumps are used when collecting samples for the analysis of volatile organic compounds in gas-charged ground water.

Scalf and others (1981, p. 45-53) discuss advantages and disadvantages of suction-lift pumps (including centrifugal and peristaltic pumps); portable submersible pumps; air-lift samplers; a nitrogen-powered, continuous-delivery, glass-Teflon pump; a gas-operated squeeze pump; a gas-driven piston pump; and bailers. They believe that sampling with suction-lift pumps, air-lift samplers, or nitrogen-powered, continuous-delivery, glass-Teflon pumps may result in degassing or loss of volatile organic compounds. They recommend use of grab samplers that allow the water to contact only sterile glass and Teflon, if only nonvolatile organic compounds are of interest and the water table is within suction lift. For sampling at depths beyond suction lift, a noncontaminating submersible pump and Teflon tubing are recommended. Bailers are recommended for sampling ground water containing volatile organic compounds.

Devlin (1986, p. 525) evaluated three pumping systems to determine recovery of volatile organic compounds in water from a well. Peristaltic, positive-displacement (bladder, no gas contact), and positive-displacement (with gas contact) pumps were used. He concluded that the positive-displacement (no gas contact) pumping system provides the least altered samples.

W.L. Bradford (U.S. Geological Survey, written commun., 1985, p. 12) lists preferred sampling devices in order of suitability, as follows: (1) Gas-bladder displacement pump, (2) gas-reciprocation pump, (3) closed Kemmerer-type[6] thief sampler, and (4) centrifugal submersible pump, provided that it is run at slow speed to avoid cavitation. He recommends avoidance of suction pumps, peristaltic pumps, air-lift pumps, and jet pumps because they involve suction, extreme turbulence, or exposure to air at some point in the device or in the lifting process.

Barcelona and others (1984, p. 38-40) and Barcelona, Helfrich, and Gibb (1985, p. 182-183) present the results of a laboratory evaluation of a positive-displacement (bladder, no gas contact) pump, a syringe sampler (vacuum-assisted fill), a gas-displacement device, a positive-displacement (helical-rotor) pump, and a peristaltic (suction) pump. They concluded that positive-displacement (bladder, no gas contact) pumps are the best suited for sampling volatile organic compounds. The gas-displacement and peristaltic pumps resulted in statistically significant losses of volatile organic compounds. The investigators conclude that the performance of grab samplers is dependent on field conditions and the expertise of sampling personnel.

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[6] A Kemmerer-type sampler is one that uses a falling messenger weight to close, and to trap water in, an open-ended bottle.

The use of suction-lift pumps, submersible pumps, air-lift pumps, positive-displacement pumps, and bailers for sampling organic contaminants in ground water is discussed by Seanor and Brannaka (1983, p. 42-46). In discussing suction-lift pumps, they state that the pumps are limited to use at shallow depths. The pumps may also subject water to negative pressures, which can affect concentrations of volatile compounds and dissolved gases. Submersible pumps are not limited as much by depth, but they require an outside power source and the installation and withdrawal of the pump from each well during sampling. Seanor and Brannaka state that air-lift pumping may cause gas stripping and a change in pH. Positive-displacement pumps are considered suitable for sampling water containing volatile compounds and dissolved gases. If withdrawn using a positive-displacement pump, the sample is under positive pressure and is not in contact with the atmosphere until it reaches the surface. They state that bailers expose samples to descending pressures as they approach the surface and to the atmosphere during transfer to a sampling bottle; such exposure may result in changes in the concentrations of volatile compounds and dissolved gases.

Imbrigiotta and others (1986, p. 10-11) field tested the following sampling devices: bladder pump, helical-rotor submersible pump, syringe sampler, gear-submersible pump, peristaltic pump, point-source bailer, and open bailer. Results of their tests indicated that the gear-submersible pump, point-source bailer, open bailer, helical-rotor submersible pump, and bladder pump were very close in effectiveness for sampling volatile organic compounds. Concentrations of volatile organic compounds in water collected with a peristaltic pump and syringe sampler were consistently lower. Ho (1983, p. 586) tested a peristaltic pump to evaluate degassing problems. Ho found that loss of a compound was related to volatility, as the lift height increased. The greater the volatility the greater the loss. Barcelona, Helfrich and Gibb (1985, p. 181-182) found significant changes in pH and Eh (oxidation-reduction potential) in water collected with peristaltic pumps. They also found that oxygen and methane losses were minimized by using positive-displacement (no gas contact) pumps.

Pearsall and Eckhardt (1987, p. 67-69) found that concentrations of trichloroethylene, 1,2-dichloroethylene, and tetrachloroethylene in water collected using three different types of submersible pumps constructed with Teflon tubing or Teflon pipe did not differ appreciably.

The U.S. Environmental Protection Agency (1986, p. 107) recommends that a positive-displacement bladder pump be used and that the pumping rate not exceed 100 mL/min (milliliters per minute) when sampling for volatile organic compounds or gases. They also state that the flow rate during sampling should not exceed the flow rate during purging.

According to Scalf and others (1981, p. 48), an advantage of portable electric submersible pumps is that they can be used to sample several wells within a short time period. They conclude, however, that many submersible pumps are not constructed of materials suitable for collecting samples for the analysis of organic compounds. Seanor and Brannaka (1983, p. 44) believe that, because submersible pumps are generally used to sample a multiple number of wells, surface soils may adhere to the pump hoses at a well site and be carried into the next well. They also note that withdrawal of a pump with a check valve is labor intensive and that submersible pumps require a power source that must be transported to the site. An advantage of submersible pumps, according to Seanor and Brannaka, is the ability to pump water from greater depths than is possible with other types of pumps. Korte and Kearl (1984, p. 28-29) cite the difficulty of decontaminating submersible pumps if a number of wells are being sampled. They also discuss an easily transportable submersible pump that fits into 2-inch-diameter well casings. Disadvantages cited are that it has a low pumpi rate and that it can only pump for a period of 15 minutes[7]. Morrison (1983, p. 89) notes that submersible pumps can provide relatively high discharge rates; however, agitation of water in the well will occur, and flow in sampler tubing will be turbulent.

Nielsen and Yeates (1985, p. 94-96) cite the following advantages of gear-drive electric submersible pumps in ground-water sampling: (1) The pumps are constructed from inert or nearly inert materials, (2) they can be used to collect samples for the analysis of organic compounds if a Teflon discharge line is used, (3) they can provide continuous samples for an extended period of time, (4) they can operate at high rates and at depths as great as 150 ft, and (5) they are easy to operate, clean, and maintain in the field. The following disadvantages are cited: (1) There is normally no control over flow rates, and (2) suspended solids in the water may damage the gears. Portable helical-rotor, electric submersible pumps are considered suitable for use in 2-inch wells because they are constructed mostly of inert or nearly inert materials and can operate at high pumping rates. However, the pumps can only be used at depths of 125 ft or less, and they are expensive compared to other pumps. Nielsen and Yeates list other disadvantages of helical-rotor, electric submersible pumps: (1) High flow rates can create turbulence that cannot be controlled, (2) the pump needs to be shut off periodically to avoid overheating, (3) suspended solids in the water can cause operational problems, and (4) cleaning and repair in the field is difficult.

Muska and others (1986, p. 241-244) report that a submersible pump and a surface "bomb" were the most accurate of several sampling devices tested in their study. The surface bomb was a stainless steel tube with ball valves at each end. The tube was mounted on a frame that has a lever arm connected to a pneumatic piston. The piston was actuated with compressed air to open or close the valves. In their study, Muska and others found, in sampling a well with a low trichloroethylene concentration (less than 10 µg/L), that samples had a lower concentration when a submersible pump was used than did samples collected with other devices. In sampling wells with moderate to high trichloroethylene concentrations (1,000 to 40,000 µg/L), samples had higher concentrations when collected with a submersible pump.

According to Nielsen and Yeates (1985, p. 90-92), an advantage of gas-drive devices is that they can provide water at a controlled, nearly continuous rate. The pumps also can be used to sample at discrete depths in wells whose diameters are as small as 1 1/2 in. They are inexpensive and

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[7] Subsequent modification of the pump eliminated the limitation on the period of continuous pumping.

portable. Permanent installation in holes without casing is also possible, although later removal of the pump may be difficult. Further, the pumps can be constructed of inert materials, and if an inert driving gas is used, oxidation and other chemical alterations are minimized. If air is used, however, oxidation and gas stripping may occur, and carbon dioxide may be driven from the water causing a change in pH. An air compressor or a large air tank and reinforced tubing are often needed to sample deep wells. This is regarded as a disadvantage because transportation of the compressor or air tank may be difficult. Care also must be taken in applying air pressure to prevent rupture of tubing. Gillham and others (1983, p. 118) believe that the first and last portions of a continuous sample may be altered by contact with the driving gas. Dissolved gases may be lost or contamination from the driving gas may occur at the gas-water interface.

Robin and others (1982, p. 64-66) describe double-tube and triple-tube gas-drive samplers designed to fit in small-diameter wells. The double-tube sampler is self-contained and is easier to operate than the triple-tube sampler. If only small samples are needed, the double-tube sampler is more efficient than the triple-tube sampler. Sampler tips, which contain a check valve and sediment trap, can be taken apart easily and cleaned between uses. Problems with check valves, which are used in the double-tube samplers, can be avoided by using a triple-tube sampler which has a small inflatable packer. The packer also prevents the water and driving gas from being forced back into surrounding deposits. For large samples, the triple-tube sampler is more efficient than the double-tube sampler; as much as six times more water can be collected in a given time period, depending on the tube diameter. Both samplers are excellent for sampling small-diameter wells if water levels are below the limit of suction lift. They also are portable and inexpensive to build and operate.

Tomson and others (1981, p. 444) describe a nitrogen gas-drive sampler that is made from glass and Teflon. The sampler was designed for sampling trace concentrations of organic compounds. The pump functions at continuous flow rates unlike most gas-drive samplers. Scalf and others (1981, p. 49-50) also discuss this device and list one of its advantages as the fact that it will fit in a 2-inch-diameter well. However, disadvantages cited include that it is more fragile than other samplers, that high-purity nitrogen is needed, and that pH-sensitive constituents may be stripped from water by carbon dioxide. Scalf and others believe that gas stripping of volatile organic compounds may also occur.

Barcelona and others (1984, p. 38) found no significant changes in pH or Eh when using gas-drive samplers. However, statistically significant losses of volatile organic compounds (chloroform, bromodichloromethane, chlorodibromomethane, and bromoform) did occur. Schalla and others (1988, p. 90) tested four sampling devices (a stainless steel and Teflon piston pump, a Teflon bailer, a Teflon bladder pump, and a PVC air-lift device) to determine recovery of trichloroethylene, perchloroethylene, and 1,1,1-trichloroethane. There was no statistical difference in recovery between the four devices.

According to Scalf and others (1981, p. 48), a high-pressure hand pump may be used to air-lift samples, although a small air compressor may be necessary when samples of deep water are being collected. Air-lift pumps can be portable or permanently installed. Scalf and others list some drawbacks to air lifting, however, including the potential alteration of water quality, the pressure limits of the tubing, and the difficulty of obtaining a suitable source of compressed air. Oxidation and gas stripping of volatile organic compounds are also disadvantages of this method. Scalf and others also state that the method seems to be unsuitable for the sampling of substances sensitive to changes in pH. Seanor and Brannaka (1983, p. 44) consider air-lift pumping to be an efficient way to evacuate a well; equipment is readily available and inexpensive.

Stolzenburg and Nichols (1986, p. 231-232) believe that it is difficult to operate air-lift pumps without aerating the sample. Morrison (1983, p. 89-90) also discusses sample agitation and the mixing of water within the well when air-lift pumps are used. He believes that the considerable air pressure required in the sampling of deep waters can result in significant changes in the Eh and pH.

Houghton and Berger (1984, p. 209-210) found numerous alterations of water quality when samples were collected with air-lift pumps. Their study showed that air-lift pumps changed the temperature of water. The pH and dissolved-oxygen concentration increased, whereas concentrations of other dissolved gases and volatile constituents decreased. The increase in dissolved-oxygen concentration led to a decrease in the concentration of dissolved metals sensitive to oxidation, specifically aluminum, cadmium, copper, iron, lead, manganese, and zinc. Alkalinity, ammonia, calcium, magnesium, boron, barium, strontium, molybdenum, selenium, and dissolved-solids concentration also decreased when air-lift pumps were used.

Gibb and others (1981, p. 35-42) report that water collected with air- and nitrogen-lift pumps had higher pH values than water collected with a peristaltic pump or a bailer. They found that the diameter of the discharge pipe affected the pH; the larger the diameter, the higher the pH. This was attributed to the fact that more air or nitrogen is required to lift the same quantity of water in a large-diameter pipe than in a small-diameter pipe. In addition, iron and zinc concentrations were less if air-lift pumps were used than when a peristaltic pump or a bailer were used. The iron probably oxidized and precipitated; zinc probably adsorbed on the precipitate. Gibb and others recommend restricting the use of air- and nitrogen-lift pumps to the collection of samples for analysis of constituents insensitive to oxidation-reduction reactions and pH changes, and for those that are nonvolatile.

Scalf and others (1981, p. 44) consider the advantages and disadvantages of sampling wells in which pumps have been installed. Advantages cited are that water samples are readily collected and that water in the well generally is not stagnant if the well is pumped frequently. Disadvantages cited are that water collected may not be representative because excessive pumping may dilute or increase contaminant concentrations, that water may be produced from more than one aquifer, and that contamination and (or) adsorption may be a problem if organic compounds are of interest. Wells without permanent pumps allow greater flexibility in the choice of sampling equipment and procedures. Scalf and others state that, prior to sampling, care must be taken to (1) ensure that all stagnant water is removed from the well, and (2) prevent sample contamination by the equipment.

Schmidt (1982b, p. 120) believes that pumps are more suitable for sampling than other devices because water-quality standards usually apply to pumped water at the well-discharge point, and pumping action can result in substantial loss of some trace organic-chemical constituents. Schmidt believes that a moderate pumping rate reduces the potential for contamination of samples by the equipment because the water is in contact with the material for only a short time. He also notes that the labor required for sampling and the potential for spreading contaminants from well to well is reduced if a pump is permanently installed.

Nielsen and Yeates (1985, p. 88) list advantages and disadvantages of using bailers for sampling. The following characteristics of bailers are considered to be advantages: (1) Bailers can be constructed from a variety of materials, including materials that are chemically inert; (2) well diameter can be accommodated by bailers because bailers can be made in almost any diameter and length desired; (3) bailers can be constructed from flexible material to permit use in nonplumb wells; (4) bailers are inexpensive, and they are easy to use and clean; and (5) bailers are lightweight, portable, and do not require a power source. The following disadvantages are discussed: (1) Well evacuation can be difficult and time-consuming in deep wells; (2) the line used to raise and lower the bailer can carry contaminants between wells unless the bailer is dedicated or the line is thoroughly cleaned or is noncontaminating; (3) the person using the bailer may be exposed to contaminants in the water; (4) bailers cannot provide a continuous flow of water; (5) the actual point of sampling within the water column is difficult to determine; (6) if there is little space between the bailer and casing, the bailer may "swab" the well casing, causing fine material to enter the water; (7) suspended solids in the water or other conditions may cause the check valves to operate improperly; and (8) aeration, degassing, and turbulence can occur either by lowering the bailer through the water column or in transferring the sample from the bailer to the sample bottle.

According to Seanor and Brannaka (1983, p. 44), there is a potential for loss of volatile compounds and dissolved gases during transfer of water from bailer to sample bottle. The sample in a bailer is also exposed to descending pressures as it is brought to the surface. Dissolved oxygen may be introduced into the sample by use of a bailer, and this may affect pH, alkalinity, and the solubility of trace metals. Check valves may freeze open in cold weather.

Bryden and others (1986, p. 71) consider a Kemmerer-type sampler to be excellent for most air-sensitive and volatile organic compounds because of its dependability and simplicity of operation. They suggest that Teflon bailers be used to sample for contaminants that are not affected by exposure to air or to loss by volatilization.

Morrison (1983, p. 88) believes that the plugs or trigger mechanisms on bailers tripped by messengers can introduce contaminants to water, and that incomplete closing of plugs and difficulties in operation may pose problems in sampling. However, Houghton and Berger (1984, p. 210-212) found that, compared to a gas-squeeze pump, a Kemmerer-type sampler produced no statistically significant alterations in water quality. A slight increase in total and dissolved organic carbon occurred if the sampler was used in acidic waters. When sampling standing water in a well with conventional bailers, an increase in the dissolved-oxygen concentration, and a decrease in iron concentration was found. Decreases in mercury concentration, alkalinity, and in the partial pressure of carbon dioxide were also observed. Houghton and Berger state that such changes in water quality could reflect degassing due to agitation during sampler insertion or within the open sampling chamber.

Gibb and others (1981, p. 35-37) believe that pH is probably the single most important property of water affecting its quality. In their study, samples collected with a bailer had pH values 1.1 units lower than samples collected with air- and nitrogen-lift samplers. The bubbles from the air- or nitrogen-lift pumps may strip water of dissolved carbon dioxide, thus increasing the pH of the water. They found that the pH of water collected with a peristaltic pump did not differ appreciably from the pH of water collected with a bailer. Water collected with a bailer had a higher concentration of iron than water collected with air- or nitrogen-lift samplers. This difference in iron concentration was thought to be related to changes in pH. Gibb and others recommend that bailers or peristaltic pumps be used when sampling pH-sensitive waters or waters containing volatile compounds. Barcelona and others (1984, p. 36-39) found that bailers produced no significant changes in pH or Eh in a laboratory evaluation. When carefully operated under controlled conditions, bailers minimized the losses of oxygen and methane. Trihalomethane compounds were also found to be accurately sampled with a bailer. Barcelona and others recognize, however, that laboratory conditions are carefully controlled, and that performance in the field may not always be as satisfactory. At three test sites, Imbrigiotta and others (1986, p. 12) found that the concentrations of volatile organic compounds in water collected with bailers did not differ greatly from those in water collected with submersible and bladder pumps.

Pearsall and Eckhardt (1987, p. 64) compared the performance of a Teflon bailer and three types of pumps in sampling ground water containing trichloroethylene and similar compounds. When the concentrations of trichloroethylene and 1,2-dichloroethylene were greater than 76 µg/L, samples collected with the bailer did not differ appreciably from those collected with a submersible pump having a ethylene propylene elastomer stator.

Concern as to whether bailers or submersible pumps are more appropriate in the collection of water samples containing volatile hydrocarbons prompted additional investigation by the U.S. Geological Survey in Michigan (T.R. Cummings, U.S. Geological Survey, written commun., 1989). In June 1987, the U.S. Geological Survey and the Michigan Department of Natural Resources jointly sampled the water from a well known to contain both aromatic and chlorinated hydrocarbons. Previously obtained data indicated that the highest concentration to be expected was 2,000 to 3,000 µg/L of benzene. The well had a diameter of 4 in. and a depth of 33 ft. It was pumped at a rate of about 10 gal/min (gallons per minute) for 15 minutes, which resulted in the withdrawal of about 20 well volumes of water prior to sample collection. Samples were collected both by using an electric submersible pump and by using a specially fabricated all-Teflon, Kemmerer-type 2-L (liter) bailer. Samples by both agencies were collected at the same time from the pump discharge and from a single withdrawal of the bailer. Samples were analyzed by each agency's laboratory. The work of both laboratories detected a total of 17 organic compounds. The concentrations of eleven of the compounds in water collected with a bailer were lower than in water pumped from the well. The average difference was 13.8 percent.

In August and September 1988, further sampling was done by the U.S. Geological Survey with submersible pumps and the Teflon bailer. Three wells known to contain chlorinated hydrocarbons (tetrachloroethylene, trichloroethylene, 1,1,1-trichloroethane, and 1,1-dichloroethane) were selected for sampling. Analyses indicated that the highest concentration was 100 µg/L of trichloroethylene; the lowest detectable concentrations were less than 1 µg/L of tetrachloroethylene and 1,1,1-trichloroethane. Periodic sampling from the three wells began about 11:00 a.m. and ended about 8:00 p.m. on August 31; pumping and sampling were resumed at 9:00 a.m. on September 1, and terminated at noon. All samples were collected and analyzed in duplicate. During the period, 96 samples were collected. Analysis of the results indicated that concentrations of the chlorinated hydrocarbons in 82 percent of the samples collected with the bailer were lower than concentrations in samples collected with pumps. The average difference was 15 percent. The average difference in concentrations found in all duplicate samples was 2.3, which seemed to rule out laboratory technique as a factor in the difference between the pumps and the bailer.

Miscellaneous Equipment

Garvis and Stuermer (1980, p. 1525) describe a portable instrument for continuously monitoring pH, Eh, specific conductance, and temperature at the wellhead. They believe that monitoring these properties until they stabilize is a useful way to ensure that water from the aquifer is being obtained. The probes are housed in a Lucite[8] block, and thus measurements can be made before the water has cooled or contacted the atmosphere. Digital displays permit the operator to monitor values of each property continuously.

According to Cordry (1986, p. 262-271), the presence and extent of ground-water contamination, including the concentration of contaminants, can be determined without drilling wells. The instrument used by Cordry consists of a stainless steel and Teflon drive point with a sample chamber. The point can be driven with either a cone penetrometer or conventional drilling equipment. The sample intake pipe is within a watertight housing to prevent contaminated soil or ground water from entering the unit as it is driven into the soil. The exterior is smooth to lessen the possibility that contaminated soil will be carried down with the sampler. A 1-L sample is collected under in situ hydrostatic pressure with no aeration and with minimal agitation. A discrete and representative sample can be collected quickly and economically. However, no permanent sampling point is installed, contaminants floating on the water surface may not be sampled, the sampler must be thoroughly cleaned after sampling, and, if a penetrometer rig is used, geologic data cannot be obtained. The water level must be within 100 ft of the surface.

Ronen and others (1987, p. 69-72) describe a modular multilevel sampler that uses dialysis cells to obtain ground-water profiles. The sampler is constructed from a PVC rod that is crisscrossed with holes 3 cm (centimeter)

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[8] Lucite is a trademark for acrylic resins consisting of a series of polymeric esters.

apart containing the dialysis cells. The cells are filled with distilled water, and the sampler is lowered into the well. The water in the dialysis cells is allowed to equilibrate with water in the well. The sampler is removed and the water in the cells is analyzed. Ronen and others suggest that the sampler may be useful as an early-warning monitoring system.

Johnson and others (1987, p. 453-459) describe a versatile sampler that is suited to the collection of samples for analysis of volatile organic compounds and dissolved gases. The sampler can be used in a well having a diameter greater than 1 cm. Samples can be obtained from any depth. The sampler contains a reservoir which acts as a sample bottle that may be transported to a laboratory. The sampler is chemically inert and easy to clean.

Rannie and Nadon (1988, p. 100) discuss a simple inertial pump of comparatively high flow capacity. Because it is inexpensive, it may be used as a dedicated sampling pump. Rapid up-and-down movement of a riser tubing attached to a foot valve in the well causes water to flow at the surface. Flow rates of 5 L/min (liters per minute) have been obtained. Rannie and Nadon state that the pump has proven suitable for sampling volatile organic compounds.

Gillham (1982, p. 36-39) describes a syringe device for sampling ground water. The syringe is lowered to the desired depth in a well and a plunger is activated to fill the syringe. Once filled, the syringe serves as a sample container for transport to the laboratory. According to Gillham, a principal advantage of syringe samplers is that a sample does not come in contact with the atmosphere prior to analysis; a disadvantage is the small sample size.

Fay and others (1988, p. 65) describe a "bomb-type" sampler suitable for collecting samples of effervescent ground water containing volatile organic compounds. The sampler is a steel tube with gastight ball valves at both ends. Water is pumped through the sampler until an equilibrium is reached; both valves are closed simultaneously, trapping water and entrained gas. Volatile organic compounds and gases are purged from the sampler to an inflatable sample container.

Hansen and Harris (1974, p. 375) describe a ground-water profile sampler that allows the collection of a number of discrete samples from predetermined depths in a single hole. The sampler consists of a series of fiberglass probes in sand-packed compartments within a screened well point. Samples from all probes can be withdrawn simultaneously.

Armstrong and McLaren (1984, p. 48) describe a stainless-steel suction-side sample collector that is installed hydraulically ahead of the intake port of the submersible pump. One-way valves above and below the collector trap the water contained within it at the end of pumping. The device may be used in conjunction with electric pumps, bladder pumps, air-lift pumps, and jet pumps. According to Armstrong and McLaren, the collector system is superior to other systems for collecting samples of volatile organic compounds because contamination of samples by a pump delivery line is not a problem, and because its position in the well is remote from disturbance caused by the pump.

Pankow and others (1985, p. 775) discuss a small ground-water sampling device that permits adsorption/thermal-desorption analysis of organic compounds. The sampler consists of a sorbent cartridge, a flow restrictor, and a tube leading to the ground surface. The device is lowered into a well and water-column pressure forces a water sample through the cartridge. In the laboratory, the water is removed from the cartridge and the sorbed compounds are thermally desorbed for analysis by gas chromatography. Pankow and others (1984, p. 330) also tested a similar device consisting of a cartridge of sorbent material attached to a syringe. Vacuum or pressure applied at the surface controls the movement of the plunger in the syringe, and the volume of the syringe determines the volume of water that passes through the cartridge. Water in the cartridge is removed in the laboratory and analyzed by gas chromatography.

A "snapshot" sampler has been used successfully to collect samples of water without many of the accessories commonly used (John Armstrong, The Traverse Group, Inc., written commun., 1986). The sampler consists of a sealed isolation bottle containing a second vacuum sample bottle floating in distilled water. A stainless steel carrier is used to lower the sampler by line into a well. A hand-operated triggering unit causes a hollow needle to pierce the septum on the sample bottle and allow water to enter. The sample bottle remains in the isolation bottle until ready for laboratory analysis.

Decontamination of Sampling Equipment

Fetter (1983, p. 64) recommends that all sampling, filtering, and collecting equipment be thoroughly rinsed and cleaned after each use. Steel or electric water-level tapes should also be cleaned. Nielsen and Yeates (1985, p. 86) state that sampling devices should be easy to disassemble for cleaning and be able to withstand decontamination procedures such as steam cleaning and rinsing with solvents. They also believe that the problem of cross-contamination can be virtually eliminated by using dedicated samplers.

Korte and Kearl (1984, p. 26-27) suggest that cross-contamination can be a severe problem when sampling a sequence of wells, especially if very low detection levels of a contaminant are required. They believe that portable submersible pumps and bailers present the greatest risk of cross-contamination, but that the large amount of water passing through a high-volume submersible pump can be sufficient to clean it. Korte and Kearl believe that peristaltic and bladder pumps are less likely to cause cross-contamination because only the bladder or pump tubing contact the water. In addition, the tubing can be easily changed if several wells are being sampled.

Dunbar and others (1985, p. 74) state that cleaning a bailer and rope by rinsing with deionized water is not adequate to remove adsorbed constituents. Steam cleaning, washing with laboratory detergent, and then rinsing with deionized water is the preferred cleaning method. They recommend that new lengths of nylon rope be used at each well site.

According to Bryden and others (1986, p. 71-72), tests of small, portable steam cleaners demonstrated the desirability of steam cleaning. The pressure was sufficient to remove particulate matter; the heat removed most organic materials, even heavy oils. Bryden and others state that vigorous steam cleaning may warp Teflon, however. After steam cleaning, they recommend that equipment be rinsed with deionized or "type II" water.

According to the U.S. Environmental Protection Agency (1986, p. 107), when collecting samples for the analysis of organic compounds, equipment should be washed with a nonphosphate detergent and rinsed with tap water followed by distilled water, acetone, and pesticide-quality hexane. Equipment should be thoroughly dried to ensure that residual cleaning agents will not contaminate the sample. For nondedicated sampling equipment, the USEPA recommends disassembly and cleaning of equipment before use.

Richter and Collentine (1983, p. 226) discuss solutions that can be used for decontaminating drilling tools and sampling equipment. They believe that a 5- to 15-percent aqueous solution of sodium bicarbonate is effective in removing acids and bases, a 10- to 20-percent aqueous solution of sodium carbonate is effective in removing inorganic acids, a 10-percent aqueous solution of trisodium phosphate is a good rinsing solution or detergent, and a 10-percent aqueous solution of calcium hypochlorite is an excellent disinfectant, bleaching agent, and oxidizing agent.

Keely and Boateng (1987, p. 311-312) describe a simple decontamination system involving the recirculation of fluids in three small polyethylene containers. The equipment is immersed in the first container, which contains soapy water, and is scrubbed for several minutes. The equipment is then immersed and scrubbed in the second container, which contains a 10-percent solution of acetone in water (methanol, isopropyl alcohol, and similar compounds also may be used). The last container holds distilled water for rinsing. In extreme conditions, a fourth rinse may be desirable because tests have shown that water discharged from a pump just before it is removed from the third container had traces of acetone. The sampling equipment is allowed to drain as it is removed from each container, and thus only a few milliliters of water wet the surface of the device. Keely and Boateng believe that because the device will be immersed in many gallons of water in the next well sampled and because the well will be purged prior to sampling, chances of detecting acetone in the next sample collected are negligible.

Lee and Jones (1983, p. 93) believe that new equipment is particularly prone to contaminating water samples. They recommend that new equipment be soaked in water for a day and then rinsed prior to sampling. W.L. Bradford (U.S. Geological Survey, written commun., 1985, p. 13) states that pumps, thief samplers, and delivery pipes should be washed before and after each use. He also states that, if the concentrations of contaminants in water are high, it may be necessary to wash equipment with hot water and detergent, followed by hot water, acetone, and a hot water rinse. If corrosive materials are present, he suggests that equipment be cleaned prior to storage.

Sampling Techniques and Procedures

Well Purging

Purging of stagnant water from a well is considered essential by many investigators to obtain a representative sample of ground water. Barcelona and Helfrich (1986, p. 1181) studied the effect of purging on ground-water quality. Their study of stagnant water samples showed a higher month-to-month variability in concentrations than did samples collected after well purging. They suggest the variability may have been related to the effect of well-casing materials and small-scale heterogeneities in water quality. Further investigation, however, showed no consistent relation between total organic carbon and type of casing material. Barcelona and Helfrich also found that samples of stagnant well water have higher temporal variability in pH and alkalinity and lower concentrations of organic and inorganic constituents than do samples collected after purging a well.

Low concentrations of organic compounds can be difficult to detect if sampling procedures are unsuitable (Gibb, 1983, p. 77; Gibb and Barcelona, 1984, p. 51); exposure of ground water to the atmosphere in an open hole or to the headspace in sampling devices can result in the loss of volatile organic compounds by partitioning into the vapor phase. Herzog and others (1988, p. 93) found that volatile organic compounds and dissolved gases in a standing column of water may volatilize or be lost within 2 hours. McAlary and Barker (1987, p. 65-67) found losses can be as much as 10 percent within about 12 hours and as much as 99 percent in about 1 month. They also studied the loss of organic compounds during sampling of a laboratory well. Losses ranged from 10 to 14 percent; the amount of headspace to which the sample was exposed was thought to be the most important factor causing losses. McAlary and Barker state that volatilization losses from standing water in a 2-inch-diameter well, if the compounds have a Henry's law constant greater than 0.001 $atm*m^3/mol$ (atmospheres per mole per cubic meter), follow a first-order decay. The decay constant is about 0.18 inverse day. They also believe that diffusion of low-molecular-weight-organic compounds in the liquid phase is rapid enough that it affects all of the standing water in a well.

Seanor and Brannaka (1983, p. 42) note that volatile organic contaminants volatilize or effervesce from stagnant well water, and that stratification by temperature or specific gravity can also occur. Sara (1986, p. 335) states that sorption losses from stagnant well water in wells cased with PVC can be as much as 20 percent.

McAlary and Barker (1987, p. 67) discuss purging of monitoring wells completed in low-permeability materials. They believe that all the water in a well should not be removed during pumping because water from the aquifer will be exposed to the atmosphere as it flows through the headspace in the sand filter pack. Exposure to the atmosphere, they believe, facilitates the loss of volatile organic compounds. They suggest that a new sampling method be developed if exposure of water to the atmosphere and turbulence cannot be avoided.

Fetter (1983, p. 63) states that water in a well can be purged by bailing or by using peristaltic, air-lift, nitrogen-lift, or submersible pumps. According to Fetter, peristaltic and submersible pumps and bailers have been found to be more suitable for purging a well than either the air- or nitrogen-lift pumps which can alter the pH of the water.

Bryden and others (1986, p. 68-69) recommend use of a Teflon bailer with noncontaminating lines when purging shallow 2-inch-diameter wells. They recognize, however, that compressed-gas driven submersible pumps may be the only option for 2-inch-diameter wells greater than 20 ft deep because few electric submersible pumps fit in a 2-inch well and because ground-level pumps cannot draw water from deeper than about 20 ft. Bryden and others found a neoprene bladder pump with a stainless steel exterior to be the most practical pump for purging small-diameter wells. They recommend that a ground-level centrifugal pump be used to purge large-diameter shallow wells and that an electric submersible pump be used to purge large-diameter deep wells. They also recommend a "chase-down" purge for wells with water containing volatile compounds or compounds that may be modified upon contact with oxygen. In "chase-down" purging, pumping is started at the water surface at a rate that is greater than the recharge rate of the well. The pump intake is lowered as the water level falls. When the intake is near the bottom of the well, the pumping rate is decreased to less than the recharge rate. As the well recharges, the pump intake is moved upward with the water level. By use of this method, fresh water from the aquifer that has been exposed to the atmosphere is removed prior to sample collection and mixing of stagnant water and water drawn from the aquifer is prevented.

Keely and Boateng (1987, p. 309) describe a method called "staged purging". The pump is placed just below the water surface and one well volume is removed. While pumping, the pump is lowered about a quarter of the depth from the initial water surface to the bottom of the well. This is repeated twice so that the final position of the pump is near the screen; two additional well volumes are then pumped. For deep wells, they suggest repetition of the procedure.

Unwin and Huis (1983, p. 259-260) state that the best way to purge a 2-inch well is from near the water surface. They state further that removal of seven well volumes by pumping near the water surface will almost completely purge all stagnant water in a 2-inch casing. At greater depth in the well, they believe that about 8 1/2 well volumes may be required. Unwin and Huis also believe that, when pumping from a depth far below the water surface, it may be difficult to determine when purging is complete because of the possible migration of water from above the pump inlet; high pumping rates may worsen the problem. They conclude, however, that pumping from below the water surface may be satisfactory if sampling is done during or just after purging and the water is drawn from well below the pump inlet. An inflatable packer to prevent the downward movement of stagnant water is suggested.

Robin and Gillham (1987, p. 90-92) also found that, in permeable geologic materials, pumping from just below the air-water interface is an effective means of removing stagnant water from a well. They believe that a representative sample of water can be obtained after removal of two to three well volumes. Pumping from a depth considerably below the air-water interface may not remove all stagnant water, but they believe, in principle, that representative water could be obtained after pumping one well volume. They state that a suitable sampling method may be to use a dedicated sampler with the intake near the bottom of the screened interval. They suggest, however, that this method of purging should be avoided because small changes in the elevation of the pump intake and in the pumping rate, as well as uncertainty as to the required volume to be purged, can cause contamination by overlying stagnant water.

Pettyjohn and others (1981, p. 182) use a standard procedure of purging a volume of water equivalent to at least 10 well volumes at 500 mL/min prior to sampling.

W.L. Bradford (U.S. Geological Survey, written commun., 1985, p. 11) states that a well must be pumped prior to sampling, to remove an amount of water equal to at least three well volumes. If the pump can also be used to collect the sample, the well should be allowed to recover before sample collection. If the pump cannot be used for sampling, it should be removed and the well allowed to recover. The sampler should be lowered to the midpoint of the screened interval. Bradford recommends that sampling lines be flushed prior to sample collection. He also suggests a procedure similar to the "chase-down" purge described by Bryden and others (1986, p. 68), with the exception that an amount equal to at least three well volumes must be purged. The pump is placed at the water surface and lowered as the water level drops. When the water level stabilizes, the pump is lowered through the remaining water to remove the stagnant water. The pump is then returned to the midpoint of the screened interval, and pumping continues. Specific conductance, pH, temperature, and depth to water are monitored until they are stable.

According to Walker (1983, p. 243-244), routine purging can put stress on seals and backfill, cause them to leak, and allow pH-altering material to enter the well cavity. In addition, air introduced into the well can alter the Eh of the ground water. Wilson and Rouse (1983, p. 107) state that overpurging in complex environmental settings can cause waters of different quality to mix, and, in extreme cases, contamination of uncontaminated aquifers can occur. Barcelona, Gibb, Helfrich, and Garske (1985, p. 48-51) state that a minimal amount of water should be pumped at hazardous waste sites where purged water must be contained and its disposal is regulated. They also believe that pumping rates should be kept to a minimum to prevent redevelopment or damage of a well. They also note that low pumping rates isolate the stagnant water in the well if the pump intake is at or near the top of the screen; thus, less water must be purged. Giddings (1983, p. 253-255) notes that water-bearing fractures in low-yield bedrock wells may be located just below the water table. If such a well is pumped dry, water cascades into the hole, and its dissolved-gas content may be altered; the dissolved-oxygen concentration may increase. If water-bearing fractures are located near the bottom of a hole and a pump is placed at the bottom of the hole, samples may not be representative. Giddings concludes that, if water-bearing fractures yield water at a rate equal to the withdrawal rate, stagnant water above the pump will not be purged and contaminants near the water surface may not be detected. He states that low-yield wells can also require several hours to recover after purging and that several days of repeated purging may be necessary to remove the required number of well volumes.

Herzog and others (1988, p. 98) address the problem of purging and sampling for volatile organic compounds from wells completed in fine-grained materials. They state that purging should be required for wells finished in fine-grained sediments. Their study suggests that samples collected 4 hours after purging can yield higher concentrations of volatile organic compounds than at earlier or later times, although the variations in concentrations that they found were not statistically significant. They conclude that it is an acceptable practice to purge a well in the morning and sample later the same day or on the following day.

Barber and Davis (1987, p. 581) discuss an equation that can be used to estimate the pumping time necessary to remove stagnant water in wells having 1- to 3-m (meter) screens. Pumping time (t_a) is given by:

$$t_a = -\ln (m) \frac{V}{Q}$$

where V = volume of well storage, Q = average pumping rate, and

$$m = \frac{C_t - C_g}{C_c - C_g}$$

where C_t is the concentration of some substance in water being pumped from the well, C_g is the concentration of the substance in surrounding ground water, and C_c is the initial concentration of the substance in stagnant water in the casing.

The U.S. Environmental Protection Agency (1986, p. 102-103) states that water should be removed not only from the well, but also from the filter pack so that water in the deposit can replace stagnant water. In high-yield deposits, the USEPA recommends that three well volumes of water be removed from above the screen in the uppermost part of the water column prior to sampling. In low-yield deposits, the USEPA recommends that water be removed from the bottom of the screened interval. They also state that a well should be evacuated to dryness once when installed in a low-yield deposit. As soon as the water level recovers, pH, temperature, and specific conductance should be measured, and samples collected. The USEPA emphasizes that a well should not be pumped to dryness if water levels recover vigorously; agitation may cause loss of volatiles. If this problem is anticipated, removal of three well volumes of water at a rate that prevents excessive agitation is recommended.

According to Scalf and others (1981, p. 43), water within and near a well is probably not representative of the aquifer water; contaminants introduced during drilling may be present in or near the well. They state that purging 4 to 10 well volumes before samples are collected is common; however, the actual purging time and volume purged from a well depends on many factors, such as the hydrogeology of the site, sampling equipment used, and the dissolved substances of interest. Schuller and others (1981, p. 46), as part of a study of sampling protocols for monitoring wells, concluded that purging four to six well volumes will, in most cases, produce samples representative of water in the deposit.

Emenhiser and Singh (1984, p. 35-36) state that a representative sample can be obtained by monitoring pH and specific conductance while purging. They suggest that a minimum of three well volumes be purged and pumping continued until two consecutive pH and specific conductance measurements do not differ by more than 15 percent. Barcelona (1983, p. 268) suggests measuring temperature, pH, Eh, and specific conductance until successive measurements are within 10 percent before sample collection. Robin and Gillham (1987, p. 93), however, found that specific conductance fluctuated slowly and randomly about a mean. They conclude that by purging until specific conductance and temperature are stable, a longer purging time is required than necessary to remove stagnant water.

Gibs and Imbrigiotta (1990, p. 68) studied three well-purging criteria for sampling volatile organic compounds. The criteria were (1) purging an arbitrary number of well volumes, (2) purging a well until field measurements of temperature, specific conductance, pH, and dissolved-oxygen concentrations stabilize, and (3) purging until water in a well is in hydraulic equilibrium with water in an aquifer. In their investigation, concentrations of volatile organic compounds stabilized after purging three well volumes in only 55 percent of the cases; field measurements stabilized after purging three well volumes in 86 percent of the cases. They also found that, in purging highly transmissive aquifers to achieve hydraulic equilibrium, the time and number of well volumes required to stabilize water-quality characteristics was consistently underestimated. Gibs and Imbrigiotta conclude that none of the three criteria can be applied reliably when collecting samples to be analyzed for volatile organic compounds.

In a study of 14 shallow wells finished in sandstone, siltstone, and shale, Pionke and Urban (1987, p. 84-85) found that, when the water level was below the casing in an open hole, purging of less than 1 well volume was required to obtain a sample of water representative of the aquifer. They conclude that an on-site investigation to determine when water-quality characteristics become stable is preferable to relying on purging an arbitrary number of well volumes prior to sampling.

Pearsall and Eckhardt (1987, p. 72-73), in a laboratory experiment, found that typical procedures for purging--such as pumping specific well volumes or measuring pH, specific conductance, and temperature until they stabilize--did not ensure stable concentrations of volatile organic compounds. In 15 tests, the common field measurements were stable within 30 minutes and after more than 10 well volumes had been purged. Trichloroethylene concentrations, however, were still changing after 3 hours of purging. The study showed that concentration changes were not due to continued mixing with standing water in the well column. Instead, the measurements indicate that changes in concentration may have been due to local spatial and vertical variations in trichloroethylene distribution and variations in hydraulic characteristics of the aquifer. Pearsall and Eckhardt believe that sampling protocols for frequently sampled wells should be designed to detect this variability. They suggest standardized sampling equipment and sampling techniques for each monitoring well to reduce the variability in concentration that may be related to effects of purging.

Unpublished data on the number of well volumes of water necessary to purge stagnant water were collected by the U.S. Geological Survey in Michigan in September 1989 (T.R. Cummings, U.S. Geological Survey, written commun., 1989). A 2-inch-diameter well and a 4-inch-diameter well, 10 ft apart and having screen settings at approximately the same depth, were used in the test. Sufficient sodium chloride solution was added to each well to raise the specific conductance to several thousand µS/cm (microsiemens per centimeter at 25 degrees Celsius). Standing water in each well was circulated with a submersible pump until measurements of specific conductance indicated that the standing water was mixed. Water was pumped from each well, in separate tests, with the pumps set just above the screen and just below the water surface. Data confirmed that purging just below the water surface results in more rapid removal of stagnant water from a well. In tests using the 4-inch-diameter well, specific conductance became stable after purging about 6 to 7 well volumes when the pump was set 4 ft below the water surface. When the pump was set 2 ft above the screen, specific conductance became stable after purging 8 to 9 well volumes. In both instances, the pumping rate was about 6.4 gal/min (gallons per minute). In tests using the 2-inch-diameter well, specific conductance stabilized after purging about 7 to 8 well volumes when the pump was set 1 ft below the water surface. When the pump was set 2 ft above the top of the screen, specific conductance had not quite reached stability after 8 well volumes had been purged.

Files of the U.S. Geological Survey in Michigan also contain other unpublished data collected during a period of years to investigate the relation of well purging to the concentration of volatile organic compounds (T.R. Cummings, U.S. Geological Survey, written commun., 1989). Most of the wells were chosen to obtain water containing different volatile hydrocarbons in a range of concentrations. Extreme care was taken in sample collection; in most instances, duplicate analyses were made. Specific conductance, temperature, pH, and chloride were also periodically measured during purging. Periods of purging ranged from a few minutes to a day and a half. The number of well volumes at which a sample was obtained ranged from less than 1 to about 2,000. In analyzing the available data, concentrations of volatile hydrocarbons and specific conductance were related to the number of well volumes of water purged. Results of the investigation raised doubts as to (1) whether general guidelines can be set with respect to the pumping time and to the number of well volumes that should be purged before sample collection, or (2) whether the stability of easily measured properties, such as specific conductance, can be used in all instances as a guide in choosing the time to sample. In general, the concentrations of volatile hydrocarbons in water from seven of nine wells increased with pumping time. In one instance, however, the ethyl benzene concentration increased and the benzene concentration decreased the longer the well was pumped. Specific conductance generally increased with pumping time, although changes in specific conductance were less pronounced than those in the concentrations of volatile hydrocarbons. Schmidt (1982b, p. 122) also cites data supporting the conclusion that water-quality stabilization occurs after withdrawing different well volumes from different wells at the same site.

Pumping Rates

According to Barcelona, Gibb, Helfrich, and Garske (1985, p. 48), pumping rates should be kept to a minimum so that stagnant water is purged without causing additional well development. Several different suggestions concerning pumping rates with regard to purging are made by investigators. Gibb and others (1981, p. 7-8) recommend that a well be pumped at a constant rate for a period of time that will result in the delivery of at least 95 percent aquifer water; they also recommend that the pumping rate and time be determined on the basis of transmissivity of the aquifer, well diameter, and results of a sampling experiment. Schmidt (1982a,b, p. 122, p. 29) suggests that, where possible, monitoring wells be pumped at rates from 20 to 50 gal/min for about 30 to 90 minutes prior to sampling.

Unwin and Huis (1983, p. 259-260) studied pumping from 1 in. below the water surface and from 35 in. below the surface. Both high-rate and low-rate pumping was investigated. They concluded that, at the pumping rates used (0.15 to 5 gal/min), purging near the water surface was the most effective way of removing stagnant water from a well.

In testing sampling devices, Imbrigiotta and others (1986, p. 11-12) observed the effects of pumping rate on five volatile organic compounds during pumping of a monitoring well. The well was pumped at rates of 3.8 L/min on the first day of sampling and 38 L/min on the second day. Results showed that the mean concentrations of the five volatile organic compounds were higher when the well was pumped at the higher rate. Imbrigiotta and others suggest that the size of the plume being sampled, the distance from the source to the well, and the rate at which the well is pumped have significant effects on the recovery of volatile organic compounds. Pumping rate, they conclude, is as significant as the type of sampling device in obtaining representative water samples.

Wilson and Rouse (1983, p. 108) studied the relation of pumping rate to changes in water quality. They concluded that mixing of aquifer water or induced leakage is more likely if a large cone of depression is created by either a high pumping rate or extended pumping. A moderate pumping rate is recommended, especially if multiple zones of a well are to be sampled. Interzonal mixing may also be reduced if a low pumping rate is used at sites where horizontal permeabilities are higher than vertical permeabilities. Wilson and Rouse suggest that low pumping rates may cause a problem if a large amount of hose is on the reel; long residence time in the hose may result in either sorption or leaching of compounds onto or from the hose.

Ho (1983, p. 585-586) studied the effect of sampling variables on the recovery of nine volatile organic compounds in water. The pumping rate had a statistically significant effect on the recovery of carbon tetrachloride, tetrachloroethene, and 1,1,1-trichloroethane. Recovery of the compounds decreased with an increase in pumping rate. Ho suggests that a normal-speed peristaltic pump be used to minimize the effect of pumping rate.

Use of Packers

According to Barber and Baxter (1983, p. 60-61), inflatable packers increase the flexibility of a sampling program by permitting vertical isolation of sampling zones, although uneven hole walls can cause problems. Johnson and others (1987, p. 451) suggest using a packer to isolate "fresh" water from the stagnant water in the casing, and from the air-water interface. Morrison (1983, p. 95), however, cautions that, over time, the expandable packer material could deteriorate and could release organic contaminants.

Welch and Lee (1987, p. 86-87) describe a multilevel packer and PVC standpipe system that provides a pressure seal between isolated intervals, allows simultaneous access to intervals, causes little or no chemical alteration of ground water, and is removable when desired. The system operated for 5 years with only minor routine maintenance. Welch and Lee recommend placing packers at both ends of low-permeability zones to reduce the volume of water that must be pumped prior to sampling. They conclude that packers have the advantages of allowing collection of water samples from discrete zones and allowing hydraulic testing and measurements of head at many depths within a single hole. One deep hole thus can provide data that would otherwise require multiple wells completed at different depths.

Burkland and Raber (1983, p. 48) note that packer blowouts and water leakage past packers are potential problems. To prevent migration of water past a single packer, Jehn (1983, p. 430-432) used two packers to ensure isolation of a sampling zone. Results of water-quality analyses indicated that this procedure was effective.

Gillham and others (1983, p. 139) discuss chemical packers contained in rubber membranes, which provide a seal between the deposit and the casing. The chemical used is a gelatinous substance that swells when in contact with water. According to the authors, tests indicate that these packers provide a good seal.

Multilevel Sampling

According to Morrison and Timmons (1981, p. 21), the most common type of well for ground-water monitoring is the single-screened well. They note that the zone within the screened interval from which the contaminants originate cannot be isolated with this type of well. If the screen does not intercept a contaminated zone, contaminants may not be detected. If a well is screened through the entire aquifer, the aquifer is thick, and the contaminated area is thin, results of chemical analyses of water may not be indicative of a problem. Further, Morrison and Timmons believe that the vertical distribution of contaminants cannot be determined with a single-screen well and that either well clusters or multiple-completion wells must be used.

Johnson (1983, p. 76) describes well clusters, well nests, or multiple-completion wells as several closely spaced individual wells, each screened at a different depth. Johnson discusses several means of construction. One method is to place a number of small-diameter (1- to 1 1/4-in.) casings within one hole, each casing completed at a different depth and separated from the others by bentonite or cement seals. Another method is to use one casing with individual ports or probes that penetrate the casing at various depths with tubes leading from the ports to the surface for sampling. Johnson notes that it may not be possible to set multiple screens, sand packs, or grout in a single hole if caving is a problem. In such cases, a well nest in which each well has a single screen and casing may be preferred. However, if caving is not encountered and if hollow-stem augers or temporary casing are used, a single hole is preferred because it can be installed more rapidly. Multiple-completion wells require a larger drilling rig than do individual wells because the hole must be larger.

According to Johnson (1983, p. 76-78), well nests are the most versatile of multilevel-sampling designs for general monitoring. He states that large-diameter wells allow a greater variety of monitoring equipment to be used, and thus confidence in the data collected is increased. Smaller-diameter casings of the multiple-completion wells are believed to be an advantage because less purging is required and the possibility that water in the casing will mix with water entering the tubing is reduced. He notes, however, that small-diameter casing can limit the types of sampling and development equipment used. For example, a 1 1/4-inch-diameter or larger casing is required for almost all water-level recorders, pressure transducers, or electronic sensing devices. Johnson also states that more time is also required to install a multiple-completion well than a single-completion well because more pipes and screens are installed; the time waiting for grout to set also is increased. The number of casings within a hole and the short seals between the screens makes a good seal difficult; therefore, the chance of well failure is greater than for single-completion wells. Johnson states that another drawback to multiple-completion wells is that the large rig required for installation may not be readily available, especially in remote areas.

Morrison and Timmons (1981, p. 21) discuss the importance of completely sealing the screens of each casing from one another in well clusters. They believe that the possibility of channeling along the casing is increased because of the increased surface area of several casing lengths; therefore, the possibility of cross-contamination between screened segments is also increased.

Scalf and others (1981, p. 38-42) discuss hole diameters and the size and number of casings that can be placed in the hole. If a hole is as much as 12 in. in diameter, casings that are 3 in. or larger in diameter and pumps can be installed. An 8- to 10-inch diameter hole allows 2-inch-diameter casings and a pump to be installed; however, a 2-inch-diameter casing limits the rate of pumping and volume of water that can be purged. A third option, which requires a 9- or 10-inch-diameter hole, involves permanently installing submersible pumps in 4-inch well screens. The installation is repeated in each zone to be sampled. Each pump discharges to the surface through a 2-inch-diameter pipe. Installation is complicated, however, and failed pumps cannot be replaced. Scalf and others recommend that multiple-completion wells be avoided because of the potential for cross-contamination between zones, unless the method is significantly more cost effective than other options. Scalf and others also describe a gun-perforated well. Such a well is commonly drilled to locate the permeable layers at a site. Casing is installed, and grout is placed in the annulus from the bottom up to surround the casing. The casing is then perforated at the deepest water-bearing layer, and the water is sampled and analyzed. If no contaminants are found, the perforated zone is cemented. The next water-bearing zone is perforated and the procedure repeated until all zones have been examined.

Nakamoto and others (1986, p. 50) suggest that multiple-completion wells can be constructed for two to three times less cost than an equal number of individual wells, largely because of the greater cost of drilling and grouting individual wells. They recommend testing the seals in a multiple-completion well by measuring the hydraulic-head difference of two adjacent wells. Differences in the water quality of the wells also can verify seal integrity.

Pickens and others (1978, p. 322, 326-327) describe a multilevel sampler that consists of several polypropylene tubes that protrude through the wall of PVC casing at different depths to permit sample collection. The tip of each tube is encased in fine-meshed stainless-steel screening. Pickens and others cite the following advantages of this sampler: (1) Ground-water samples and hydraulic-head measurements can be obtained, (2) samples can be collected from a known point rather than from a mixed zone, (3) the volume of stagnant water to be removed prior to sampling is minimal, (4) samples are collected quickly so that the opportunity for degassing or oxidation is minimal, (5) the design is inexpensive and easily constructed, and (6) the device is permanently installed.

Cherry and others (1983, p. 37-44) describe four devices used to obtain vertical sample profiles of water from a single hole. One, an auger-head suction sampler, consists of a porous tip that is attached to the lead end of a hollow-stem auger and connected to the surface by a tube within the auger stem. Samples are drawn to the surface by applying a vacuum to the tubing. Cherry and others state that the auger-head sampler can provide a rapid survey of water quality in relatively undisturbed zones. A suction-type multilevel sampler with screened sampling points at different depths is also described. Polyethylene or polypropylene tubes extend from the sampling points to the surface. Samples are obtained by suction lift at the surface. According to Cherry and others, the suction-type multilevel sampler can accommodate 20 or more tubes and thus produce detailed profiles, but sampling depth is limited by suction lift. A positive-displacement multilevel sampler, similar in design to the suction sampler, also can be used to obtain samples from greater depths because it is not limited by suction lift. The screened sampling point is attached to a tube that branches into two tubes, one of which extends to the surface and the other which extends to the syringe pump. The pump is operated by applying pressure from the surface through the pressure tube. The sample is completely isolated from the atmosphere; thus, changes in the dissolved-gas content of samples are prevented. Positive-displacement samplers can sample at any depth, but they cost considerably more than bundle piezometers. According to Cherry and others, bundle piezometers may be constructed of polyethylene tubes that are perforated at the ends with holes or slots and wrapped with nylon cloth. The tubes are taped around a rigid central pipe and extend to different depths. Samples are collected by suction lift or bailing.

Burkland and Raber (1983, p. 49-52) discuss a method of drilling and completion of multilevel sampling wells. A hole is drilled through an aquifer into an underlying confining bed. Temporary stainless steel casing is set to within 6 in. of the bottom of the hole. Stainless steel is recommended because of the possibility of breakage of PVC by drill rods in subsequent drilling. Quick-setting expansive grout is emplaced. Standing water is removed from the well, and the well is checked for leaks. If there is no leakage, drilling proceeds. The hole is drilled through the grout plug, the confining bed, and into a lower aquifer. A number 3 sand[9] footing is placed in the bottom of the hole, and a sampler-transducer assembly is lowered onto the sand footing. Number 3 sand is added to completely cover the assembly. A 2-ft thick fine-sand cap is then placed on the number 3 sand, followed by a 5-ft thick bentonite plug and grout to within 2 ft of the next assembly location. The temporary casing is then removed and the slotted section is packed with number 3 sand, followed by a 2-ft thick fine-sand cap and grout to land surface.

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[9] Number 3 sand has a diameter of 0.25 in.

Another drilling procedure to prevent cross-contamination between multiple aquifers is discussed by Gandl and Webb (1985, p. 148-149). In this procedure, threaded flush-joint steel casing is driven into the hole as the hole is deepened. The casing is approximately the same size or slightly larger than the hole. When a lower clay zone is reached, the upper zones are effectively sealed off from the lower zones. A depth of 120 ft has been reached using this method.

Riha (1981, p. 738) describes a multistage ground-water sampler that is equipped with rubber packers at the bottom and top of the intake pipe to ensure that water is from a discrete zone. In large-diameter casing, the sampler can be used to collect water from the upper zones. In small-diameter casing, a narrower sampler can be inserted into the first sampler to collect water from lower zones. Water samples from multiple aquifers can be taken simultaneously without mixing. The standard unit is constructed entirely of thermoplastic.

Wood (1976, p. 3-4) suggests the use of a flow-meter survey to determine if multiple-aquifer flow exists. He recommends avoidance of multiple-aquifer wells, although he believes that pumping from between well packers can yield representative water samples.

Multiple-aquifer penetrations may be indicated during drilling if large changes in hydraulic head are observed in combination with changes in lithologic facies, according to Claassen (1982, p. 19-21). Claassen believes that water from wells that penetrate multiple aquifers is a mixture of water from those aquifers, and that the degree of mixing is dependent on aquifer hydraulics. He suggests that, if the pump intake is placed in an aquifer of interest and the pumping rate does not exceed the aquifer's ability to yield water, very little water from other aquifers will be present in the discharge from the pump. He also believes that the only way to avoid the complexities of mixing is to isolate the desired producing interval. Kelly (1982, p. 185), however, recommends that monitoring wells be constructed so that they are open to only one aquifer. He also suggests that samples be collected within a single aquifer zone if the well is open to multiple aquifers.

CONCLUSIONS

A range of methods have been used to install monitoring wells in investigations of ground-water contamination. The most common methods have been rotary drilling, augering, and cable-tool drilling. Each of these methods, as well as those less frequently used, has advantages and disadvantages that depend on geologic and hydrologic conditions and on the objectives of the investigation at a specific site.

The most suitable materials for well casings and screens are those most resistant to deterioration and those that do not adsorb or absorb chemical substances from ground water or release them to it. In general, Teflon and stainless steel are recommended by most investigators if cost is not a major concern, but plastics (such as PVC) and galvanized steel are believed to be suitable materials for many investigations. Most investigators have used wells ranging from 2 to 6 in. in diameter, and each size has advantages. Wells having 4-in. diameters seem to be most practical when cost constraints are not severe and when information other than water-quality data are required. Annular seals, either improperly installed or of unsuitable materials, are known to modify water quality. Cement and bentonite seem to be the most commonly recommended seals, provided that their permeability is one or two orders of magnitude less than that of surrounding deposits. When fluids are required in well drilling, the amount used should be kept to a minimum to prevent a subsequent effect on water quality. If wells are to yield representative samples of water, proper well development is necessary. Several methods are used, depending on the type of well installed. Repetitive reversals or surges of flow through the screen are generally considered essential.

Materials used in collection of samples of water for chemical analysis should be durable, easy to clean, and free of contaminating substances. Adsorption, absorption, and leaching should be minimal. Teflon, stainless steel, and glass are generally considered the most suitable materials. Although opinions differ as to the best sampling devices, most investigators conclude that bladder (no gas contact) pumps, submersible pumps, and bailers are best for sampling of volatile organic compounds. Suction pumps, air-lift pumps, peristaltic pumps, and pumps that allow sample contact with air should be avoided if possible.

Purging of wells to remove stagnant water prior to sample collection is considered essential by all investigators. Results of tests to determine the number of well volumes that should be purged differ. Suggestions generally range from about 3 to as many as 10 well volumes, depending on site-specific conditions. Multilevel sampling, although difficult at places, is generally considered a useful means of obtaining information on the vertical distribution of contaminants at comparatively low cost.

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