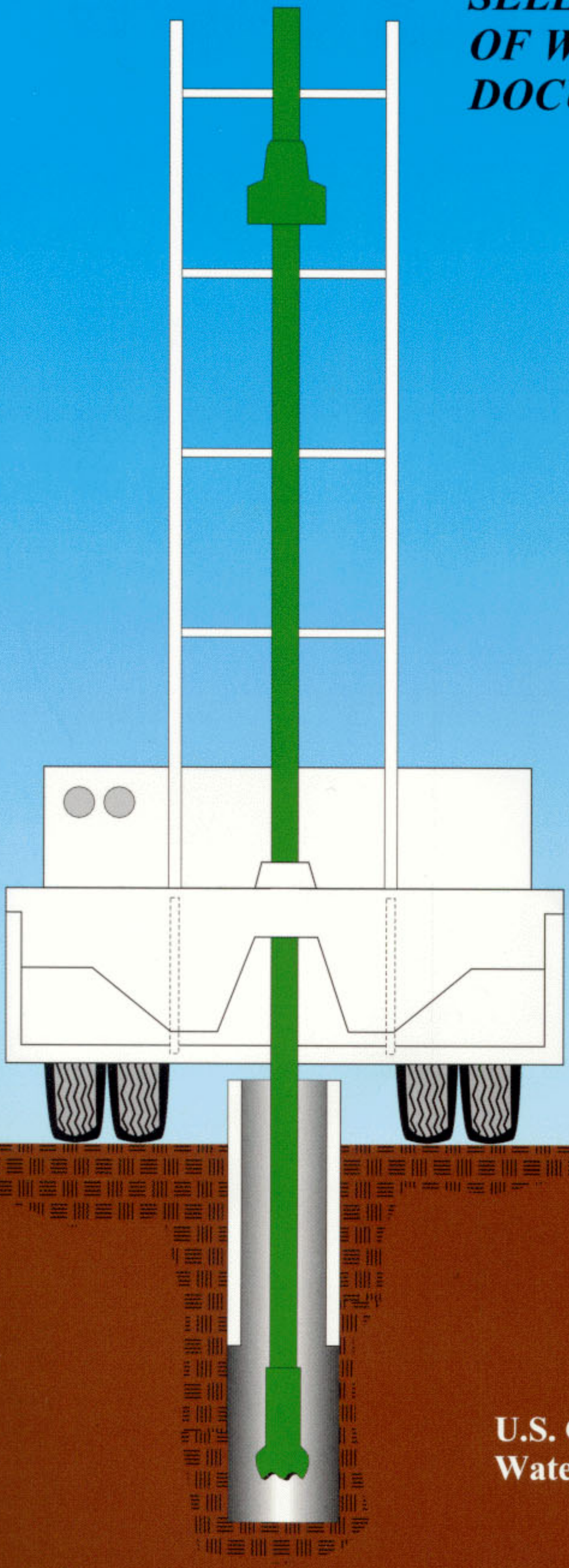
GUIDELINES AND STANDARD PROCEDURES FOR STUDIES OF GROUND-WATER QUALITY:

SELECTION AND INSTALLATION OF WELLS, AND SUPPORTING DOCUMENTATION



U.S. DEPARTMENT OF THE INTERIOR
MARCH 3, 1849

U.S. Geological Survey
Water-Resources Investigations Report 96-4233

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By Wayne W. Lapham, Franceska D. Wilde, *and* Michael T. Koterba

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CONVERSION FACTORS, WATER-QUALITY UNITS, VERTICAL DATUM, ABBREVIATIONS, AND SYMBOLS

Multiply	By	To obtain
	Length	
inch (in.)	25.4	millimeter (mm)
	2.54	centimeter (cm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Volume	
pint	0.473	liter (L)
gallon (gal)	3.785	liter
	3785	milliliter (mL)
cubic foot	23.317	liter
	Hydraulic Conductivity	
foot per day (ft/d)	0.3048	meter per day (m/d)
	0.00035	centimeter per second (cm/sec)
meter per day (m/d)	0.00115	centimeter per second (cm/sec)
	Weight	
pounds (lbs)	0.4536	kilograms

Physical and Chemical Water-Quality Units

Temperature: Water and air temperature are given in degrees Celsius (°C), which can be converted to degrees Fahrenheit (°F) by use of the following equation:

$$°F = 1.8(°C) + 32$$

Specific electrical conductance (conductivity): Conductivity of water is expressed in microsiemens per centimeter at 25 degrees Celsius (µS/cm). This unit is equivalent to micromhos per centimeter at 25 degrees Celsius.

Milligrams per liter (mg/L) or micrograms per liter (µg/L): Milligrams per liter is a unit expressing the concentration of chemical constituents in solution as weight (milligrams) of solute per unit volume (liter) of water. One thousand micrograms per liter is equivalent to one milligram per liter. For concentrations less than 7,000 mg/L, the numerical value is the same as for concentrations in parts per million.

Millivolt (mv): A unit of electromotive force equal to one thousandth of a volt.

Nephelometric turbidity unit (NTU): A measure of turbidity in a water sample, roughly equivalent to Formazin turbidity unit (FTU) and Jackson turbidity unit (JTU).

Vertical Datum

Sea level: In this report, “sea level” refers to the National Geodetic Vertical Datum of 1929--a geodetic datum derived from a general adjustment of the first-order level nets of the United States and Canada, formerly called *Sea Level Datum of 1929*.

Abbreviations

ASTM	American Society for Testing and Materials
GC/MS	gas chromatography/mass spectrometric detector
GWSI	Ground-Water Site Inventory
MEK	methylethylketone
MIBK	methylisobutylketone
NWIS	National Water Information System
PE	polyethylene
PP	polypropylene
PTFE	polytetraflouroethylene
PVC	polyvinylchloride
QWDATA	Quality of Water Data
SS	stainless steel
THF	tetrahydrofuran
TSP	trisodium phosphate
USGS	U.S. Geological Survey
VOC	volatile organic compounds

Symbols

~	approximately equal to
=	equal to
<	less than
≤	less than or equal to
>	greater than
≥	greater than or equal to
±	plus or minus

GUIDELINES AND STANDARD PROCEDURES FOR STUDIES OF GROUND-WATER QUALITY:

SELECTION AND INSTALLATION OF WELLS, AND SUPPORTING DOCUMENTATION

By **Wayne W. Lapham, Franceska D. Wilde, and Michael T. Koterba**

ABSTRACT

This is the first of a two-part report to document guidelines and standard procedures of the U.S. Geological Survey for the acquisition of data in ground-water-quality studies. This report provides guidelines and procedures for the selection and installation of wells for water-quality studies, and the required or recommended supporting documentation of these activities. Topics include (1) documentation needed for well files, field folders, and electronic files; (2) criteria and information needed for the selection of water-supply and observation wells, including site inventory and data collection during field reconnaissance; and (3) criteria and preparation for installation of monitoring wells, including the effects of equipment and materials on the chemistry of ground-water samples, a summary of drilling and coring methods, and information concerning well completion, development, and disposition.

INTRODUCTION

The mission of the U.S. Geological Survey (USGS) is to assess the quantity and quality of the earth resources of the Nation and to provide information that will assist resource managers and policymakers at Federal, State, and local levels in making sound decisions about the use of these resources. This report addresses those aspects of this mission that involve investigations into the quality of the Nation's ground-water resources.

The guidelines and standard procedures in this report will help ensure that sound technical and scientific principles are applied in ground-water-quality studies of the USGS, specifically for well selection and in the selection of methods, procedures, equipment, and materials used for well installation. The criteria used by a specific water-quality study to guide well selection and well installation are determined within the context of the study's scope, conceptual framework, objectives, testing hypothesis, and scientific approach (table 1). This entails examining available information to describe the three-dimensional volume of materials to be sampled, and to design a data-collection network. The network design identifies general criteria that relate to the selection or installation of wells, such as the required number and distribution of wells (areally and with depth). It is assumed in this report that all these elements of study and network design have been clearly articulated and completed before beginning well selection and well installation (table 1).

The protection of sample integrity is the guiding principle for studies of ground-water quality. Although the diversity among USGS ground-water-quality studies in relation to study objectives, environmental settings, and spatial and temporal scales precludes the establishment of all-encompassing protocols, three protocols apply to all such investigations and will help ensure and document data quality:

- Design and implement each aspect of the study to reduce undesirable bias in the data collected.
- Integrate quality-assurance procedures into workplans and activities.
- Integrate documentation into each phase of the study.

Each study or program is responsible for the development of those specific criteria and protocols needed to meet its objectives and to ensure compliance with USGS scientific and technical standards.

Purpose and Scope

This report is intended to help professional personnel plan specific well-selection and well-installation aspects of ground-water-quality studies and to increase their awareness of how the choices made could affect sample integrity and analytical results. The report describes the types of information used to document well selection and well installation, and the USGS guidelines and standard procedures used for selecting supply wells and installing monitoring wells from which water-quality samples will be collected.

Table 1. *Contents of this report in relation to the basic elements of ground-water-quality studies*[1]

[The steps shown are a simplification of an iterative and complex process. The shaded section indicates the part of this process covered by this report.]

BASIC ELEMENTS OF GROUND-WATER-QUALITY STUDIES

- State the problem that initiated the study
- Define the purpose and scope of the study
- Develop a conceptual framework for the study, including a description of the environmental setting
- Define the objectives of the study and formulate hypotheses to be tested
- Develop a scientific and technical approach for network design, data collection, and quality assurance
  - Incorporate a multidisciplinary perspective, if appropriate (for example, hydrogeological, geophysical, and statistical methods)
  - Use knowledge of site geology and hydrology to determine location of wells and sample-collection (screened or open) intervals
- Implement the approach for network design, data collection, and quality assurance including[2]:
  - Select and install wells, and complete supporting documentation
  - Collect water-quality and quality-control samples and related data, and complete supporting documentation
- Analyze and interpret data
- Report results

[1] Adapted from a general approach to ground-water-quality studies being developed by the Intergovernmental Task Force on Monitoring Water Quality, with the U.S. Geological Survey as an active participant (O.L. Franke, U.S. Geological Survey, written commun., 1996).

[2] For the purpose of this report, additional elements usually included in an approach for network design and data collection for water-quality studies are not represented; for example, site reconnaissance, collection of geologic data, or determination of aquifer characteristics.

Table 1 indicates the contents of this report with respect to other elements for planning and conducting studies of ground-water quality. The information provided is general, as this report is not intended to be a comprehensive guide to USGS water-quality studies, but can be used in conjunction with other reports that address the design of well networks and wells (Alley, 1993); the development of study and quality-assurance workplans (Shampine and others, 1992; Cohen, 1994), and the need to follow specific program or project protocols (Koterba and others, 1995; Lapham and others, 1995). In addition, this report supplements technical documents, such as the National Handbook of Recommended Methods for Water-Data Acquisition (USGS, 1977), Claassen (1982), Keyes (1986 and 1990), Shuter and Teasdale (1989), and USGS internal memorandums (see “Internal Documents”).

Acknowledgments

The authors wish to acknowledge the technical contributions, advice, and encouragement of colleagues in the preparation of this document. Louise V. Parker of the Army Corps of Engineers Cold Regions Research and Engineering Laboratory provided important critique and references on well materials. Members of the following American Society for Testing and Materials (ASTM) task groups also provided valuable review of selected sections of this report: Site Characterization for Environmental Purposes (D18.01.06), Direct Push Sampling (D18.21.01), Monitoring Well Drilling and Soil Sampling Procedures (D18.21.03), Monitoring Well Design and Construction (D18.21.05), and Ground-Water Sample Collection and Handling (D18.21.07). J. Russell Boulding, Joseph S. Downey, and Edwin D. Gutentag of ASTM task group D18.01.06 provided information that improved the quality and comprehensiveness of this report.

Special thanks go to Warren E. Teasdale, U.S. Geological Survey (retired) and Jeffrey A. Farrar, U.S. Bureau of Reclamation, who provided iterative and extensive reviews of the well-construction sections of this report. Jeffrey Farrar supplied the basic information on direct-push technology.

The authors also are indebted to USGS colleagues Alan W. Burns, Robert E. Faye, Larry J. Mann, John S. McLean, Johnette C. Shockley, and Alan H. Welch for their comprehensive technical critiques of earlier versions of this report; to John A. Izbicki, LeRoy L. Knobel, and Dennis W. Risser for peer reviews of the final draft; to Iris M. Collies, Rosemary Musson, and Emily Sabado for editorial assistance in the preparation of this report; and to Rebecca Bruno and Suzanne C. Roberts for preparation of illustrations.

SUPPORTING DOCUMENTATION

Studies of ground-water quality require careful and complete documentation of site information and criteria and methods used for the selection and installation of wells. Such documentation is integrated throughout each well-selection and well-installation process. Systematic documentation is a basic component of quality assurance for any study, and often aids interpretation of ground-water data. It also provides a historical reference for future use of the well. Documentation involves the establishment of a well file that includes electronic and paper records for each well, compilation of available information, the addition and verification of information at the field site, and record-keeping during each phase of the study.

This section summarizes the types of documentation generally required for the well file and for that part of the file used during field visits (the field folder) (fig. 1). Information required to establish an electronic well record in the USGS National Water Information System (NWIS) also is described (table 2).

Well File and Field Folder

A well file must be established for each existing well selected or new well installed for a water-quality study. The well file is the paper and electronic repository of the information, documents, and records compiled during development of a conceptual framework and network design for the study, site selection, well inventory, well selection or installation, and sample collection. A subset of this file is also kept in a field folder, which is used for ready reference at the field site. The field folder includes a written log of field activities and observations, along with the forms used to record specific information such as water levels and other field measurements, well location and construction information, and permission forms.

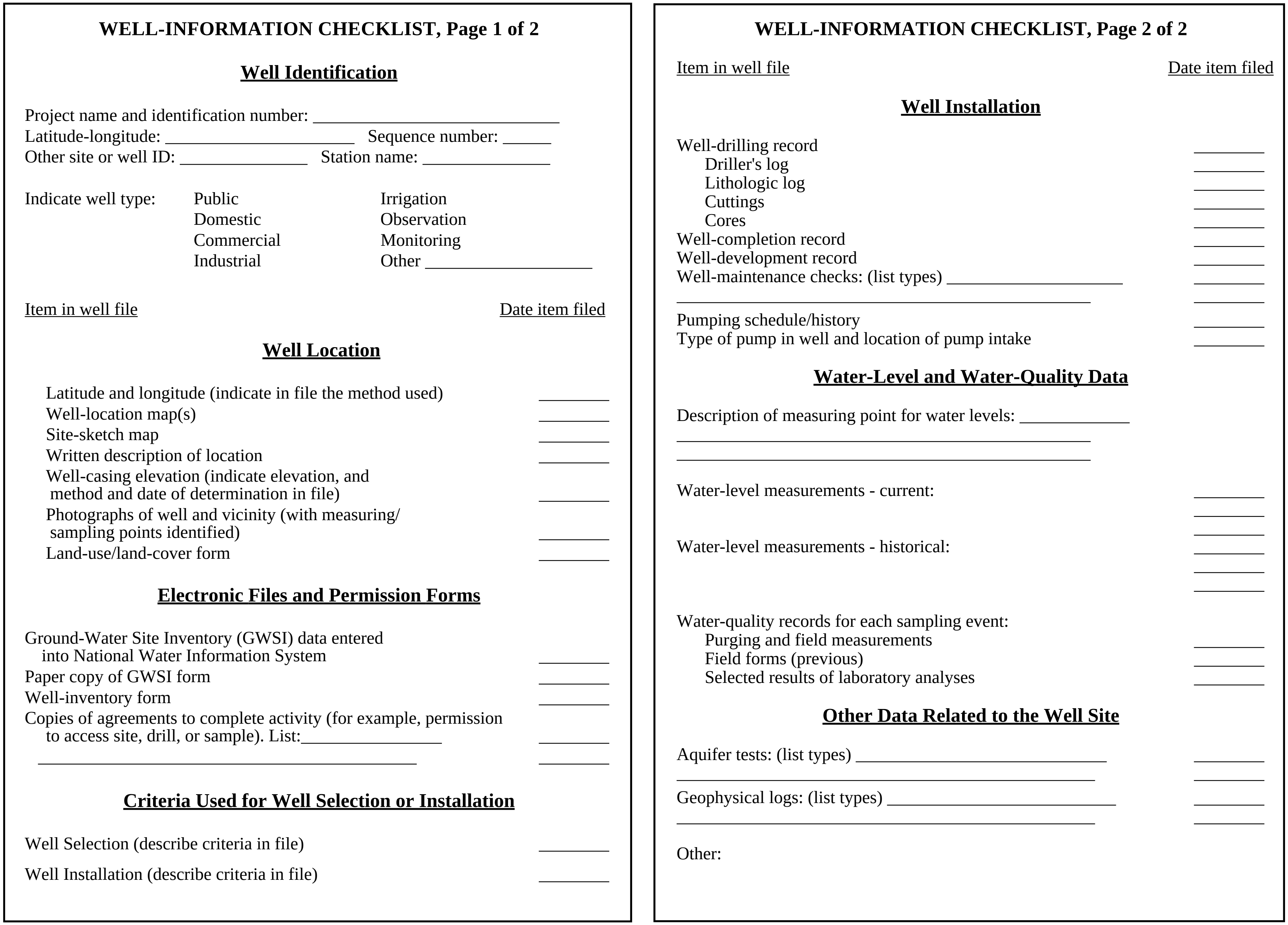
MANDATORY: ESTABLISH WELL FILES AND KEEP CURRENT WITH DATA ENTRY.

At the outset of the study, create a checklist of the items and types of information needed for the well file (fig. 1). Information commonly includes: well identification number, well location, electronic files and permission forms, criteria used for well selection or installation, well-construction information, water-level and water-quality data, and other data related to the well site (fig. 1). As this information is added to the well file, the data are recorded or the information checked off. This helps track the well-file contents and what might be missing.

The well file and field folder must include enough information to identify and locate each well: latitude and longitude, well sequence number, a map indicating the location of the well, and a sketch of the site. The utility of photographs or land-use and land-cover information and the degree of detail recorded depends on the individual study or program.

Electronic files are mandatory and are discussed below in greater detail. A paper copy of some portion(s) of NWIS files often are kept in the field folder. Copies of agreements signed by the owner(s) granting site access; permission to install, maintain, and use a test hole or observation well (fig. 10a, page 78); permission for use of an abandoned test hole or well (fig. 10b, page 80); and permission to (originally or eventually) publish the data collected also are needed for the well file and field folder (see Water Resources Division Memorandums No. 88.021 and No. 94.008 in “Internal Documents”). (Additional USGS memorandums cited in this report are also listed in “Internal Documents.”)

The information available for the well file depends to some degree on whether the well is selected or installed. When an existing well is selected, information about the well often is limited; this lack of information could be the basis for rejecting use of the well (Lapham and others, 1995). For wells that are installed, the amount of information available is considerable. A well file should include documentation of the selection or installation criteria, how the criteria were prioritized and implemented, and information acquired from the site inventory or during the well-selection or well-installation process. If a well becomes unavailable for sampling for any reason, the criteria for selecting a replacement can be simplified by reviewing the well file. Documentation for either well selection or well installation also include well-construction, water-level, and water-quality data. Other data included in the well file, as available, are field logs, laboratory and field analyses, plots of water-quality-related data, and other hydrologic, geologic, biologic, or geophysical information (fig. 1). Well-construction information allows the well to be evaluated for future studies. Well-installation information is carefully documented during installation of new wells and includes the methods and materials used for construction, completion, and development (described in detail in respective sections under “Installation of Wells”).



WELL-INFORMATION CHECKLIST, Page 1 of 2

Well Identification

Project name and identification number: ____________________________
Latitude-longitude: ______________________ Sequence number: ______
Other site or well ID: _______________ Station name: _______________

Indicate well type:
Public
Domestic
Commercial
Industrial
Irrigation
Observation
Monitoring
Other ___________________

Item in well file — Date item filed

Well Location

Latitude and longitude (indicate in file the method used) ________
Well-location map(s) ________
Site-sketch map ________
Written description of location ________
Well-casing elevation (indicate elevation, and method and date of determination in file) ________
Photographs of well and vicinity (with measuring/ sampling points identified) ________
Land-use/land-cover form ________

Electronic Files and Permission Forms

Ground-Water Site Inventory (GWSI) data entered into National Water Information System ________
Paper copy of GWSI form ________
Well-inventory form ________
Copies of agreements to complete activity (for example, permission to access site, drill, or sample). List:________________ ________
____ ________

Criteria Used for Well Selection or Installation

Well Selection (describe criteria in file) ________

Well Installation (describe criteria in file) ________

WELL-INFORMATION CHECKLIST, Page 2 of 2

Item in well file — Date item filed

Well Installation

Well-drilling record ________
Driller's log ________
Lithologic log ________
Cuttings ________
Cores ________
Well-completion record ________
Well-development record ________
Well-maintenance checks: (list types) ____________________ ________
____ ________

Pumping schedule/history ________
Type of pump in well and location of pump intake ________

Water-Level and Water-Quality Data

Description of measuring point for water levels: _____________
____
____

Water-level measurements - current: ________
____
____

Water-level measurements - historical: ________
____
____

Water-quality records for each sampling event:
Purging and field measurements ________
Field forms (previous) ________
Selected results of laboratory analyses ________

Other Data Related to the Well Site

Aquifer tests: (list types) _____________________________ ________
____ ________

Geophysical logs: (list types) __________________________ ________
____ ________

Other:

Figure 1. *Example of a well-information checklist for a well file.*

Table 2. *Minimum data elements and sample data required for electronic storage of site- and ground-water-quality data in U.S. Geological Survey National Water Information System (NWIS)*[1]

Information required for creation of a site file in the Ground-Water Site Inventory (GWSI) data base[2]

Data description	Component (C) number for data entry into GWSI	Sample data (Description of code)
Reporting agency	C4	USGS
Station name	C12	Alpha
Site (Station) Identification Number (latitude/longitude/sequence no.)	C1	394224075340501
Latitude	C9	394224
Longitude	C10	0753405
Station locator sequence number[3]	C815	01
District/User	C6	24 (Maryland)
State	C7	10 (Delaware)
County	C8	003 (Sussex)
Agency use	C803	A (Active)
Station type	C802	6 (Well)
Data reliability	C3	C (Field checked)
Site type	C2	W (Well)
Use of site	C23	O (Observation)

Information required for storage of sample analyses in the Quality-of-Water data base (QWDATA)

Data description	Parameter code	Sample data (Description of code)
Reporting agency	AGNCY	USGS
Station Identification Number	STAID	394224075340501
Sample medium	MEDIM	6 (ground water)
Sample type	STYPE	2 (blank sample)
Hydrologic ("Hydro") event	EVENT	9 (routine sample)
Hydrologic ("Hydro") condition	HSTAT	A (not determined)
Begin Date and Time (month/day/year, standard 24-hour clock time)	DATES/TIMES	090988, 1530 hrs
Analysis status	ASTAT	H (initial entry)
Analysis source	ASRCE	9 (USGS laboratory and field)

[1] Numerous additional data fields from those shown are available in GWSI and QWDATA that can be useful or mandatory for meeting study objectives and data analyses, such as indicating if a non-USGS agency collected the data.

[2] From Ground-Water Site Schedule Form No. 9-1904-A, May 1991. Also refer to Maddy and others (1989).

[3] Does not appear on Form 9-1904-A. This code is generated from the 14th and 15th characters of the Site Identification Number.

The field folder contains a subset of this well information, such as depth from land surface to the top of the well screen or open interval, length of screened or open interval, and well diameter. Examples of field forms used to document site inventory and well installation are provided in the section “Examples of Forms Cited in the Report,” but Federal, State, or local regulatory agencies may require specific forms to document all field activities.

Electronic Files

USGS policy requires specific elements of routine ground-water data collected to be stored in the electronic files of the National Water Information System (NWIS) (Edwards and others, 1987; Hubbard, 1992; WRD Memorandum No. 92.059). The USGS Office of Ground Water defines "routine" data as including "all ground-water data collected by WRD basic-data programs and district projects" (Office of Ground Water Technical Memorandum 93.03). One purpose of this policy is to enable all USGS work to be verifiable and repeatable to the extent possible (Hubbard, 1992).

Within the NWIS[1] system, ground-water-quality and related data currently are stored in two data bases, GWSI (Ground-Water Site Inventory) and QWDATA (Quality of Water Data). GWSI primarily stores descriptive information about the site, well and historical water levels. Results of water-quality analyses, including those for quality-control samples, are stored in QWDATA. Specific minimum information for establishing electronic files in GWSI and QWDATA is required (table 2). Additional data fields from those shown are available in GWSI and QWDATA; these can be useful or mandatory for meeting study objectives and data analysis. All information input to NWIS, or other computer files into which information relating to the study is stored, must be verified systematically and updated periodically. Much of the documentation and ancillary information entered into NWIS is verified and compiled as part of the ground-water site inventory or reconnaissance visit, described in detail under “Selection of Wells.”

SELECTION OF WELLS

Wells available for use in water-quality studies include supply wells (municipal, industrial/commercial, irrigation, and domestic wells), observation wells (those previously installed for hydrologic observation), and monitoring wells (those previously installed for water-quality monitoring). Selection of these wells, especially supply wells, can be a cost-effective alternative to new well installation and is a strategy frequently used for investigations involving regional water-quality surveys or regulatory assessments. Criteria, limitations, and advantages associated with the selection rather than the installation of wells for water-quality studies are discussed in this section.

Ultimately, the decision to select a well follows a process of information collection and evaluation to ensure that data collected from that well will be suitable for the intended purpose. Well selection involves: (1) developing selection criteria that address data-collection objectives, (2) completing office and (or) on-site inventories of wells that are available in the area of interest, and (3) applying selection criteria to determine which well will be used from among those available.

Well-Selection Criteria

Well-selection criteria are used to ensure that wells selected for ground-water analyses will yield samples that accurately represent the water chemistry of the hydrogeologic system delineated for study. Well-selection criteria are developed with respect to the conceptual framework of the study and the data-collection objectives (table 1). These criteria are used to reduce the likelihood that characteristics of the wells selected will result in a bias that compromises study objectives.

Development of well-selection criteria for most water-quality studies requires knowledge of (1) the location of the wells, (2) well-construction methods and materials, (3) pump characteristics and sampling-point locations, and (4) well capacity (table 3). The type of information and level of detail required depend on data-collection objectives. Although the minimum information required to select any well for study is that needed to establish a GWSI file (table 2), additional information on site and well characteristics, such as lithologic, driller’s, and well-construction logs, often

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[1] Replacement of the NWIS data base or use of supplementary data bases might change some of the data-entry requirements.

Table 3. *Considerations used to develop well-selection criteria for water-quality studies*

Location of wells

Areal and depth distribution must conform to the conceptual or statistical design developed for the study.

Site characteristics and potential influences on ground-water chemistry are identified.

Design of wells

Screened or open intervals must be within the subsurface interval defined for the study.

- The hydrogeologic unit(s) represented by the measured water level must be known.
- The hydrogeologic unit contributing water to the well must be known. If the well is open to more than one unit, then the contribution from each unit must be known.[1]
- Depth to each screened or open interval must be known.
- Wells with filter packs or open interval extending over an interval that is long compared to the screened or targeted depth interval should be avoided to reduce uncertainty about the source of water to the well.
- Type, length, and diameter of well screen are appropriate for study objectives.

Well-installation methods, well materials, and well maintenance

Evaluate effect of methods, materials, and well integrity on the water-quality constituents of interest.

- Potential of the drilling or borehole construction method to have contaminated the sampling interval (for example, from drilling fluids or lubricants).
- Potential of well-development method to have contaminated the sampling interval.
- Well was developed sufficiently or requires redevelopment.
- Potential of materials used in well completion to have biased water chemistry.
- Well-maintenance records are kept; records indicate sound casing and screen or borehole integrity (age of well can be an important consideration) and good hydraulic connection of well with aquifer.[2]

Pump characteristics and sampling-point locations

Effect of pump type and materials on water-quality constituents of interest.

Effect of pumping rate on water-quality constituents of interest.

Location of pump intake with respect to sampling interval.

Sample-collection point is located before water treatment, pressure tanks, or holding tanks, if ground-water quality assessment is a study objective.

Well capacity

Well yield is adequate for sampling: typically 1 or more gallons per minute (3.8 liters per minute).

[1] Usually determined by field measurements of well depth and by geologic and geophysical borehole logs indicating the depth to the top and bottom of each open interval and the depths of the hydrogeologic unit(s) at the well.

[2] Checks on the maintenance of well casing and screen or the borehole include use of borehole-geophysical methods, yield of sediment on a continuous basis during pumping, and depth-to-bottom measurements; well integrity is evaluated by aquifer tests.

must be available for the well to be usable by a study. The suitability of the well for collecting data other than water-quality data, such as water levels and geophysical logs, may also be a determining factor in well selection.

Location, Design, and Construction of Wells

Site conditions and characteristics that can affect data collected from a well or that otherwise produce an intended or unintended bias in interpretation need to be identified. Bias can result from natural or anthropogenic processes and can occur seasonally, continuously, or catastrophically. Examples of such influences include tides, agricultural practices, nearby well fields, and industrial discharges.

Wells must be designed and constructed in a manner that assures that the water-quality samples collected or the water level measured is of the hydrogeologic unit or units targeted for study. In addition, other aspects of well installation, such as completion and development, can affect the quality of the water. Consider that:

- Wells with filter packs extending over a long interval of the well annulus can lead to uncertainty about the source of water to the well, and hence to uncertainty about the water quality (see “Well Completion”).
- Measuring the hydraulic head in a well constructed with multiple screens in several hydrogeologic units, each with a different head, will reflect an integrated average that accounts for the heads in all of the screened units rather than the head in any one of the units.
- Mixing of waters with different quality can occur in wells with long or multiple screens because of wellbore flow. On the other hand, wells with short screens relative to the total thickness of an aquifer might be screened in intervals that miss major zones of interest, such as zones with high transmissivity or zones with contamination.

MANDATORY: WELL DESIGN AND CONSTRUCTION MUST ENSURE THAT THE WATER-QUALITY SAMPLE COLLECTED OR WATER LEVEL MEASURED IS OF THE AQUIFER(S) TARGETED FOR STUDY.

- In general, selecting several wells in close proximity with differing well-screen depths and short-screen intervals is the most common means of evaluating changes or differences in water quality with depth. Wells with multiple screens can be used if the appropriate interval(s) can be isolated successfully with packers. Packer tests, however, are expensive, and successfully isolating the interval of interest is not always possible.
- The top of the screen generally should be located at least 3 ft (1 m) below the lowest anticipated position of the water table to reduce the chance of the well going dry during some periods of the year and to avoid problems with interpreting data from partially saturated open intervals. One exception to this criterion is if data pertaining to the saturated-unsaturated zone interface are needed.
- Some drilling methods require circulation of a drilling fluid (such as a bentonite slurry or air) in the borehole. These drilling fluids can carry contaminants vertically along the borehole and can infiltrate the aquifer, thereby affecting water chemistry or biochemistry (see “Well Construction”).
- Well-construction materials can bias water-quality data. Well screens and casing can leach or sorb metals and organic compounds (see “Casing and Screen Materials”). In general, flush-threaded rather than glued PVC casing is preferred.
- If possible, wells should be selected that were installed with casing and drilling equipment that were cleaned prior to well installation. Decontamination of well-construction materials before well installation reduces the risk of water-sample contamination.
- Bias can result from the selected specific type of well, such as municipal, industrial/commercial, irrigation, or domestic supply wells. For example, selecting only irrigation or domestic wells can be inadequate to address certain types of investigations, such as occurrence and distribution of chemical constituents or aquifer vulnerability to contamination. If only municipal wells are selected for these types of studies, shallow wells are likely to be excluded in many areas. It must be determined that the study intends to produce this bias in the data collected. If unintended bias compromises study objectives, wells need to be installed or study objectives revised.

- Land-use and land-cover information can help identify an unintended bias. In studies that relate land use to ground-water quality, for example, a bias can be caused by failing to consider point sources such as chemical storage, mixing, or turnout areas in agricultural areas. In studies of ground-water quality along a flowpath, a bias can be caused by failing to consider the influence of pumping nearby wells.

Pump Type and Access Points

The type of pump installed in a supply well can affect the chemistry of a ground-water sample. During well selection, consider that:

- Wells equipped with a submersible, water-lubricated (oil-less) pump are preferred and, depending on data-collection needs, could be necessary. Oil can leak from the pump casing and contaminate water coming in contact with the pump. Often, a column of oil can be found floating on the water column in a well equipped with an oil-lubricated pump.
- Suction-lift pumps can induce loss of oxygen and other gases such as radon, hydrogen sulfide, and organic compounds such as chlorofluorocarbons from a sample during withdrawal because of the drop in pressure in the sample line caused by a vacuum.
- Jet pumps use circulation water pumped through a venturi to carry sample water to the surface. Both the mixing of circulation water with sample water and the drop in pressure of the circulation water across the venturi can affect the quality of the sample water.

STANDARD PROCEDURE: SELECT WELLS WITH SUBMERSIBLE, WATER-LUBRICATED PUMPS IN PREFERENCE TO WELLS WITH OTHER TYPES OF PUMPS. THIS COULD BE A MANDATORY SELECTION CRITERION.

The accessibility and location of a sampling point at a supply well is an important selection criteria. Many water-supply wells will have an access point for sampling. This access point, however, often is located after water passes through on-site treatment systems, downhole treatment lines, pressure tanks, and holding tanks. These tanks and the treatment systems can affect the chemistry of the water sample. Highly volatile organic compounds, such as ethylene dibromide, can be lost to the head space in a pressure tank (Roaza and others, 1989), and trace-element concentrations can be biased if ground water is sampled from a holding tank instead of directly from the aquifer.

- Sample-collection points should be located on the intake side, before water enters pressure tanks, holding tanks, or treatment systems (unless the effects on water chemistry are not pertinent to study objectives).
- At wells where an access point close to the well is not available, it is sometimes possible to have a valve installed at the well head for sample collection.
- The downhole treatment line needs to be turned off before collecting water-quality samples.

STANDARD PROCEDURE: WELLS MUST PERMIT COLLECTION OF THE WATER SAMPLE BEFORE THE WATER ENTERS A PRESSURE TANK, HOLDING TANK, OR TREATMENT SYSTEM.

Well Capacity

Well capacity relates to the pumping-rate capability of a given well-and-pump system. Pumping rates of domestic wells generally are low, whereas pumping rates of municipal, commercial/industrial, and irrigation wells generally are high. The advantages and disadvantages associated with selecting either a low-capacity or high-capacity well for water-quality studies must be weighed with respect to the study design and data objectives (table 4). Before selecting a well with a low or high capacity, consider the effect of the pumping rate on the aquifer and on water-quality field measurements and samples. Pumping a few tens of gallons per minute from a well screened in a poorly transmissive aquifer might induce significant leakage from confining beds, whereas pumping a few thousands of gallons per minute from a well screened in a highly transmissive aquifer might not induce such leakage.

Table 4. *Advantages and disadvantages of high-capacity and low-capacity water-supply wells for water-quality studies (modified from Alan Welch, U.S. Geological Survey, written commun, 1992)*

HIGH-CAPACITY WATER-SUPPLY WELLS

Advantages:

- Documentation of well construction commonly is good, but can differ greatly among wells.
- High-capacity wells generally are well developed and frequently purged.
- Long-term access often is possible, particularly for municipal wells.
- High-capacity wells generally provide a larger vertical mix of water moving through the aquifer to the well than lower-capacity wells; thus, they can provide a more integrated measure of the quality of water throughout its depth. (This may be at odds with study objectives.)
- Much of the water produced for irrigation and municipal use is from high-capacity wells, allowing a direct sample of the used resource.
- Long-term water-quality data could be available that predates monitoring by the study.

Disadvantages:

- High-capacity wells might not have flow-rate controls and a sampling point near the well head. Sample collection at high flow rates can be difficult. Losses of gases such as oxygen, chlorofluorocarbons, radon, and hydrogen sulfide are possible.
- Pumping schedules could be irregular; for example, irrigation wells generally are pumped seasonally. Water-quality investigators, on the basis of such wells, might need to account for seasonal variations in water quality that actually are an artifact of the pumping regime.
- High-capacity wells could have a long vertical filter pack, or multiple open intervals that span more than one aquifer or aquifer system.
- Wells with high pumping rates can draw water from water-bearing units other than those screened, even if the well is screened solely within one unit. The vertical integration of water from water-bearing units could be unknown.
- Local hydraulics could be atypical of regional ground-water movement as a result of compaction or enhanced downward flow.
- Municipal wells that produce water not meeting water-quality standards are usually abandoned, implying that the remaining population of municipal wells is biased toward those with acceptable water quality.
- Downhole chlorination or other chemical treatment could occur and affect water quality.
- Depth-dependent differences in water quality could be lost, given water sampled could reflect a mixture of water obtained at different depths.
- Irrigation wells without antibacksiphon devices that are used for chemigation can lead to ground-water contamination.
- Pump oil can cause local downhole contamination.

LOW-CAPACITY WATER-SUPPLY WELLS

Advantages:

- Domestic wells are a major source of drinking-water supply for rural populations, so wells reflect this resource use.
- Good-to-excellent areal and depth coverage in some areas, particularly for unconfined aquifers.
- Low-capacity pumping rates limit withdrawal of water from water-bearing formations other than those screened.

Disadvantages:

- Domestic wells generally are not available in urban and suburban areas.
- Domestic wells that produce water not meeting water-quality criteria are usually abandoned, implying that the remaining population of domestic wells is biased toward acceptable water quality.
- Documentation of well construction could be poor or unavailable.
- Well construction or use of pressure tanks, chemical treatment(s), and/or certain pumps could preclude sample collection at the wellhead. (It might be possible to bypass these difficulties by installing an appropriate valve at the wellhead.)
- Centrifugal or jet (Venturi) pumps often are used to lift water from this type of well. Those pumps can cause degassing and other changes in water quality.
- Local factors such as septic systems, chemical storage areas, compost piles, and road maintenance (salting) could affect ground-water quality and must be considered in relation to well location in order to correctly assess what conditions water-quality data truly reflect.

One problem with water-quality sampling at a low rate (for example, 1 to 4 gal/min or 3.8 to ~15.1 L/min), particularly from deep wells, is that the transit time for water to move upward through the wellbore or casing to land surface can sometimes exceed several hours. During that time the water sample could have degassed and reacted chemically to the well environment. In general,

- High-capacity wells can be expected to provide a more integrated measure of regional ground-water quality than low-capacity wells because of the larger vertical mix of water from an aquifer caused by a high pumping rate in comparison to a low pumping rate.
- Withdrawal of water from low-capacity wells is limited to water in the vicinity of the well screen. Consequently, low-capacity wells can be expected to provide a better measure of the water quality in the immediate vicinity of the open interval of the aquifer. For example, selection of only low-capacity wells, rather than high-capacity wells or a mix of low and high capacity wells, might be an important selection criteria in studies of shallow ground-water flow systems that have short flowpaths.

Site Inventory

A site inventory is used to collect and document information needed to select wells for data collection and to create well and field files for those wells. A site inventory is completed by reviewing files in the office (see "Supporting Documentation") and by making site visits to verify information and collect additional information about the wells. Site visits to candidate wells are often necessary to collect and verify information about the wells and to evaluate the wells with respect to the well-selection criteria (table 3). Field verification before sample collection can save time, money, and effort in the long run, and should be incorporated into the workplan for studies for which it is appropriate. Study design and plans should strive to provide for this effort. Before making a site visit, written or oral permission must be obtained from the owner to gain site access and to collect data from the candidate well.

The site inventory can be used to evaluate selection criteria (such as identifying areas of ground-water recharge and discharge and potential sources of contamination) or to collect preliminary data on well hydraulics and physical and chemical field measurements. The site inventory also can be used to test field equipment and data-collection protocols. Identifying areas of ground-water recharge and discharge and potential point and nonpoint sources of ground-water contamination can help development of the conceptual framework and the well-selection and sample-collection strategies. Factors that can affect the hydrologic or geochemical system include contamination from land-use practices (such as road-salt, agricultural, and urban chemical applications); drawdown caused by pumping at a nearby well field; and aquifer dewatering at nearby mining operations. Preliminary data from slug tests and field measurements of turbidity, pH, specific electrical conductance, temperature, dissolved oxygen, temperature, or analyte screening (for example, for high concentrations of VOCs) can be extremely helpful in developing well purging and sampling plans. The site inventory also can be used to compile information to help develop strategies for sample collection. For example, utility records indicating electricity demand by a pumping well can be used to estimate the frequency and duration of pumping. The duration of pumping, combined with pump capacity, can then be used to estimate the volume of water discharged from a well over time. This is used to estimate the amount of time that will be needed to purge and sample the well, and to aid in identification of times that facilitate purging and sampling.

STANDARD PROCEDURE: USE INFORMATION FROM A SITE INVENTORY TO SELECT WELLS.

A well- and site-inventory form (fig. 11, page 82) usually is used by the study to compile information needed for NWIS files. This information is stored in the well file and entered in the NWIS system as soon as possible after it is obtained (see "Supporting Documentation"). The information that cannot be stored or retrieved using NWIS should be reviewed and stored as paper copies or in computerized well files set up by the study. This includes, but is not limited to, available records of well installation and development, well maintenance, geophysical logs and surveys, aquifer tests, geological and geochemical data, and land use.

Much of the information obtained during the site visit is indicated on the well- and site-inventory form (fig. 11, page 82) and is self explanatory or referenced elsewhere in this report. Additional information and guidelines are provided below on four activities related to the site inventory visit and the final well selection: description of well location and site features, determination of well elevation, measurement of water levels, and well maintenance and integrity checks.

Description of Well Location and Site Features

A description of the well location and site features is completed during the site visit. The latitude and longitude must be identified for each well. These often are determined by referring to U.S. Geological Survey 7 1/2-minute quadrangle maps, by surveying, or by using global positioning systems. The well location and site features are illustrated by location maps, site sketches, and possibly photographs, and by documenting land use and land cover.

A unique identification number by latitude and longitude is required for each site.

- The latitude and longitude number is followed by a well-sequence number for wells with identical latitude and longitude.
- Many States have their own well-identification numbers that are established by the State or by a local agency that has well-numbering authority. These numbers are also documented.

Location map(s) and a site sketch (figs. 2a and 2b) are prepared that include sufficient detail and scale to enable field personnel unfamiliar with the site to readily locate the well. Location maps are marked and a site sketch is drawn to indicate well location. Compass directions, latitude and longitude, a horizontal scale, and the date of the inventory are indicated on the location map(s) and site sketch.

- Information on the location map(s) typically includes roads, topography, water bodies, landmarks, and distances to the well site from milepost markers or other permanent cultural features (fig. 2a).
- The site sketch identifies the location of the well in relation to nearby features such as roads, railroad lines, fences, houses, barns, and buildings. Electrical meter numbers or nearby telephone pole numbers often provide a long-term identification for the site (fig. 2b).
- A sketch of the wellhead identifies features of the well such as the height of the top of the casing in relation to land surface and the point from which water levels are measured.

Photographs of well sites and surrounding features complement site sketches. A chronological series of photographs of each well site provides a visual record for well identification, well location, water-level measuring points, and water-quality sampling points, and also documents land use and land cover near the well. A new set of photographs is taken when changes occur at or near the well site. Changes could occur in the reference datum of the well, land use near the well, or access to the well. Photographs can also aid in the explanation and interpretation of analytical results.

- On each photograph, record a description of the subject matter, date, name of the photographer, project name and identification (ID) number, and the site or well ID.
- A set of photographs could include: the well and surrounding area as seen when approaching the well; a close-up of the well, water-level measuring point and water-quality sampling point; views of the area north, east, south, and west of the well; and additional documentation of land features that might influence the chemistry of water collected from the well.

Written descriptions of the site and the well complement site and wellhead sketches and provide additional useful information that can be critical to smooth field operations and to personnel safety. Examples include:

- Directions for gaining access to the site, such as if owner notification is required before sampling, the well is locked, or special tools are required.
- Difficulties that might be encountered that relate to well location, water-level measurement, or sample collection.
- Conditions that might affect the safety of field personnel (for example, roaming or potentially dangerous domestic or wild animals, and toxic organic compounds in storage or in the atmosphere). It is advisable to use electronic sensors to test the air for volatile organic gases in and around well structures, landfills, airfields, and any field area that was subject to waste disposal and spills.

Documenting land use and land cover (fig. 12, page 84) in the vicinity of a well can help relocate a well, provide information to help evaluate a well's suitability for sample collection, and provide qualitative information that can be used to analyze and interpret ground-water-quality data. If recorded, land-use/land-cover information usually is rechecked each time a well is sampled, and any changes are noted on the form (fig. 12, page 84).

Determination of Well Elevation

The elevation of the measuring point of the well is important in most water-quality studies that require establishing the direction of ground-water flow. The method used to determine well elevation depends on the accuracy required. The well elevation often is estimated from U.S. Geological Survey 7 1/2-minute quadrangle maps, or determined more accurately by ground surveying (leveling) or by using global positioning systems.

While global positioning systems are becoming more widely used, ground surveying by differential leveling with an engineer's level and leveling rod is still a common method for determining well elevation (Kennedy, 1989). Leveling measurements and notes are recorded on a form in the surveyor's log book (fig. 13, page 87) and a copy of the survey notes is placed in the well file. Detailed descriptions of differential-leveling procedures are discussed in numerous references, including Smirnoff (1961), Davis and others (1966), U.S. Geological Survey (1966), and Kennedy (1990).

The basic procedure of differential leveling to determine the elevation of the measuring point of a well consists of a series of backsight and foresight readings (U.S. Geological Survey, 1966). First a backsight reading is taken to a rod held on a point of established elevation. The rod reading is added to the known elevation to obtain the height of the instrument (HI). A foresight reading is then taken to a rod held on a point forward along the line of progress toward the well. The elevation of the forward point is obtained by subtracting the foresight rod reading from the HI. The level is moved forward to a new setup, for which the established foresight point of the first setup serves as the backsight point, and subsequent backsight and foresight readings are taken. As the procedure is repeated, the elevation determined is carried forward to each setup from backsight point to instrument to foresight point. Checks are made of successive elevations along the line by taking the final foresight on a point of established elevation, for example the starting point or another point of known elevation. Subtracting the known elevation from the terminal elevation as carried through the line gives the error of closure, which is an indication of the accuracy of the leveling.

Note that:

- Before leveling, the desired accuracy of the elevation of a measuring point needs to be determined and the appropriate class of leveling used to achieve that accuracy selected. Leveling is classified in four orders of decreasing accuracy, according to the limits specified for line and circuit closures, for the agreement between forward and backward runs, and also generally according to the methods and instruments used (U.S. Geological Survey, 1966; Kennedy, 1990).
- Levels run by the USGS have closure errors that typically are less than $0.003\sqrt{n}$ ft, where "n" is the total number of instrument setups in the circuit; sight lengths are usually less than 100 ft (30.5 m); and the leveling rod is read to 0.001 ft (0.3 mm) (Kennedy, 1990, p. 4)[2]. Fourth-order levels generally have closure errors less than $0.05\sqrt{M}$ ft, where "M" is the total length of the circuit in miles; sight lengths are less than 300 ft (91 m); and rod readings are to 0.01 ft (3 mm).
- Well elevation should be recorded on location maps and site sketches.

Measurement of Water Levels

Measuring water levels is a routine aspect of a well inventory (unless well construction makes measurement impossible) (fig. 14, page 88), and of well development (fig. 17, page 93). The water level is measured before collecting a water-quality sample, both in wells with direct access for the measurement and in wells in which a device has been installed for indirect measurement. The water level is needed to determine the depth of sample collection in relation to the screened or open interval of the well. Water-level measurements also aid in well selection and in the interpretation of ground-water-quality data. Water levels also are needed to help determine hydraulic gradients and, thereby, directions of flow, rates of flow, locations of ground-water recharge and discharge, the amount of water in storage in an aquifer, the change in storage over time, and aquifer hydraulic characteristics. Repeated measurements of water levels over time provide a chronology of water-level fluctuations that can aid interpretation of water-quality data. For example, seasonal variations in recharge or changes in recharge induced by nearby pumping can cause changes in hydraulic gradients that can correspond to changes in water quality.

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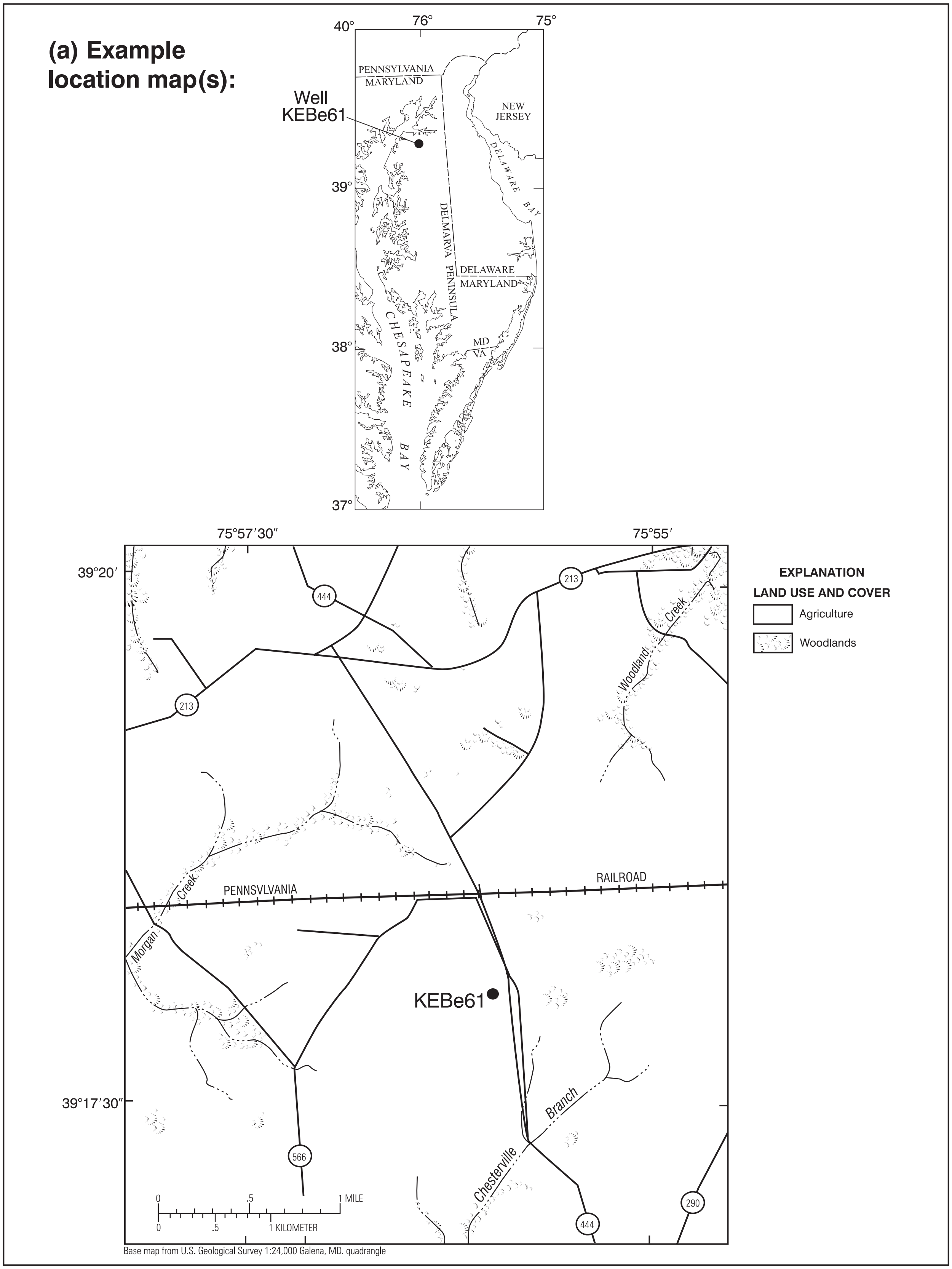
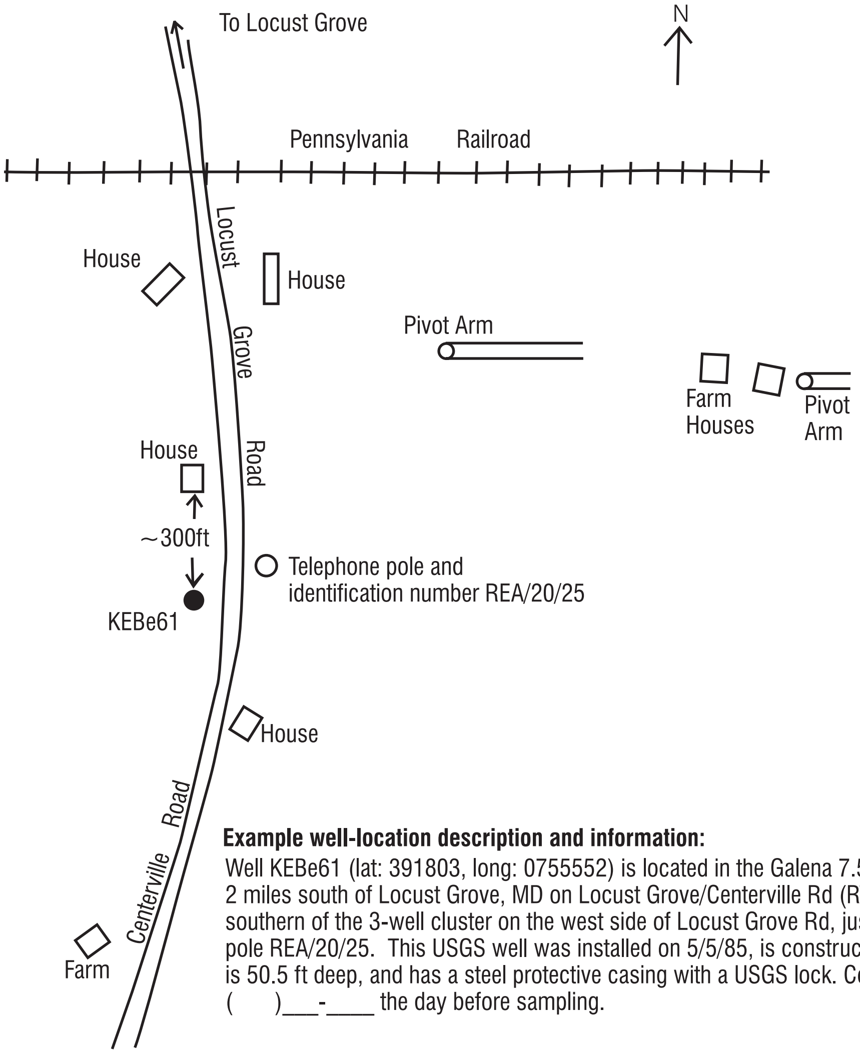
[2] The citation discusses determination of elevation by leveling at gaging stations, but this and the information that follows are generally applicable to leveling activities for USGS ground-water studies.



Base map from U.S. Geological Survey 1:24,000 Galena, MD. quadrangle

Figure 2. *Well location and site features illustrated by (a) well-location maps and (b) site sketch.*

(b) Example of site sketch:



Example well-location description and information:

Well KEBe61 (lat: 391803, long: 0755552) is located in the Galena 7.5 min quadrangle about 2 miles south of Locust Grove, MD on Locust Grove/Centerville Rd (RT444). The well is the most southern of the 3-well cluster on the west side of Locust Grove Rd, just southwest of telephone pole REA/20/25. This USGS well was installed on 5/5/85, is constructed of 2-inch diameter PVC, is 50.5 ft deep, and has a steel protective casing with a USGS lock. Contact property owner at ( )___-____ the day before sampling.

Figure 2. *Well location and site features illustrated by (a) well-location maps and (b) site sketch--Continued.*

Water-level measurements during the inventory are recorded on the well- and site-inventory form (or other form) and subsequently are entered into GWSI. Detailed procedures for correct measurement of water levels using various methods are documented in U.S. Geological Survey (1977, p. 2-8). Additional information regarding ground-water technical procedures can be obtained from the USGS, Office of Ground Water, in Reston, Virginia.

- The point from which the water level is consistently measured (the "measuring point") must be clearly identifiable in the field by a notch or other permanent indicator on the well. The measuring point must be recorded and indicated on sketches (and photographs, if available) in the well file.
- Records should show if a vertical reference point has been established near the well that can be used to check the measuring-point elevation and to re-establish a measuring point that has been changed or destroyed.

Various types of equipment are available for measuring water levels in wells. Specific procedures and equipment used depends on factors such as depth to water, accessibility of the well, well construction, measurement frequency, and intended use of data. Some aspects of water-level measurement that pertain to specific instruments are noted below.

- In wells with depth to water of less than 200 ft (61 m) and with direct access for measurement, water levels can be measured to an accuracy of 0.0l ft (3 mm) and a precision of 0.02 ft (6 mm) for two or more consecutive measurements, using a steel or electric tape. Although it is not always possible to obtain accurate measurements in supply wells, water levels are to be measured to the degree of accuracy possible and difficulties should be documented.
- If a weighted steel tape or electric tape is used, the weight should be constructed of nontoxic material to prevent possible contamination of the well water should the weight be lost during measurement. **Lead weights must not be used.**
- Electrical sensors are available that indicate the depth of nonaqueous fluid (such as oil floating on the water table) as well as the water level.
- Pressure gages must be calibrated to a master gage and must be accurate and dependable, with a range that only slightly exceeds the anticipated change in water level. Gages can be installed permanently in wells.
- Electrical pressure-sensitive transducers measure water level indirectly and can be used for measuring rapid water-level changes (Hollett and others, 1994). A transducer should be selected with an accuracy of at least one percent of the range of the measurement of head (Ritchey, 1986), and that is easy to reconfigure in the field (Latkovich, 1993). If the transducer is not vented to the atmosphere, corrections must be made in the water level measured for changes in barometric pressure. Long-term drift, temperature compensation, and leaks are problems that can be encountered with transducers (Latkovich, 1993).
- Acoustic probes can measure depth to water from about 25 to 1,500 ft (~7.6 to 457 m) in open wells with diameters of at least 4 in. (~10 cm) with a measurement accuracy of approximately ±1 ft (30.5 cm) (Ritchey, 1986).
- Float recorders provide a continuous record of water level in wells that range from 1.6 to 6 in. (~4 to 15 cm) in diameter. The measurement accuracy is about 0.1 percent. The float and wireline tend to hang up on the well casing in wells with less than a 4-in. diameter.

Well-Maintenance Checks and Well-Integrity Tests

Well-maintenance checks and well-integrity tests are necessary to confirm that the structure of a well remains intact. A deteriorating well structure can cause a bias to data that might be difficult to detect and might even be interpreted as a data trend.

Well-maintenance checks can indicate if changes in well performance are caused by physical deterioration of the well structure. Well-maintenance records are a log of specific checks and measurements to help determine if the well screen and casing or borehole are damaged. Well-maintenance logs indicate if the well has been or needs to be restored. Well restoration typically involves redevelopment of the well (Driscoll, 1986).

Well-integrity tests help evaluate if there is a good hydraulic connection between the well screen and the aquifer. A loss of hydraulic connection can result from a corroded well casing or screen, from plugging of the well screen by sediment and chemical or biochemical precipitates, and from an accumulation of native geologic or foreign materials in the well casing or borehole. The well screen can collapse or the screen and casing can break during well construction, completion, or development; while installing or removing a pump; or because of natural processes such as land subsidence and rock faulting. Metal well casings are subject to degradation over time from exposure to corrosive ground waters (pH of less than 6.0). Polyvinylchloride (PVC) casing can dissolve in the presence of PVC solvent or if a pure organic product reaches the well in high concentrations from chemical spills or leaking storage tanks.

For wells to be used for ground-water studies:

- Well-maintenance records should be kept, including periodic checks measuring depth to the bottom of the well, and the use of borehole-geophysical and other tools.
- Well-integrity tests can be conducted as part of the well-inventory or subsequent site-selection visits. They commonly are short-term slug tests or injection, pressure, or partial-vacuum aquifer tests (Stallman, 1971; Lohman, 1972; U.S. Geological Survey, 1980; Driscoll, 1986; Bedinger and Reed, 1988).
- At a minimum, the depth to the bottom of a well is to be measured annually (U.S. Geological Survey, 1980). If the site visit occurs less frequently, depth to bottom is checked the next time the well is visited (U.S. Geological Survey, 1980). If wells do not allow access for making a depth measurement, this should be recorded in field notes.
- Borehole-caliper and downhole-camera video logs can identify damaged or broken well casing. A downhole camera also is an effective tool to identify a plugged screen or the collection of sediment or other materials in the well.
- Comparison of water-level fluctuations over time in the well can indicate a possible change in hydraulic connection of the well to the aquifer. For example, a long-term decline in the water level in a well could indicate gradual plugging of the well screen.
- The external physical condition of the well, its protective casing, the surface seal, and the condition of any instrumentation associated with the well also should be noted.

INSTALLATION OF WELLS

If wells that meet well-selection criteria are not available at the locations needed, new wells to monitor water quality are installed. The process of well installation requires establishing well-installation criteria; designing wells; decontaminating equipment; and selecting the appropriate construction, completion, and development methods. Installing a monitoring well for studies of ground-water quality is expensive; consider using installation practices that allow a broad spectrum of data to be collected beyond use for the current study. The guidance in this section is designed to help identify appropriate criteria and methods for installing wells for water-quality studies.

MANDATORY: EACH ASPECT OF WELL INSTALLATION MUST COMPLY WITH FEDERAL, STATE, AND LOCAL REGULATIONS (unless a written variance has been obtained from the regulatory agency).

Well-Installation Criteria

Well-installation criteria are developed to ensure that the wells installed will yield samples that accurately represent the water chemistry of the hydrogeologic system delineated for study. Well-installation criteria also are developed with respect to the conceptual framework and the data-collection objectives of the study (table 1). These criteria are used to reduce the likelihood that characteristics of the wells installed and well-installation methods will result in a bias that compromises study objectives.

Criteria must be developed for the selection of well-installation sites, as well as for the actual well installation. The proper placement of a well and its screened or open interval in 3-dimensional space is of paramount importance, particularly for small-scale investigations. Well placement is part of the network-design phase of a study and requires knowledge of subsurface conditions, including the geology and hydrology of the site.

The primary consideration for selecting well-installation methods and materials is to minimize the effects on the chemical and physical properties of the ground-water sample. Criteria for well installation are developed using considerations similar to those described for developing well-selection criteria (table 3), and the considerations for well design and installation listed on table 5. The resulting criteria are prioritized according to data and study requirements. If a study is part of a larger program, program protocols and objectives form a framework for developing criteria for selecting the well-installation methods (see, for example, Lapham and others, 1995).

Documentation of the methods and materials used for well installation is required for each new well installed and is to be completed as the information becomes available. Federal, State, or local regulatory agencies could require use of specific forms. In the absence of such a requirement, forms have been developed to document different stages of well installation for USGS water-quality studies (see “Supporting Documentation”).

Field activities associated with well installation, from preparation of the drilling site to well development, are potentially hazardous. Prefield activities for well installation include drafting a safety plan. Basic safety information related to USGS activities is provided in U.S. Geological Survey (1989). Safety procedures at drilling sites are discussed in Acker (1974) and in National Drilling Federation (1985). To reduce hazards, use common sense and pay careful attention to accident prevention guidelines and safety regulations.

- Before drilling begins, project and drilling personnel must contact utilities to determine the location of subsurface power lines, gas lines, sewer and storm pipes, and other infrastructure.
- In the field, personnel must carry with them (1) a first aid kit, (2) phone numbers for the local fire and police departments, and (3) the phone number and address for, and a map showing the location of, the nearest hospital or trauma center.
- Depending on the official hazard rating level, employees must complete at least 40 hours of special training, in addition to using site-specific evaluation, health, and safety plans; medical surveillance programs; and required site and engineering controls, work practices, and personal protective clothing and equipment (U.S. Department of Labor, 1995).

Safety and accident-prevention measures include (1) training employees in the work task and in first aid, safe storage of materials, and safe transport of materials to and from field sites; (2) establishing general safety rules at a work site; (3) wearing protective clothing appropriate for the work environment (for example, safety footwear and glasses, work gloves, and a hard hat); (4) using an electronic detector at well sites with potentially dangerous chemical vapors; (5) maintaining a clean work environment; (6) using tools and

Table 5. *Factors to consider when installing wells to monitor water quality*

Data and study requirements
Type of water-quality data and required accuracy and precision (for example, chemical constituents being measured; constituent concentrations in nanograms, micrograms, or milligrams)
Collection of cores or cuttings (for example, identify the analyses that will be needed)
Collection of borehole geophysical data (for example, determine if a fluid-filled borehole will be needed)
Collection of hydraulic or other data
Mandates from regulatory agency or funding agency
Design of wells
Degree of consolidation of subsurface materials (unconsolidated, partly consolidated, or consolidated)
Well casing and screen (material, diameter, length, construction)
Depth interval of screened or open-hole section(s)
Length of filter pack(s) compared to well screen and depth below land surface
Depth to water and to the aquifer of interest
Well installation (borehole construction, well completion, well development)
Types and competency of water-bearing units to be penetrated and sampled (unconsolidated or consolidated)
Total depth anticipated
Potential sources and degree of aquifer contamination from installation methods
Controls on drilling-fluid use and disposal
Degree of physical disturbance to aquifer
Logistics
Access to the drilling site and avoidance of damage to environmentally sensitive sites
Constraints on equipment set up at drilling site
Ability to obtain permits and approval to drill at the site
Availability of necessary equipment and personnel
Ease of equipment decontamination at and between sites
Time allowed to complete drilling and well development operations
Regulations on disposal of solid and liquid wastes from drilling
Ability to develop and sample well
Costs of drilling, collecting cores or cuttings, well completion, and well development
Personnel available to complete drilling and well development

machinery properly; (7) lifting, moving, and carrying heavy objects in a manner that avoids personal injury; and (8) taking a cellular phone on site visits. Special precautions and training are required at sites designated as hazardous; for example, at sites using remote-controlled drilling (Vroblesky and others, 1988).

Well Design

The design of the monitoring well is established before the drilling and completion methods are selected. Numerous designs exist. The guiding principle for well design—to be followed to the extent possible—is that the design is compatible with the types of data to be collected. The goal for water-quality studies is to have the well design compatible with requirements to obtain samples that accurately represent the chemical constituents of concern in ground water. Whenever possible, wells should be designed for use not only by the immediate study but also for other current and future studies.

Considerations for well design include:

- The nature of the subsurface materials that comprise and overlie the aquifer of interest (for example, if materials are unconsolidated, partly consolidated, or consolidated, and if consolidated materials are fractured or have openings caused by dissolution).
- How subsurface materials and conditions influence the selection of the well screen to be installed.
- Well-casing and screen material.
- Screen length and type.
- Diameter of casing and screen (or open borehole).
- Depth to static water level.
- Depth to the top of the aquifer of interest.
- Depth to the zone in the aquifer to be monitored.

Operational constraints that play a role in well design include budget, the availability of drilling equipment, and the need to minimize damage in environmentally sensitive areas.

STANDARD PROCEDURE: PVC IS THE BEST COMPROMISE CHOICE FOR WELL CASING AND SCREENS WHEN SAMPLING FOR INORGANIC AND ORGANIC COMPOUNDS, PROVIDED THAT PURE PRODUCT OR PVC SOLVENT ARE NOT PRESENT.

Screened, Open-Hole, and Multilevel Designs

In unconsolidated materials, a common monitoring-well design consists of a well screen and casing installed in a well bore with the annular space filled with a primary and secondary filter pack and with annular and surface seals (fig. 3). Variations of this design depend on specific State and local requirements for well design and completion, and on requirements for specific data-collection objectives, site conditions, and the drilling method. For example, hand-driven steel wire-wound well screens can be attached to the bottom of steel casing and used to investigate water chemistry at the zone of ground-water discharge to surface water. Blank-pipe extension can be attached to the bottom of the screen to prevent the screen from plugging in aquifers containing fine-grained material.

In partly consolidated and consolidated materials, three possible designs consist of (1) an open borehole at the interval of interest, with well casing installed in the borehole above this interval (fig. 4a); (2) packers installed in the open borehole to isolate that part of the borehole targeted for water-quality sampling (fig. 4b); or (3) a well screen with filter packs installed at the interval of interest, with an annular seal installed above this interval to land surface (fig. 4c). Each design or modification of that design has advantages and disadvantages that must be evaluated.

Referring to figure 4a, the casing is extended to the selected depth, beyond which the borehole remains open. The annular space between the casing and the formation is sealed. The open interval is of the length and depth required for study.

The second design shown (fig. 4b) uses borehole-packer systems in wells to isolate the interval intended for study from the rest of the borehole (Cherry and Johnson, 1982; Hess, 1993; Hsieh and others, 1993; Latkovich, 1993). Packer systems are designed for measurement of head, hydraulic testing, and sampling from individual fractures or fracture zones. Some packer systems are permanent installations; others, such as wireline-powered inflatable packers (Hess, 1993), are designed to be removed to permit other borehole investigations, such as geophysical logging. Use of packers does not guarantee isolation of a fracture or fracture zone from the rest of the open borehole because a fracture in the packed-off zone might be connected to the borehole above or below the packed-off zone by connecting fractures away from the borehole.

The third monitoring-well design (fig. 4c) involves installing a well casing and screen in the open borehole and completing the well with a filter pack around the screen and an annular seal between the cas-

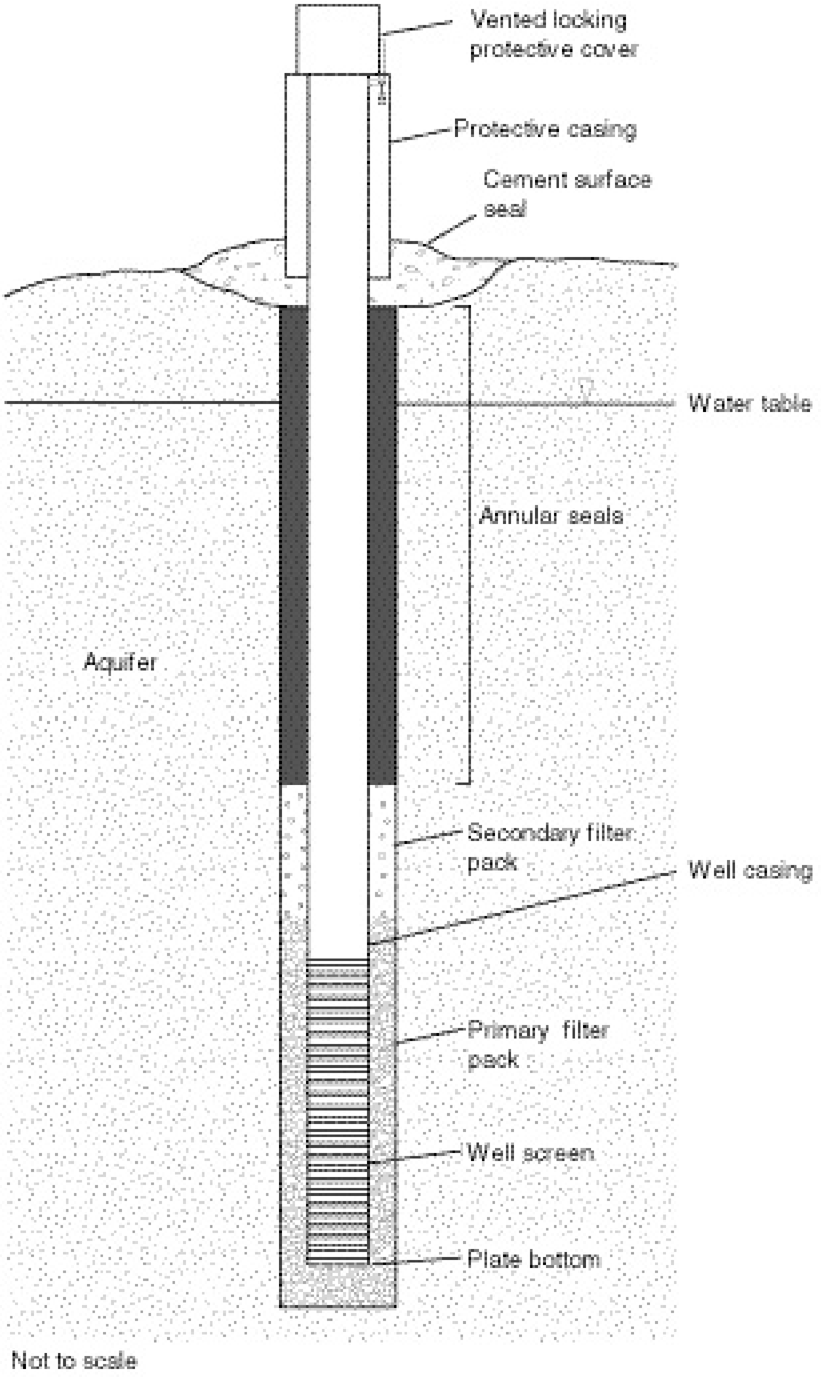


Figure 3. *Example of a monitoring-well design in unconsolidated materials.*

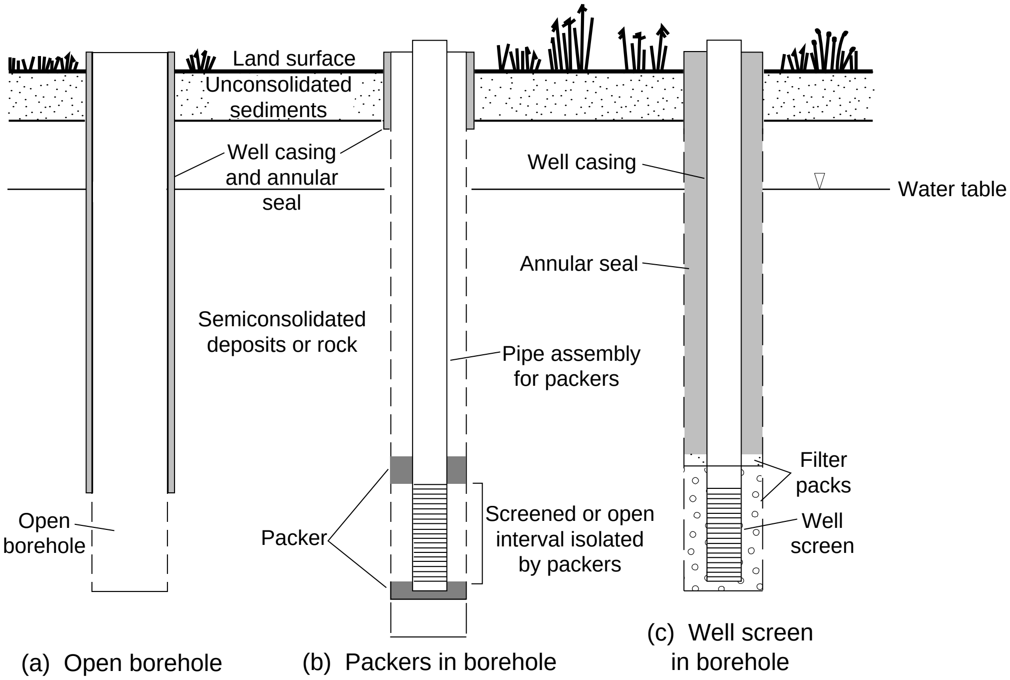


Figure 4. *Examples of monitoring-well designs in partly consolidated and consolidated materials.*

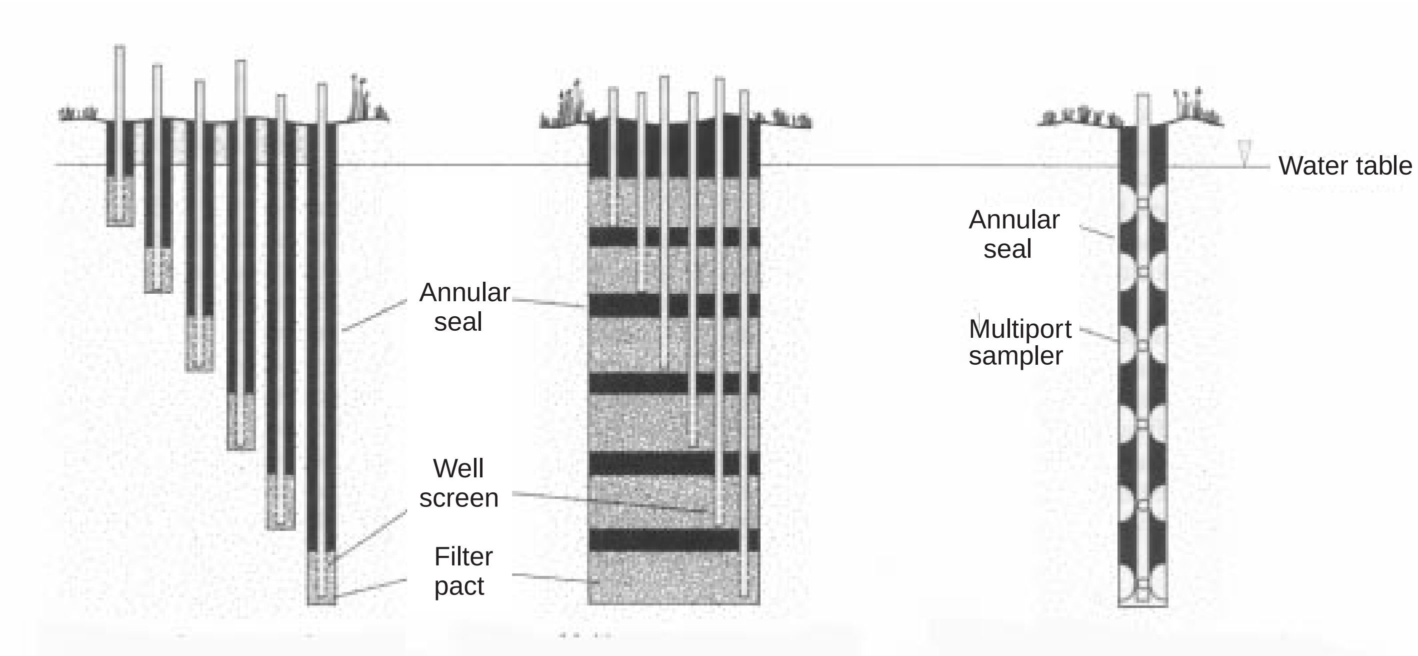
ing and borehole wall. This design is similar to that described earlier for a monitoring well in unconsolidated materials (fig. 3).

In all three designs, vertical flow in the open interval of the borehole between multiple water-bearing solution cavities, joints, or fractures (referred to here generally as fractures) in consolidated materials can result in a mix of water quality throughout the length of the open borehole. Water from the well during sampling can be derived from fractures along the entire open borehole. Also, depending on the orientation and interconnection of fractures in the vicinity of the open interval, water can be derived from above or below the open interval. Sealing the annular space between the well casing and borehole wall above the open interval (figs. 4a and 4c) can help prevent water affected by drilling from entering the open interval through fractures that connect the open interval and the annular space above the open interval.

The first and third designs (fig. 4a and 4c) are permanent installations. They can be costly because of the required installation-casing down to a given depth or to the interval of interest for sampling and emplacement of an annular seal between the casing and the borehole wall. However, these designs help ensure that water contributed to the well is not from fractures above or below the open or screened interval.

Installing borehole packer systems (fig. 4b) for measurement of head and sample collection from individual fractures or fracture zones also can be costly. The use of packers, however, has the advantage over the other two previously discussed designs (fig. 4a and 4c) in that the packers can be moved to other intervals along the borehole, or from one well to another, and permit other borehole investigations, such as geophysical logging.

Multilevel well designs are used where data are needed on the vertical distribution of water quality and hydraulic head, or when it is suspected that contaminated water might bypass the screened interval of a single monitoring well. Several multilevel well designs suitable for water-quality sampling and water-level measurements include: (1) monitoring wells with short screens, each installed in its own borehole (fig. 5a); (2) multiple monitoring wells, each with a short screen, installed in a single borehole, with an annular seal between each screened interval (fig. 5b); or (3) a single well that contains a series of multiport samplers, installed in a single borehole, with each port separated by an annular seal, or by a packer (fig. 5c) (Pickens and others, 1978; Jelinski, 1990; LeBlanc and others, 1991; Stites and Chambers, 1991).



(a) Monitoring wells with short screens, each installed in its own borehole

(b) Multiple monitoring wells with short screens installed in a single borehole

(c) A series of multiport samplers installed in a single borehole

Figure 5. *Examples of three multilevel well designs.*

The decision to use one design over another depends on a number of factors related to project objectives. For example, the interpretation of change in chemical concentration with depth at the centimeter scale can be problematical if well screens are not located in the same borehole (Gibs and others, 1993). Consequently, if measurement of small-scale features of contamination is an objective of a study, a single-borehole design of monitoring wells might be preferred. On the other hand, ensuring the chemical integrity of the interval sampled could become just as problematical with this design. Isolating sampling intervals by constructing each well in its own borehole can be expected to produce more reliable data, especially when the depth-interval scale of interest is on the order of meters. The cost of constructing the latter design, however, might be considerably more than single-hole designs.

In addition to consideration of factors related to project objectives, design selection requires consideration of important practical differences. Individual wells, each installed in its own borehole (fig. 5a), are suitable in any type of water-bearing unit and are simple in design. This type of multilevel well design is relatively easy to install. Reliable filter pack and annular seals often are more readily installed in individual wells than in wells where all screens or sampling ports are installed in a single borehole (fig. 5b and 5c). Nevertheless, as many as five 2- to 3-in. (~5- to ~7.6-cm) diameter monitoring wells have been successfully installed in a single 10-in. (25.4-cm) diameter borehole in situations where the annular seals are several tens of feet (several meters) thick (J.A. Izbicki, oral commun., 1996). Emplacing effective seals vertically between screens or sampling ports is possible, but can be difficult if the annular seals are thin. For some single-borehole designs, the seal between well screens or ports is dependent on the collapse of the aquifer material against the well casing (LeBlanc and others, 1991). Tests can be conducted between screens or sampler ports to evaluate the effectiveness of seals. Possible tests include pumping one screened interval and measuring the hydraulic response in another, or injecting a tracer in one screened interval and searching for the presence of that tracer in other intervals (Meiri, 1989; LeBlanc and others, 1991).

The design of the well constrains the type of pump that can be used for water-quality sample collection and imposes a depth limitation. Water from single-hole wells (fig. 5b and 5c) with small diameters (less than 1 in. or 2.54 cm) usually is withdrawn using a peristaltic pump that has a lift capacity of from 25 to 30 ft

(~7.6 to ~9 m). Well design also affects the length of time required to withdraw water and the amount of water that can be withdrawn. Purging standing water from such wells or ports takes considerably less time than purging the same number of standard-diameter monitoring wells installed in separate boreholes (fig. 5a). However, because only small volumes of water generally can be withdrawn from wells in single-borehole designs, collection of representative samples can be a problem, especially if fluid was introduced during drilling. In some single borehole designs, sampling can only be achieved using suction-lift pumps because of the small diameter of the casing or tubing. Use of suction-lift pumps can preclude the collection of some chemical constituents, such as volatile organic compounds (for example, chlorofluorocarbons), radon, and hydrogen sulfide, and usually leads to negatively biased data.

Well Casing and Well Screens

The casing and screens used for a monitoring well can affect the quality of a ground-water sample. Characteristics of the casing and screen that can affect water quality include materials and construction, the screen or open-interval length, and diameter.

It is not always possible to select the optimum construction material for well casing and screens. For example, in an area inaccessible to a drill rig, a hand-driven monitoring well constructed of steel casing and drive point might be the only available means of sample collection. The quality of data obtained from such a monitoring well could be difficult to interpret. It is necessary to recognize that where a less-than-optimum well design is used, the increased risk of data bias needs to be considered and any potential bias must be explicitly identified, defined, and reported.

Casing and screen materials

The materials used for the well casing and screen must be suitable for their intended use. To evaluate their suitability, three characteristics require consideration: (1) tensile strength is important with respect to the intended length of casing string, and in terms of removing the casing if the well is abandoned (see “Well Disposition”); (2) leaching and sorption are important with respect to the chemical analytes of interest; and (3) chemical resistance, or the longevity of the casing material, is important with respect to subsurface chemical conditions.

The deeper the well, the more important becomes the tensile strength of the casing (see table 6). Biased water-quality data can result from chemical and physical interaction between ground water and materials used to construct monitoring wells (tables 6 and 7), such as leaching, sorption-desorption, or volatilization of casing materials. Because of the large surface area exposed to ground water, the well screen can alter water quality to a greater degree than the well casing. The screen is the part of the monitoring well most susceptible to corrosion and/or chemical degradation, and provides the highest potential for leaching or sorption of contaminants (Aller and others, 1989, p. 192). Therefore, it is also important that the well screen be made of materials resistant to leaching or sorption/desorption so that it does not contribute to sample bias (tables 6 and 7). Selection of a well screen and casing material is based, to the extent possible, on understanding and evaluating the physical and chemical characteristics of the water to be sampled, and the constituents to be analyzed.

Leaching is the removal from the casing of compounds inherent in the casing material; sorption is the removal of constituents or compounds from the water onto the casing; desorption is the removal of compounds from the casing that previously were sorbed to it; and volatilization is the loss of compounds from the casing as vapor. Leaching, desorption, and volatilization can cause positive bias by adding to constituent concentrations in a sample; sorption, however, causes a negative bias by removing constituents and thereby lowering the constituent concentration. Investigations of leaching and sorption or desorption between water and casing materials are described by Hewitt (1992, 1994a); Barcelona and others (1983); Curran and Tomson (1983); Sosebee and others (1983); Parker and Jenkins (1986); Reynolds and Gillham (1986); Cowgill (1988); Gillham and O’Hannesin (1990); Parker and others (1990); Reynolds and others (1990); Parker and Ranney (1994); and Ranney and Parker (1994). Parker (1992) provides a recent summary of the findings of several of these and other studies.

Amounts and rates of leaching or sorption/desorption of individual compounds can differ within each major class of compounds. For example, results of a study by Reynolds and Gillham (1986) indicated that polytetrafluoroethylene (PTFE) rapidly sorbed tetrachloroethylene, and slowly sorbed 1,1,1-trichloroethane, but did not sorb bromoform. Also, ranking the use of materials for well casing and screens on the basis of their tendency to leach versus sorb compounds can differ. For example, Hewitt (1992), in a study of Cd, Cu, Pb, Fe, and Ni, found that stainless steel 316 (SS 316) (an alloy of stainless steel) had less tendency to leach these metals than stainless steel 304 (SS 304) (another alloy of stainless steel). However, SS 316 had a greater ability to sorb these metals than SS 304.

Table 6. *Some general characteristics of materials used for well casing and screens (modified from T.E. Imbrigiotta, U.S. Geological Survey, written commun., 1989)*

[PTFE, polytetrafluoroethylene; PVC, polyvinylchloride; SS, stainless steel; ~, approximately (for accurate conversions, use conversion factors from “Conversion Factors, Water-Quality Units, Vertical Datum, Abbreviations, and Symbols”)]

Polytetrafluoroethylene (PTFE) [1,2]

- Virgin PTFE readily sorbs some organic solutes (Parker and Ranney, 1994).
- Ideal material in corrosive environments where inorganic compounds are of interest.
- Useful where pure product (organic compound) or high concentrations of PVC solvents exist.
- Potential structural problems because of its low tensile and compressive strengths, low wear resistance, and the extreme flexibility of the casing string as compared to other engineering plastics (Driscoll, 1986, table 21.6; Dablow and others, 1988; Aller and others, 1989, table 25).
- Potential problems with obtaining a seal between the casing and the annular sealant because of PTFEs low coefficient of friction and antistick properties as compared to other plastics (Aller and others, 1989, p, 151).
- Maximum string length of 2-in. (~5-cm) diameter schedule PTFE casing should not exceed about 375 ft (~115 m) (Nielsen and Schalla, 1991, p. 262).
- Expensive.

Polyvinylchloride (PVC)[1,2]

- Leaching of compounds of tin or antimony, which are contained in original heat stabilizers during polymer formulation, could occur after long exposure.
- When used in conjunction with glued joints, leaching of volatile organic compounds from PVC primer and glues, such as THF (tetrahydrofuran), MEK (methylethylketone), MIBK (methylisobutylketone) and cyclohexanone could leach into ground water. Therefore, threaded joints below the water table, sealed with o-rings or Teflon tape, are preferred.
- Cannot be used where pure product or high concentrations of a PVC solvent exist.
- Maximum string length of 2-in. (~5-cm) diameter threaded PVC casing should not exceed 2,000 ft (~610 m) (Nielsen and Schalla, 1991, p. 250).
- PVC can warp and melt if neat cement (cement and water) is used as an annular or surface seal because of heat of hydration (Johnson and others, 1980; Driscoll, 1986, p. 324).
- PVC can volatilize CFCs into the atmosphere within the unsaturated zone, which can be a potential problem for studies of gas and moisture transport through the unsaturated zone.
- Easy to cut, assemble, and place in the borehole.
- Inexpensive.

Stainless steel (SS)[1]

- Generally has high corrosion resistance, which differs with type.
- Corrosion can occur under acidic and oxidizing conditions.
- Corrosion products are mostly iron compounds, with some trace elements.
- Primarily two common types:

  (1) SS 304: Iron alloyed with the following elements (percentages): chromium (18-20 percent), nickel (8-11 percent), manganese (2 percent), silicon (0.75 percent), carbon (0.08 percent), phosphorus (0.04 percent), sulfur (0.03 percent).

  (2) SS 316: Iron alloyed with the following elements (percentages): chromium (16-18 percent), nickel (11-14 percent), manganese (2 percent), molybdenum (2-3 percent), silicon (0.75 percent), carbon (0.08 percent), phosphorus (0.04 percent), sulfur (0.03 percent).
- Corrosion resistance is good for SS 304 under aerobic conditions. SS 316 has improved corrosion resistance over SS 304 under reducing conditions (Parker, 1992).
- Expensive.

Table 6. *Some general characteristics of materials used for well casing and screens (modified from T.E. Imbrigiotta, U.S. Geological Survey, written commun., 1989)--Continued*

Galvanized steel[1]
• Less corrosion resistance than SS 304 or SS 316 and more resistance to corrosion than carbon steel (see "Carbon steel" below). • Oxide coating could dissolve under chemically reduced conditions and release zinc and cadmium, and raise pH. • Weathered or corroded surfaces present active adsorption sites for organic and inorganic constituents. • Inexpensive.
Carbon steel[1]
• Corrosion products can occur (for example, iron and manganese oxides, metal sulfides, and dissolved metal species). • Sorption of organic compounds onto metal corrosion products is possible. • Weathered surfaces present active adsorption sites for organic and inorganic constituents. • Inexpensive.

[1] Residues, such as threading lubricants used in production or contamination during shipping, require that all materials be cleaned inside and out before installation.

[2] Possible construction alternative is to use a PTFE screen with threaded PVC casing.

On the basis of chemical interactions, leaching and sorption/desorption studies between water and materials used to construct wells provide some general guidelines for selection of well casing and screen materials for ground-water sampling for major classes of compounds (table 6). The polymer PTFE is generally considered the best material of those listed for most inorganic chemical constituents. The polymer polyvinylchloride (PVC) also is a good choice. Both PTFE and PVC are preferable over stainless steel for collecting samples for analysis of inorganic constituents. Stainless steel generally is the best material to use for studies that sample for organic compounds. Highly halogenated aliphatic compounds, however, are degraded by stainless steel as well as by other metals (Reynolds and others, 1990). Both PVC and PTFE have been shown to sorb chlorinated and nitroaromatic organic compounds, but rates of sorption onto PVC are lower than sorption rates onto PTFE (Parker and others, 1990; Parker and Ranney, 1994; Ranney and Parker, 1994). Hewitt (1994a) reports that under pumping conditions, rigid PVC performed equally well compared with rigid PTFE with regard to leaching and sorption of inorganic and organic constituents.

If minor and trace constituents and organic (including trace-organic) compounds are to be studied, PVC is the best compromise choice of those materials listed (table 7). For this reason, PVC generally is used for water-quality studies that include a broad suite of inorganic and organic constituents.

Threaded rather than glued pipe joints are recommended for PVC well casing. For wells constructed with threaded PVC casing, use of O-rings or Teflon tape on threaded joints below the water table helps prevent leakage of water through the joints. The problem of leakage of water through threaded joints can be particularly problematic in low-yielding aquifer materials (some tills and loess) in which the leakage can be a significant source of water to a well when compared to the amount of water contributed through the well screen (van der Kamp and Keller, 1993).

PVC primer and PVC adhesives used to join sections of well casing and screen or to construct bailers have been shown to leach volatile organic compounds in laboratory test samples and environmental field samples (Sosebee and others, 1983). Conclusions drawn from the reported data suggest that adhesives and primers are likely to be the source of a fairly narrow range of compounds that exhibit a relatively wide range of concentrations. Compounds from PVC primers and (or) adhesive create problems in VOC analysis by co-eluting with other VOCs during sample analysis and thereby masking the identification of other VOCs.

Table 7. *Relative leaching or sorption/desorption ranking of well-casing and screen materials for inorganic constituents and organic compounds*

[Actual amounts and rates of leaching or sorption/desorption of individual chemical components can differ within each category for inorganic constituents and organic compounds. The tendency of a material to leach compounds can differ from the ability of the material to sorb constituents or compounds. Rankings are based on review of the literature cited. 1, least leaching or sorptive/desorptive; 5, most leaching or sorptive/desorptive; PTFE, polytetrafluoroethylene; PVC, polyvinylchloride]

Material	Inorganic constituents	Organic compounds
PTFE[1] (rigid)	1	2-4
PVC[2] (rigid)		
• Flush-threaded joints	1-2	2
• Glued joints[3]	3	5
Stainless steel[4]	4	1-2
Galvanized steel	5	4
Carbon steel	5	4

[1] PTFE was shown to be highly sorptive of some organic compounds in laboratory tests; compound sorption may diminish as equilibrium of casing with ground water is approached (Parker and Ranney, 1994; Ranney and Parker, 1994; Louise Parker, U.S. Army Corps of Engineers, written commun., 1995).

[2] PVC usually is the best compromise choice if sampling for both organic and inorganic constituents.

[3] Volatile organic compounds leached from glue can include THF (tetrahydrofuran), MEK (methylethylketone), MIBK (methylisobutylketone) and cyclohexanone (Sosebee and others, 1983).

[4] Generally, SS 316 is more resistant to corrosion than SS 304.

- Compounds listed as ingredients in one or more of six PVC adhesives and one primer included THF (tetrahydrofuran), MEK (2-butanone or methylethylketone), MIBK (methylisobutylketone), cyclohexanone, and DMF (N, N-dimethylformamide).
- Compounds detected in water samples after laboratory leaching tests of PVC adhesives and primers from freshly glued PVC pipe were THF, MEK, cyclohexanone, and MIBK. The durations of these laboratory leaching tests are short (for example, 5 days) compared to the length of time monitoring wells are in place in the field before sampling. Therefore, it is uncertain how transferrable the results of the laboratory tests are to actual field situations.
- Compounds detected in ground-water samples obtained with glued PVC bailers were THF, MEK, and cyclohexanone.

On the basis of cost, strength, and chemical considerations, American Society for Testing and Materials (ASTM) approved schedule 40 or schedule 80 flush-threaded PVC casing generally is recommended for well casing and screens when sampling for a wide range of water-quality constituents. Schedule 80 PVC casing has a thicker wall than schedule 40 PVC casing, which results in a smaller inside diameter. As a result, pumps or geophysical tools that readily fit down a well constructed of 2-in. (~5-cm) diameter schedule 40 PVC casing might not fit down a well constructed of 2-in. diameter schedule 80 casing. This problem is especially severe for deep wells or when casing bends or is slightly warped by the heat of curing from cement seals. Schedule 80 casing is less likely than schedule 40 casing to warp or bend. If pure product or high concentrations of a PVC solvent are present (table 7), PTFE or stainless steel (SS 316) casing and screen are needed. Alternatives to all-PTFE casing are to use PTFE for the screened interval and PVC for the rest of the casing or to install PVC casing above and PTFE casing with screen below the water table.

Design of well screen

A well screen serves as the intake of a monitoring well. It permits water to enter the well from the aquifer, prevents geologic materials from entering the well, and serves structurally to support the filter pack or native unconsolidated materials that surround the screen. Well-screen types, design, and construction are described by U.S. Environmental Protection Agency (1976), Barcelona and others (1983), Driscoll, (1986), Aller and others (1989), and ASTM (1992). The well screen should have a large percentage of open area; it should have nonclogging slots; it should be constructed of material that is resistant to corrosion; and it should be of sufficient column and collapse strength for the intended application (Driscoll, 1986, p. 395). Common screen designs appropriate for water-quality studies are continuous-slot wire-wound screens and machine-slotted casing.

The design of the screen aperture is important. The aperture needs to have a percentage of open area sufficient to allow a sample to be withdrawn but openings small enough to prevent continuous entrainment of sediment into the well. Selection of screen-slot size is based on the size of the aquifer material. A slot size that is too large can result in continuous entrainment of sediment in the water from the well. A slot size that is too small can lead to excessive drawdown in the well during sampling, which in turn could lead to cavitation of the pump during sampling, and (or) aeration of the aquifer. A slot size that is too small also can slow the recovery of the water level in the well after purging or sampling.

Length of well screen

The length of well screen selected is relative to the vertical scale of investigation, and to the thickness of the hydrogeologic unit of interest. The longer the screened (or open) interval relative to aquifer thickness, the less likely will be the ability to distinguish differences in water quality at specific depth intervals. Mixing of waters within the screened interval can lead to constituent concentrations that do not necessarily represent the maximum or minimum concentrations of those constituents at any point. For this reason, relatively short screens are used if the objective is to investigate water quality at discrete intervals and to define chemical stratification within the aquifer. If determining the vertical distribution of water quality in an aquifer is the data-collection objective, installing wells at different depths, each with a relatively short screen length, is often the most effective design.

Screen lengths for monitoring wells typically range from 2 to 20 ft (~0.6 to 6 m). As a general rule, screen lengths of 20 ft or less generally are appropriate for most assessment studies, while screen lengths of 5 ft (~1.5 m) or less generally are better suited for studies to determine fate, transport, and geochemistry of ground-water constituents. A screen length of 5 ft might be too long if information suggests that marked vertical differences in the distribution of hydraulic head or water quality occur on the order of a few feet or less.

The length of the open interval also depends on the scale of the investigation. For example, a 20-ft-long screen is too long for an investigation of a 5-ft-thick contaminant plume, whereas it might be considered too short in an investigation of the water quality of an aquifer that is several hundreds of feet (tens to hundreds of meters) thick. A 100-ft (about 30.5-m) long open interval might be considered short in an investigation of the water quality of an aquifer 1,000 ft (~305 m) thick. Additional factors to consider when deciding on screen length are:

- A short screen generally provides measurements of hydraulic head and ground-water quality that more closely represent point measurements in the aquifer than measurements provided by a long screen.
- Samples taken from wells with long screened intervals could exhibit smaller concentrations or a higher frequency of samples with nondetectable concentrations (leading to a “false negative” assessment) in comparison to samples taken from wells with short screened intervals (McIlvride and Rector, 1988).
- A long well screen also can induce mixing of waters of different chemistry in comparison to a short well screen because of vertical flow along the screened interval and because of differences in head along the screened interval (well-bore flow). Well-bore flow can occur even in homogeneous aquifers with very small vertical head differences (Reilly and others, 1989). Well-bore flow might contribute to aquifer contamination by providing a pathway for contaminant movement from contaminated to uncontaminated zones along the screened interval(s).

Diameter of casing and screen

The diameter of monitoring wells for water quality typically range from 0.5 to 6 in. (~1.3 to 15 cm). Two-in.-diameter wells are used most commonly for environmental studies in relatively shallow materials. Three- or 4-in. (~7.6- to 10-cm) diameter wells often are used for environmental studies of ground water at greater depth and to accommodate geophysical and other instruments. Characteristics of small- and large-diameter wells to consider when selecting the diameter of the well casing and screen include:

- Small-diameter wells can minimize disturbance of the ground-water flow field.
- Large (4-6 in.) diameter wells more easily accommodate water-level recorders, geophysical tools, and sampling equipment. For example, geophysical equipment such as electromagnetic tools might not fit in 2-in. (~5-cm) diameter wells. Nevertheless, transducers for recording water levels and small-diameter pumps for sampling are now commonly available for use in 2-in.-diameter wells.
- Small-diameter wells generally require smaller drilling equipment for installation, making them easier to install in many places. An exception is small diameter wells installed with a mud rotary drilling method, which may be difficult to develop adequately.
- Purging times generally are longer, and therefore costlier for larger diameter wells than for smaller diameter wells.
- Small-diameter wells can minimize the disposal of wastewater during pumping.
- Water in a larger diameter well is less likely to be in contact with well-casing materials because the ratio of volume of water stored in the well casing to casing surface area increases with increasing well diameter. The effect of well diameter, however, is mitigated by purging a well of standing water before sampling.
- A 2-in.-diameter or larger well may be necessary to accommodate a pump for sampling that meets the minimum lift requirements for the well.

Decontamination of Equipment and Materials

Decontamination of well installation and sampling equipment, casing, and screens is necessary to avoid introducing contaminants to hydrogeologic units. Contaminants include grease, steel or PVC filings, organic solvents, and other machining and manufacturing residues that often are present on well casings and screens as received from the manufacturer. In addition, oil, grease, and other lubricating materials or geologic materials not cleaned from equipment from previous field activities can introduce detectable levels of compounds to ground water. These must be removed.

Decontamination of materials received from the manufacturer and of equipment between well-installation sites is important in preventing contamination of a site or possible cross contamination between sites. At a site where multiple wells are being installed, decontamination of equipment between installations also will help prevent cross contamination between boreholes.

Most equipment used in a borehole requires decontamination. This includes:

- Well casing and screen or other materials that will be permanently installed.
- Pumps or other samplers, including those that will be permanently installed.
- Drilling, coring, well-completion, and well-development equipment (for example, drill stems, drill bits, thick-wall and thin-wall samplers, tremie pipes, bailers, and air lines).

CRITICAL: DECONTAMINATION OF ALL EQUIPMENT AND MATERIALS USED FOR WELL INSTALLATION IS NEEDED TO AVOID SAMPLE AND AQUIFER CONTAMINATION.

The drill rig and other support vehicles should be kept clean and must be checked to be sure that no oil or fuel leaks exist. Some materials should be disposed of after one use. This applies to porous materials such as wood, cloth, filters, and other materials that are difficult to decontaminate. Well tapes used for water-level measurements are wiped dry after each use, primarily to prevent rust (in steel tapes) or mold (on plastic tapes), and may be cleaned on occasion with water or detergent and water. Concern is expressed occasionally regarding the potential of cross contamination of wells with microorganisms (for example, iron bacteria) on well tapes. Such cross contamination is unlikely, but if there is reason for precaution, the wetted portion of the well tape can be wiped with a 70-percent or stronger alcohol (isopropyl or ethanol) solution or with Lysol (D.N. Myers, USGS, oral commun., 1996).

The frequency of decontamination during the installation of a monitoring well depends on subsurface conditions at the drill site. In situations where cross contamination between water-bearing units in a single borehole is likely, decontamination of drilling and coring equipment is repeated as the drilling proceeds. This can occur, for example, if it is suspected that drilling will penetrate contaminated materials and continue into underlying, uncontaminated materials. In this case, it is necessary to remove the equipment after drilling through the contaminated materials to prevent contamination of underlying materials.

The standard procedure for decontamination of well-installation equipment, well casings, screens, and other materials consists of washing the outside and inside (if possible) of equipment and materials with a low-sudsing, non-phosphate detergent, followed by high-pressure steam cleaning (table 8, fig. 6). The seven-step decontamination procedure (table 8) might have to be modified somewhat for a project depending on (1) data-collection requirements, including the analytes targeted for sampling, and analyte concentrations; (2) local, State, and Federal regulations; and (3) the contaminants expected to be contributed by the equipment and methods used for installation and completion of the well. Different cleaning agents can be used in the decontamination process (table 9) where it is known or suspected that the routine procedures described might be inadequate.

For some studies (table 8), quality-control samples are collected to evaluate the effectiveness of a decontamination procedure and to modify it, if necessary. The only way to demonstrate clearly that the equipment was clean of contaminants of interest, either before its use or following decontamination, is from collection and analysis of quality-control samples. Records of the decontamination procedures followed must provide sufficient documentation for studies involving regulatory concerns.

STANDARD PROCEDURE: TO DECONTAMINATE EQUIPMENT AND MATERIALS, USE A LOW-SUDSING, NON-PHOSPHATE DETERGENT WASH FOLLOWED BY A HIGH-PRESSURE STEAM CLEANING.

Table 8. *Seven-step procedure for decontamination of well-installation equipment and materials (modified from Aller and others, 1989, p. 62)*

1. Identify equipment that requires decontamination.
2. Determine the frequency of decontamination for each piece of equipment.
3. Select a location for decontamination procedures:
    - Avoid spilling decontamination fluids at drilling site;
    - Prepare clean area for cleaned equipment.
4. Select the decontamination procedure and type of cleaning solutions to be used.
   The standard procedure for decontamination of well-installation equipment and materials is to:
    - Wash outside of equipment and materials used during well installation using a low-sudsing, non-phosphate detergent;
    - Wash inside and outside of well casing and screen with non-phosphate detergent;
    - Complete decontamination procedure with high-pressure steam cleaning (use of potable tap water is acceptable in most cases) (fig. 6).
5. Contain residual contaminants and cleaning solutions, if necessary, and dispose of these in accordance with regulations.
6. Collect some quality-control samples to evaluate the effectiveness of the decontamination procedure (for example, a sample of the rinse water that was used to steam clean or remove all residues and additional samples of rinse water taken from the equipment after it has been decontaminated).
7. Document for site (well) the decontamination procedures used and the results of quality-control samples.

Figure 6. *High-pressure steam cleaning of auger flights and well casing. (Photographs courtesy of Mary Jo Baedecker.)*

Table 9. *Chemical solutions used for decontamination of equipment and materials during the installation of wells (modified from Richter and Collentine, 1983; Moberly, 1985)*

[lbs, pounds; gal, gallons; chemicals must be handled appropriately as they can be hazardous to health by causing burns or noxious fumes]

CHEMICAL	SOLUTION[1]	USES/REMARKS
Potable water	Tap water	Used under high pressure or as steam to remove heavy mud and dirt, or to rinse off other solutions.
Low-sudsing non-phosphate detergents[2]	Typical concentrations are 0.5- to 2-percent solution by volume	General all-purpose cleaner for lightly to moderately contaminated equipment.
Sodium carbonate (Washing soda)	4 lbs/10 gal water	To neutralize inorganic or organic acids and remove heavy metals and metal processing wastes.
	10-20 percent aqueous solution	Good water softener, which increases the effectiveness of detergents.
Sodium bicarbonate[2] (Baking soda)	4 lbs/10 gal water or 5-15 percent aqueous solution	Used to neutralize either acidic or basic contaminants.
Trisodium phosphate[2] (TSP Oakite)	2 lbs/10 gal water	Similar to sodium carbonate.
	10 percent aqueous solution	Strong initial or intermediate detergent or rinsing solution for heavily contaminated equipment.
	4 lbs/10 gal water	Useful for removing solvents and organic compounds (such as toluene, chloroform, trichloroethylene, and polychlorinated biphenols).
Calcium hydrochloride[2]	8 lbs/10 gal water	Disinfectant, bleaching and oxidizing agent used for pesticides, fungicides, chlorinated phenols, dioxins, cyanides, ammonia and other non-acidic inorganic wastes.
	10 percent aqueous solution	Excellent disinfectant, bleaching and oxidizing agent.
Hydrochloric acid[2] Nitric acid[2]	1 pint/10 gal water	Used to neutralize inorganic bases, alkali, and caustic wastes.
Citric, tartaric, oxalic acids or their respective salts[2]	4 lbs/10 gal water	Used to remove heavy-metal contaminants.
Organic solvents, such as acetone, methanol, and methylene chloride	Concentrated	Used to clean equipment and materials contaminated with organic compounds and to clean well casing and other equipment of surface oils. Before using equipment downhole, evaporate solvent to dryness.

[1] 4 lbs/10 gal = 1.8 kg/38 L; 2lbs/10 gal = 0.91 kg/38 L; 8 lbs/10 gal = 3.6 kg/38 L; 1 pint/10 gal = 0.47 L/ 38 L.

[2] Follow with thorough potable water rinse.

Considerations When Collecting Hydraulic, Geophysical, and Geologic Data

Data-collection requirements are defined by the purpose, scope, objectives, and scientific approach of the study. Collection of hydraulic, geophysical, and geologic data commonly are components of water-quality studies that evaluate ground-water chemistry; these data can be critical in interpreting the chemical data from well samples.

Although the governing principle for selecting a well-installation method is that the method and materials used will not affect the data quality required for the ground-water samples, the decision to collect other types of data (hydraulic, geophysical, and geologic) could necessitate some compromise in the well-installation methods selected. For example,

- Many of the most useful borehole-geophysical logs must be run in uncased, fluid-filled boreholes. This requirement is at odds with drilling methods that avoid use of drilling fluids.
- Installation of a small-diameter well could fulfill study needs to limit the volume of waste from a contaminated system, but such a well may be inadequate to conduct certain aquifer tests.

The advantages and disadvantages of possible construction, completion, and development methods must be assessed in relation to water-quality and other data-collection objectives. Benefits of collecting hydraulic, geophysical, and geologic data may have to be weighed against using well installation methods that most effectively avoid potential contamination of the ground-water system or that meet other study objectives. While it is beyond the scope of this report to describe procedures for conducting aquifer tests and borehole geophysical surveys, and sampling for geologic materials, considerations and constraints for how collection of these data affect well-installation methods are summarized below. This information is provided to encourage the collection of these types of data as part of water-quality studies where these additional data could aid in the interpretation of water-quality data.

GUIDELINE: DATA NEEDED IN ADDITION TO WATER-QUALITY DATA MIGHT CONSTRAIN THE SELECTION OF A WELL-INSTALLATION METHOD.

Hydraulic Data

Knowledge of hydraulic properties of the subsurface systems being studied often is necessary for valid interpretation of ground-water-quality data. Collection of hydraulic data can constrain the type of well that can be constructed or installed.[3]

An aquifer test, for example, can provide an overall estimate of hydraulic conductivity and storage of water-bearing units within several hundred feet or more of the pumping well. It usually involves measuring the response of an aquifer system to pumping by measuring changes in water levels in observation wells in the vicinity of the pumping well. Analysis of the response to other hydraulic stresses, such as injection of water into the system, also is possible. Typically, wells for an aquifer test consist of one large-diameter (4-in. (~10-cm) or greater) pumping well that is associated with wells that can be of smaller diameter in which drawdown is measured as pumping proceeds. The larger diameter normally is required for the pumping well to ensure that the well can be pumped at a rate sufficient to cause measurable drawdown in the observation wells. Monitoring wells with a diameter as small as 2 in. (~5 cm) are suitable for measuring water levels and can be used as part of an array of wells from which drawdown is to be determined, but generally are not suitable as the pumping well.

A slug test at an observation well for example, can provide an estimate of hydraulic conductivity of the unit in the immediate vicinity of the well screen. A slug test is conducted in a single observation or monitoring well that usually is small in diameter (less than about 4 in.). Slug tests involve the instantaneous addition or removal of water from the well. Measurement of the recovery of the water level in the well is used to determine hydraulic conductivity at the screened interval.

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[3] Aquifer-test methods are numerous. The body of literature on these methods is extensive, and covers the selection, planning, design, and implementation of a test, and the analysis of results. Only a few of the many publications on aquifer-test methods are referenced below. A review of field procedures for conducting an aquifer test and a summary of the principal aquifer-test methods are provided in Stallman (1971) and Bedinger and Reed (1988). Bedinger and Reed (1988) provide a glossary of terms and a syllabus of aquifer-test methods, classified by aquifer condition, control-well characteristics, recharge and discharge function, and boundary conditions. A matrix of selected literature on aquifer tests in terms of site conditions treated and subject emphasis is provided in U.S. Geological Survey (1977, table 2-3). Description of the basic principles of well hydraulics and principal aquifer-test methods with examples of their application are described in Lohman (1972). Practical information related to aquifer-test planning and interpretation of aquifer-test data is given in Stallman (1971). Other texts that discuss aquifer tests include DeWiest (1965), Freeze and Cherry (1979), and Driscoll (1986).

Borehole-Geophysical Surveys

Choice of drilling method can depend, in part, on the need for borehole geophysical surveys[4] (tables 10 and 11). For example, a fluid rotary-drilling method often is needed to obtain geophysical data (most electric and sonic geophysical-logging tools require uncased, fluid-filled boreholes), even though methods that avoid use of drilling fluid are preferred for water-quality-monitoring wells in order to avoid affecting the ground-water chemistry.

The need for borehole geophysical data that require fluid rotary drilling must be weighed against the potential effect of drilling fluid on ground-water chemistry and the potential increase in time and cost it could take to remove the fluid with well development techniques. The information provided in table 11 summarizes applications of borehole geophysics and provides additional information regarding method limitations and borehole conditions required for borehole geophysical logging. This information can be used to help evaluate the compatibility of drilling requirements for geophysical logging with those for water-quality sample collection.

Geologic Materials

If samples of geologic materials will be collected, selection of a drilling method partially is determined by the type and quality of sample and the sampling device needed to collect these materials. Samples of geologic materials are collected as cores and drill cuttings.[5] A core is a cylindrical sample of unconsolidated or consolidated geologic material obtained in situ by means of a thick-wall, thin-wall, or rotating coring device. Cuttings are defined here as small-sized fragments of unconsolidated, partly consolidated, or consolidated geologic materials that are transported to the surface by (1) a stream of air or other fluid used during drilling, (2) bailing or grabbing from a drill rig, (3) sticking to drill bits or auger flights, (4) return from auger flights (noncoring methods that use pocket and spoon, window or door), or (5) sidewall grab sampler (samples returned from this method, while not a core sample, nevertheless often are distinguished from cuttings).

Samples of geologic materials are collected for three general purposes: (1) measurement of physical and hydraulic properties, (2) measurement of chemical and biological properties, and (3) identification of lithologic, geologic, mineralogical, and gross physical properties. Most core samplers provide good to excellent samples for all three purposes (Boulding, ASTM, written commun., 1996). Depending on the method used, drill cuttings are unsuitable for measuring in situ properties, but are acceptable representative samples for some visual descriptions of subsurface materials. The relative quality of the sample also is a function of the type of drilling method used and type of sample-collection device. The quality and intended use of the data dictate whether cores or cuttings should be collected, and what drilling method and (or) sampling device is applicable (Shuter and Teasdale, 1989, p. 80).

The quality of geologic samples can be classified in relative terms as undisturbed, representative, or nonrepresentative, in respective order of the degree to which specific in situ properties are preserved (undisturbed) or unpreserved (disturbed) (table 12). The disturbance to the geologic materials sampled caused by the sampling process is a function of the sampling device (for example, thin-wall coring devices), the sampling method or technique (for example, pushing, driving, or rotating), and the physical nature of the geologic materials. Also, a sample can be considered "undisturbed" with respect to one property (for example, mineralogy or stratigraphy), but disturbed and unsuitable for analysis for another (for example, hydraulic conductivity). A general correlation between sample quality and sample objective is summarized on table 13.

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[4] When the issue is strictly installing a well for borehole-geophysical logging, the choice of drilling methods is described Hodges and Teasdale (1991). Guidelines relevant to ground-water studies on the selection of borehole-geophysical logs to meet different study objectives are provided in Keys (1990) (see table 16). Taylor and Dey (1985) compiled a bibliography of borehole geophysics by subject heading relevant to application of borehole-geophysical logging to ground-water hydrology. References cited below cover the following topics: principles and instrumentation, calibration and standardization, volume of earth material investigated, and interpretation and application of borehole-geophysical methods to ground-water investigation (Keys, 1986; Keys, 1990; Paillet, 1993; Paillet and Williams, 1993; Paillet and Crowder, in press; Paillet and Pedler, in press); description of the calibration and standardization of geophysical well-logging equipment for hydrologic applications (Hodges, 1988); general applications of borehole geophysical methods (Keys and MacCary, 1971; Nelson, 1982; Hearst and Nelson, 1985; Doveton, 1986; Tittman, 1986; Respold, 1989; Keys, 1990; Roscoe Moss Company, 1990; Hodges and Teasdale, 1991; Boulding, 1993).

[5] Digging is used sometimes to obtain relatively shallow samples. Information on field techniques for various methods of sample collection is beyond the scope of this document, but is provided in an extensive body of literature. Some basic references include: Campbell and Lehr (1973), Acker (1974), ASTM (1983, 1984), Driscoll (1986), Lehr and others (1988), Aller and others (1989), Shuter and Teasdale (1989), Roscoe Moss Company (1990), Ruda and Bosscher (1990), Australian Drilling Industry Training Committee Limited (1992).

Table 10. *Summary of potential applications of borehole-geophysical logs commonly used in ground-water investigations*

Potential applications		Type of Log													
		Spontaneous potential	Single-point resistance	Multi-electrode	Gamma	Gamma-gamma	Neutron	Acoustic velocity	Acoustic televiewer	Caliper	Temperature	Conductivity	Flow	Radar	Electro-magnetic induction
Borehole or casing	Diameter									√					
	Volume									√					
	Casing inspection								√						
	Cement bond							√							
	Cement curing										√				
	Salinity of borehole fluid											√			
	Borehole flow										√	√	√		
Aquifer and confining unit property or characterization	Bulk density					√									
	Moisture content					√	√								
	Porosity					√	√	√							
	Lithology	√	√	√	√	√	√	√		√					√
	Shale content	√													
	Radioisotopic identification				√										
	Neutron activity						√								
	Rock structure													√	
	Fracture														
	-Location		√					√	√	√					
	-Orientation								√						
	-Characterization							√	√						
	Bedding														
	-Strike								√						
	-Dip								√						
	Hydraulic conductivity												√		
	Geothermal gradient										√				
	Salinity of pore waters	√		√											√
Water quality	Location of contaminant plumes											√			√
	Location of injection water										√				√

Table 11. *Criteria for the selection of borehole-geophysical logs*

[Modified from Keys, 1990, table 2; cm, centimeter]

Type of log	Varieties and related techniques	Properties measured	Potential applications	Required borehole conditions	Other limitations
Spontaneous potential.		Electric potential caused by salinity differences in borehole and interstitial fluids.	Lithology, shale content, salinity.	Uncased hole filled with conductive fluid.	The salinity difference needed between borehole fluid and interstitial fluids is correct only for NaCl fluids.
Single-point resistance.	Conventional or differential.	Resistance of rock, saturating fluid, and borehole fluid.	High-resolution lithology, fracture location by differential probe.	Uncased hole filled with conductive fluid.	Not quantitative; hole-diameter effects can be significant.
Multi-electrode.	Normal, focused, or guard.	Resistivity, in ohm-meters, of rock and saturating fluids.	Quantitative data on salinity of interstitial water, and on lithology.	Uncased hole filled with conductive fluid.	Normals provide incorrect values and thicknesses in thin beds.
Gamma.	Gamma spectral.	Gamma radiation from natural or artificial radioisotopes.	Lithology—can be related to clay and silt content, and permeability; spectral identifies radioisotopes.	Any hole conditions, except for large diameter, or several strings of casing and cement.	- -
Gamma-gamma.	Compensated (dual detector).	Electron density.	Bulk density, porosity, moisture content, lithology.	Optimum results in uncased hole; qualitative through casing or drill stem.	Severe hole-diameter effects.
Neutron.	Epithermal, thermal, compensated activation, pulsed.	Hydrogen content.	Saturated porosity, moisture content, activation analysis, lithology.	Optimum results in uncased hole; can be calibrated for casing.	Hole-diameter and chemical effects.
Acoustic velocity.	Compensated wave form, cement bond.	Compressional wave velocity.	Porosity, lithology, fracture location and character, cement bond.	Fluid-filled, uncased hole, except for cement bond logs.	Presence of secondary porosity might not be detected; cement bond and wave form require expert analysis.
Acoustic televiewer.	Acoustic caliper.	Acoustic reflectivity of borehole wall.	Location, orientation, and character of fractures and solution openings, strike and dip of bedding, casing inspection.	Fluid-filled, 3- to 16-inch diameter (~7.6 to ~41 cm).	Heavy mud or mud cake attenuates signal; very slow logging.

Table 11. *Criteria for the selection of borehole-geophysical logs--Continued*

Type of log	Varieties and related techniques	Properties measured	Potential applications	Required borehole conditions	Other limitations
Caliper.	Oriented, 4-arm high-resolution bow spring.	Hole or casing diameter.	Hole-diameter corrections to other logs, lithology, fracture, location, hole volume for annular seals, and so forth.	Any conditions.	Significant resolution difference between tools.
Temperature.	Differential.	Temperature of fluid near sensor.	Geothermal gradient, in-hole flow, location of injection water, correction of other logs, curing cement.	Fluid-filled.	Accuracy and resolution of tools vary depending on type
Conductivity.	Resistivity.	Most measure resistivity of fluid in hole.	Quality of borehole fluid, in-hole flow, location of contaminant plumes.	Fluid-filled.	Conductivity.
Flow.	Spinner, radioactive tracer, brine tracer, thermal pulse.	Velocity of fluid flow in well bore.	In hole-flow, location and apparent hydraulic conductivity of permeable interval.	Fluid-filled.	Flow.
Radar.	Single-hole reflection, crosshole tomography, borehole-to-surface measurements.	Radar wave reflection.	Rock structure.	Dry or fluid- filled, uncased or PVC-cased hole.	Radar.
Electromagnetic induction.		Electromagnetic conductivity.	Lithology, water quality.	Fluid-filled, uncased or PVC-cased hole.	Electromagnetic induction.

Table 12. *Description of undisturbed, representative, and nonrepresentative samples of geologic materials*

Sample quality	Description[1]
Undisturbed[2]	**Core,** collected using thin-wall or double-tube rotating coring devices. • Sample in which in situ properties such as structure, density, moisture content, and sensitive chemical properties[3] are preserved. • Suitable for most engineering testing and other laboratory analyses. • Accurately represents a known depth interval for most physical and chemical properties of geologic materials.
Representative[4] (Disturbed)	**Core,** collected using thick-wall coring devices. • Disturbed to the degree that some structural, hydraulic, and sensitive chemical properties do not survive or are moderately or poorly preserved. • Suitable for mechanical and chemical analysis for nonsensitive chemical constituents and lithologic logging. • Accurately represents specific depth interval with respect to in situ properties such as moisture content, grain size and gradation, and nonsensitive chemical properties.
Nonrepresentative (Disturbed)	**Drill cuttings (**coring devices not used). • Disturbed sample consisting of drill cuttings or other incomplete or contaminated portions of subsurface materials. In situ structural, hydraulic, and sensitive chemical properties are not preserved. • Suitable for lithologic logging[5] but generally not suitable for testing or analysis. • Depth interval of sample usually is not known accurately. • If collection procedures are used that define depth interval, cuttings can be considered representative for geologic logging.[6] In addition, if methods are used to avoid sample contamination, characterization of nonsensitive chemical constituents and mineralogical analysis are possible.

[1] Adapted from U.S. Geological Survey (1977, p. 2-79).

[2] The term “undisturbed” can be misleading as a sample always is affected by the sampling process.The degree of core-sample disturbance increases with (1) increasing sampler-wall thickness, (2) decreasing diameter of sampler tube, and (3) increasing length of sampler tube.

[3] Sensitive chemical constituents include volatile organic compounds and redox-sensitive chemical species.

[4] The term “representative” is applied in a nonstatistical sense: sample is representative of geologic materials encountered, but does not necessarily represent the hydrogeologic unit being sampled.

[5] Lithologic logging: general description of shape, color, visible mineralogic components.

[6] Geologic logging: general description of stratigraphy, grain-size distribution, mineralogy, and so forth.

In general, thin-wall coring devices provide undisturbed samples and best preserve the physical and chemical characteristics of the interval being sampled in unconsolidated materials. Thin-wall devices are necessary for preserving and testing in situ hydraulic properties in unconsolidated materials. Thick-wall coring devices can produce excellent samples in unconsolidated materials for all other purposes (table 14). Although cores are required for most engineering tests, the quality of the core and its suitability for the test needed depends a great deal on the nature of the material sampled. Cohesive, fine-grained material (like silt and clay) or hard rock for the most part produce better quality samples than sands, gravels, or friable formations. In situ characteristics are, for the most part, destroyed in cuttings, but the degree to which cuttings can represent some lithologic, geologic, or mineralogic features depends on the equipment and methods used.

Cores

Devices for coring include thin-wall samplers, thick-wall samplers, and rotating core samplers, all of which are restricted in use to specific drilling, driving, pushing, rotating, or vibrating advancement methods (table 14). The coring device and the advancement

Table 13. *Type and quality of geologic samples needed for selected sampling objectives*

Sampling objective (tests or analysis to be performed)	Sample quality and type (√ indicates sample that can be used for indicated objective)		
	Undisturbed: core	**Representative: core**	**Nonrepresentative: cuttings**
Physical/hydraulic properties			
Hydraulic conductivity/permeability	√		
Specific yield	√		
Pressure head	√		
Moisture characteristic functions	√		
Water content	√		
Particle size distribution	√	√	√[1]
Bulk density/porosity	√		
Strength properties	√		
Compressibility	√		
Geology			
Lithology	√	√	√[2]
Stratigraphy	√	√	√[1]
Structure	√		
Fracture characteristics	√		
Hydrogeologic units	√	√	
Gross mineralogy	√	√	√[3]
Thin section morphology	√		
Surface properties			
Ion exchange capacity	√	√	
Sorption (batch tests)	√	√	
Sorption (core flowthrough tests)	√		
Sorption site density	√	√	
Surface area	√	√	
Nonsensitive chemical parameters			
Elemental concentrations	√	√	√[3]
Carbonate content	√	√	√[3]
Organic carbon content	√	√	√[3]
Sensitive chemical parameters and microorganisms			
Microorganisms	√	√	
Nitrogen-containing species	√	√	
Sulfur-containing species	√	√	
Redox-sensitive species (As, Cr, Fe, Mn, Se)	√	√	
Volatile organic compounds	√		

[1] Requires casing advance or other method for accurate knowledge of depth interval.
[2] Drilling rate must be recorded.
[3] Requires casing advance method to avoid sample contamination.

Table 14. *Type, advancement method, and use of selected coring devices*

[1 inch = 2.54 centimeters]

Coring device (sampler)[1]	Advancement method[2]	Use of coring devices[3]
Thin-wall (Shelby) samplers: commonly 1.5- to 3-inch outside diameter; can be as large as 5-inch diameter.		
Standard open tube sampler (also Denison, Pitcher, and Ring-lined barrel with thin-wall extension samplers)	Drive, push, vibration, and drill rod	Applications • Undisturbed cores in cohesive sands, silts, and clays above the water table for physical and hydraulic testing; use Denison for dense materials and Pitcher for weathered rock. • Analyses of all chemical constituents—use of liner recommended. • Geologic logging. Limitations • Poor core recovery in saturated, cohesionless, gravelly, or very soft unconsolidated materials. • Standard Shelby can require driving to penetrate dense materials, and cause sample disturbance—therefore, use Denison or Pitcher sampler for dense materials.
Piston sampler (includes fixed-piston types and free or semifixed piston)	Push and drill rod	Applications • Representative samples in saturated, cohesionless, and soft unconsolidated materials. • Reduces contamination from drilling mud or borehole material (core barrel is sealed until sampler is in sampling position). • Prevents sample contamination from ground water (free-piston). • Retains loose materials better than open tube because of vacuum created by the piston. Limitations • More time consuming than open-tube samplers. • More complex construction increases possible malfunction.
Thick-wall samplers: commonly 2- to 3-inch outside diameter; can be as large as 5-inch diameter.		
Solid barrel and split barrel sampler (split barrel or "spoon" is the most common type)	Solid barrel: drive, push, vibration, drill rod, and wireline Split barrel: drive, push, drill rod, and wireline	Applications • Cohesive unconsolidated materials (for soft clay, thin-wall extension is needed). • Analyses for texture, mineralogy, chemistry. • Standard penetration test for engineering properties. • Excellent geologic logs when barrel diameter exceeds 3 inches (used with continuous hollow-stem-auger). • Use of liner possible. Limitations • Not for analyses that require an undisturbed sample. • Recovery and quality of geologic samples below water table can be problematic.

Table 14. *Type, advancement method, and use of selected coring devices--Continued*

Coring device (sampler)[1]	Advancement method[2]	Use of coring devices[3]
Rotating core sampler.		
Single tube and double tube sampler	Single tube: rotation, drill rod, and wireline Double tube: push, rotation, drill rod, and wireline	Applications: • Single tube: consolidated materials; continuous cores for visual description. • Double tube (swivel type): undisturbed cores in friable, soluble, or highly fractured rock for laboratory tests and analyses of physical and hydraulic properties, chemistry, and mineralogy. • Use of split liner recommended. Limitations: • Not used, generally, in unconsolidated materials. • Drilling fluids can alter physical and chemical properties of sample (especially for single-tube samplers). • Physical and hydraulic properties can be altered using vibration and rotation advancement methods. • In situ moisture content is altered using air rotary method.
Sidewall core sampler: commonly 13/16 to 1 inch diameter, 1 3/4 inch length.		
(see also Pitcher and Denison samplers, under thin-wall samplers)	Wireline	Applications: • Samples collected from the sidewall of borehole. • Used to correlate lithologic and geologic logs with cuttings at selected depth interval, or with fractures or other structural features.

[1] Numerous core samplers are available that are variants or operate on different principles from those shown on this table. For information on specialized samplers and equipment, refer to O'Rourke and others (1978).

[2] Refer to description of drilling methods.

[3] Refer to table 13 for a description of the terms **undisturbed**, **representative**, and **nonrepresentative** as they relate to the quality of geologic samples.

method can affect the representativeness of the sample, and selection of a coring device requires consideration of the following:

- The coring device selected should be suitable for the geologic materials to be encountered, and limit the degree of sample disturbance to that needed to achieve the desired sample quality.
- In general, thin-wall and rotating double-tube swivel core samplers minimize the degree of sample disturbance.
- The degree of sample disturbance increases with (1) increases in sampler-wall thickness, (2) decreases in the diameter of sampler tube, and (3) increases in the length of sampler tube.
- Depending on the material being sampled, the same sampler can cause different degrees of disturbance; for example, the hydraulic conductivity of clays or silts that are compressible can be decreased compared with that of granular materials.
- Driving the sampler can disturb a sample more than pushing the sampler.
- Open thin-wall and thick-wall samplers can cause cross contamination of soil samples by including material from a higher interval with that from a lower interval. Piston samplers better isolate the sample from contamination above and below a water table than open thin-wall and thick-wall samplers.

Most drilling or other borehole construction methods provide the option to collect either continuous or intermittent cores. Except for continuous sampling with a hollow-stem auger, continuous core sampling takes more time and therefore is more expensive than intermittent sampling.

Liners used in coring devices usually are needed when undisturbed samples will be used for laboratory measurements of hydraulic or physical properties and for sensitive chemical constituents. Liners can provide a convenient receptacle for the preliminary logging or storage of cores of unconsolidated materials. Accurate logging, however, requires removal of the cores from the liners and examination of the core interior. Liners are available in a variety of materials. Plastic liners are excellent for cores collected for chemical analysis of nonsensitive chemical constituents. Stainless steel or brass liners are recommended if volatile organic compounds will be analyzed (Lewis and others, 1991).

Drill Cuttings

Two types of sampling devices used to collect cuttings are borehole grab samplers and sidewall grab samplers. Borehole grab samplers have rotating cutting heads that destroy the structural features of the sample and cuttings from various drilling methods. Borehole grab samplers also are used with solid-stem augers to clean out loose cuttings before core sampling ("spoon" sampler) and with drill rigs used to sample gravels and sands ("window" sampler). Sidewall grab samplers are used to retrieve materials scraped from the side of a borehole (Morrison, 1969; Shuter and Teasdale, 1989). Augers that retain the cuttings inside the device rather than on its surface also are considered borehole grab samplers and include barrel augers and bucket augers (USACE, 1972). Without casing advancement, use of augers can result in contamination of samples.

All drill cuttings are disturbed and nonrepresentative samples and therefore are unsuitable for meeting many of the sampling objectives listed on table 12. In some cases, for example if a casing is advanced during borehole construction, samples of drill cuttings could be considered representative because properties determined using the sample accurately represent properties of the geologic material at a known depth. Drill cuttings can be used to determine such properties as grain size distribution, mineralogy, stable chemical constituents, and geology if a casing advancement method is used and cuttings are collected incrementally.

Well Construction

This section is intended as a guide to aid project personnel in preparing for well construction[6] and in the selection of a well-construction method appropriate to the need of the study. To provide this guidance, information is presented on (1) preconstruction preparations, (2) method-selection considerations, and (3) applications and limitations of specific well-construction methods.

Selection of the construction method requires an understanding of site characteristics and the potential of the method to result in subsurface contamination from the use of drilling fluids, as well as knowledge of equipment limitations. No single method is available that can be universally recommended as "best" for all water-quality studies. It is necessary to review references on well drilling and other well-construction methods[7] and consult manufacturers of well-installation equipment for more detailed information. An experienced well driller should be consulted to select the construction method most appropriate for (1) existing site conditions and aquifer characteristics and (2) study data-collection objectives.

GUIDELINE: A DRILLING METHOD THAT TEMPORARILY CASES THE BOREHOLE AND AVOIDS USE OF A DRILLING FLUID REDUCES POTENTIAL AQUIFER CONTAMINATION.

Monitoring wells should not be constructed without an understanding of the ambient geohydrologic site conditions. Advance knowledge of subsurface conditions and characteristics (including stratigraphy, geology, hydrogeology, and zones of con-

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[6] The term "**well construction,**" as used in this report, refers to the process of creating a borehole from which ground water will be withdrawn for water-monitoring purposes. The borehole can be constructed as a fully cased, partially cased, or uncased well, with either screened or open sample-collection intervals, and can be a permanent or temporary installation.

[7] Driscoll (1986) and Ruda and Bosscher (1990) describe in detail drilling methods commonly used in the water-well industry. Shuter and Teasdale (1989) describe drilling methods most commonly used for USGS investigations in quantitative ground-water hydrology. U.S. Geological Survey (1977) provides a synopsis of rotary and cable-tool drilling methods and cites references that provide more information about each method. Hodges and Teasdale (1991) discuss drilling methods appropriate for borehole geophysical logging. ASTM (1992, 1995) describe methods for the installation of monitoring wells. National Council of the Paper Industry for Air and Stream Improvement, Inc. (1981), Korte and Kearl (1985), Keely and Boateng (1987a), and Aller and others (1989) also describe methods for the installation of monitoring wells. Dumouchelle and others (1990) provide a literature survey of information on well installation and sample-collection procedures used in investigations of ground-water contamination by organic compounds.

tamination) at the well site is required in order to determine the best areal placement of the well and the depth of the well screen. For many studies, especially those concerned with delineating or tracking a contaminant plume, detailed screening of the site is an important and cost-effective strategy to help determine the location of permanent wells that will yield useful data. Increasingly, this is being achieved using technologies associated with direct-push systems and includes exploratory coring, in situ water-sample analysis, and determination of hydraulic characteristics using a cone penetrometer (see "Direct-push systems"). For the purpose of this report, it is assumed that the study will have collected the information necessary for appropriately locating the well and the well network in three-dimensional space (table 1).

Preconstruction Preparations

Routine preparations, such as those listed below, are necessary to smooth and successful field operations. The following preparations are required before well construction begins:

- A drilling contract and permits from State and local agencies must be obtained. It is wise to obtain expert—possibly legal—advice and oversight for drawing up the drilling contract. The drilling contract should include any special instructions necessary to ensure compliance with study plans and regulatory mandates.
- Specific instructions regarding well-construction practices and protocols that are to be implemented to avoid, control, and reduce potentially adverse effects to sample quality or to the environment need to be identified and included in the drilling contract and field folder. Three examples of important practices are that (1) engine exhaust from the drill rig should be directed away from compressor intakes or exhausts if volatile organic compounds or polyaromatic compounds will be analyzed in samples; (2) precautions must be taken to prevent spilling fuel, oil, or other engine fluids; and (3) drilling fluids should be contained and not spilled on site.
- Utility companies must be contacted to determine the location of buried power and telephone lines, as well as sewer, water, and gas lines. Before drilling, for the safety of all field personnel as well as of the immediate community, the field site must be clearly marked for the location of power, telephone, sewer, water, and gas lines and cables.
- Plans that comply with Federal, State, and local regulations must be written for well installation and for disposal of solid and liquid wastes. If drilling in contaminated areas, special arrangements and procedures could be required for the proper storage and disposal of drilling fluids, geologic materials brought to the surface, and ground water. Such requirements should be included in the drilling contract.
- Equipment must be clean: Drill rigs, augers, well casing and screens, as well as other well-construction equipment are cleaned before field work begins (see "Decontamination of Equipment and Materials"). Decontamination procedures need to be documented on the well-construction form (fig. 15, page 89).
- The field folder must be prepared with (1) specific instructions regarding well-construction practices and protocols, and (2) the appropriate site information, documents, and well-installation forms (see "Supporting Documentation"). Field records are kept by the well-construction and scientific field teams of the methods, equipment, and procedures used, and of the ambient geohydrologic materials and conditions observed. The forms used for well construction (fig. 15, page 89) are placed in the field folder before leaving for the construction site.

Method-Selection Considerations

The primary criterion for selecting a method of monitoring-well construction is that the effects on water chemistry will be minimal or readily removed through well development (see "Well Development"). Selecting a method that most minimizes subsurface contamination often is subject to practical and logistical considerations, related to site characteristics and equipment limitations. The considerations shown on table 15 pertain to concerns regarding aquifer contamination and protection (the use of drilling fluid and if the borehole can be temporarily cased as it is being drilled); site characteristics (equipment capability to penetrate various types of geologic materials); and equipment limitations (the maximum borehole depth and diameter, the ease of well completion without withdrawing construction equipment from the borehole, and the capability to collect cuttings or cores using a given method).

Table 15. *Summary of well-construction methods (drilling, direct push, and vibration)*

[Modified from W.E. Teasdale, USGS, written commun., 1996; 1 foot = 0.3048 meter; 1 inch = 2.54 centimeters]

Well-construction method[1]	Drilling fluid	Casing advance possible	Geologic materials (u, unconsolidated; R, consolidated; s, some restrictions apply—see text)	Borehole depth (in feet)[2]	Borehole diameter[3] (common range of sizes, in inches)	Well completion with filter pack and annular seal possible	Geologic samples obtainable from cuttings or return	Core samples possible
Hollow-stem power auger	None	Yes	U (slightly indurated)	less than 150	6 to 18	Yes	Yes	Yes
Solid-stem power auger	None	No	U (slightly indurated)	less than 150	2 to 10	Can be difficult	Yes	Yes
Power bucket auger	None	No[4]	U (slightly indurated)	less than 150[5]	18 to 48	Can be difficult	Yes	Yes
Hand auger (with/without power)	None	No[4]	U	less than 70[5]	2 to 6	Can be difficult	Yes	Yes
Direct rotary with water-based fluid	Water, mud	Yes	U, R, (s)	at least 1,000	2 to 36	Yes	Yes	Yes
Wireline rotary	Water, air, foam	Yes	U, R	at least 1,000	3 to 6	Yes	Yes	Yes
Dual-wall reverse circulation rotary	Water, air, mud, foam	Yes	U, R	at least 1,500	12 to 36	Yes	Yes	Yes
Reverse rotary: with water-based fluid; with air assistance	Water, mud, air, foam	Yes	U, R, (s)	less than 2,000	12 to 36	Yes	Yes	Yes
Air rotary: Direct rotary air and down-the-hole air hammer; with casing driver[6]	Water, air, foam	Yes	U,R	less than 2,000	4 to 16	Yes	No[7]	Yes
Cable tool	Water	Yes	U, R	approx. 5,000	6 to 8	Yes	Yes	Yes
Jet wash and jet percussion[8]	Water	No	U	less than 50	2 to 4	No	Yes	No
Direct push[9]	None	No	U	less than 100[9]	0.5 to 4	No	Yes	Yes
Vibration	None, water, air	Yes	U, R	approx. 500	4 to 12[3]	Yes	Yes	Yes

[1] Refer to text and tables 16-22 for more information on drilling methods and method-selection considerations and procedures. Refer to Conversion Factors table for conversion of English units to metric units.

[2] Depths can be greater than shown, depending on site conditions and equipment used (for example, large, high-torque auger rigs can reach depths exceeding 300 feet under favorable site conditions).

[3] Borehole diameters achievable can differ, and can be larger than indicated for some methods, depending on site conditions, equipment used, and the application intended. For vibration drilling, the optimum diameter is 8 in or less; with diameter of 10 inches or greater, borehole depth is limited to approximately 100 feet.

[4] Casing (culvert for bucket auger) advance is not routine but possible if needed for special applications.

[5] Above water table only. Below water table, borehole must be kept full of drilling fluid.

[6] Casing-driver systems are used in combination with rotary rock bits or down-the-hole hammers for penetrating consolidated and difficult unconsolidated (cobbles and boulders) materials; penetration depth usually is limited to approximately 300 feet.Wells can be completed through the advanced casing and cores and cuttings collected.

[7] Coring is possible in combination with additional equipment and methods.

[8] Jet wash/jet percussion methods are not recommended for water-quality monitoring wells.

[9] Some direct-push systems allow for backfilling and sealing the well; for example, the double-tube system. Depth is less than 50 feet for driven wells.

Additional considerations that influence selection of the well-construction method include:

- Requirements inherent in the chemical constituents targeted for sampling, their anticipated concentrations, and the accuracy needed to meet study objectives.
- The type of well or sample-collection network—for example, multiport wells (see "Well Design").
- Plans to collect data other than water quality, as previously discussed under "Considerations when collecting hydraulic, geophysical, and geologic data."
- The geological, hydrological, chemical, and physical characteristics of the site.
- Compliance with regulatory and funding agency requirements. (The specific drilling method or allowable alternatives could be dictated by other agencies; for example, if data collected must address regulatory concerns, or if water from the well will be used for consumption, in which case the National Sanitary Foundation lists acceptable drilling fluids.)

Methods that temporarily case the borehole as well construction proceeds and those that avoid use of drilling fluid and lubricants reduce the potential for long-term contamination of ground water (table 15). Temporary casing of the borehole precludes or reduces: the invasion of drilling fluid into the borehole wall; the loss of circulation in porous materials; and the uncertainty of whether the aquifer-material and ground-water samples originate from the aquifer being drilled rather than from elsewhere along the borehole. Ground-water chemistry is affected by well construction through (1) cross contamination between aquifers by drilling fluids and lubricants, pore water, and drill cuttings; and (2) the possibility of drilling-fluid contamination of subsurface units and pore water. Nevertheless, selecting a construction method that employs drilling fluids and (or) lubricants is often necessary. If such a method is selected:

- The drill team should include a mud engineer. The mud engineer can implement procedures to minimize invasion of drilling fluid into the borehole wall (see "Drilling Fluids").
- Collection and chemical analysis of ground-water samples during well development can be used to screen for and identify compounds introduced by drilling fluids and lubricants during well construction.

Site characteristics

Site characteristics can place restrictions on the use and implementation of well-construction methods. Selection of the well-construction method best suited for the field site requires, in part, (1) an evaluation of available information about or from near the site (possibly from nearby wells), and (2) reconnaissance of the field site.

Much of the information used for site evaluation has been described earlier in this report (see "Site Inventory"). Sources of available data that could be useful for site evaluation include borehole and other geophysical surveys, well data bases, topographic maps, aerial photography, satellite imagery, information from reconnaissance drilling, geologic and water-resource maps and reports, state or county soil surveys, mineral resource surveys, reports of subsurface investigations of nearby or adjacent investigations, and local utility company records. Local drillers often are a useful source of information.

Reconnaissance of the field site is needed to evaluate access to the site and conditions for using the equipment, as well as to formulate and verify an initial concept of geohydrologic conditions. Surface geophysical surveys and direct-push methods for geologic-materials and ground-water data collection can be cost-effective and useful for site evaluation and for planning the location of permanent well installations, detecting the presence of toxic or hazardous materials, and gaining preliminary insight on hydraulic and geologic site characteristics (Benson and others, 1984; Haeni, 1988; Boulding, 1993; J.A. Farrar, U.S. Bureau of Reclamation, written commun., 1996).

Drilling fluids

Method requirements and subsurface characteristics can dictate the need to use a drilling fluid, and some drilling methods require specific types of fluid (table 15). A drilling fluid is defined by Driscoll (1986, p. 887) as a "water- or air-based fluid used in the water-well drilling operation to remove cuttings from the hole, to clean and cool the bit, to reduce friction between the drill string and the sides of the hole, and to seal the borehole." The hydrostatic head of the drilling fluid maintains pressure on the borehole wall and prevents its collapse. Water-based drilling muds build a filter cake or rind on the borehole wall. This exerts a positive hydrostatic pressure against the borehole wall, preventing inflow of ground water into the borehole. It also helps maintain borehole stability, which helps to prevent invasion of the fluid into the borehole wall (fig. 7) and reduce cross contamination between aquifers. During drilling, a mud engineer should be present to monitor drilling-fluid viscosity and circulation pressure and to implement the procedures needed to minimize invasion of drilling fluid into the borehole wall and avoid causing fractures in the geologic material (W. E. Teasdale, USGS, written commun., 1996). With proper control, drilling mud should only penetrate the borehole to 0.25 in. (about 0.64 cm), making subsequent well development relatively easy.

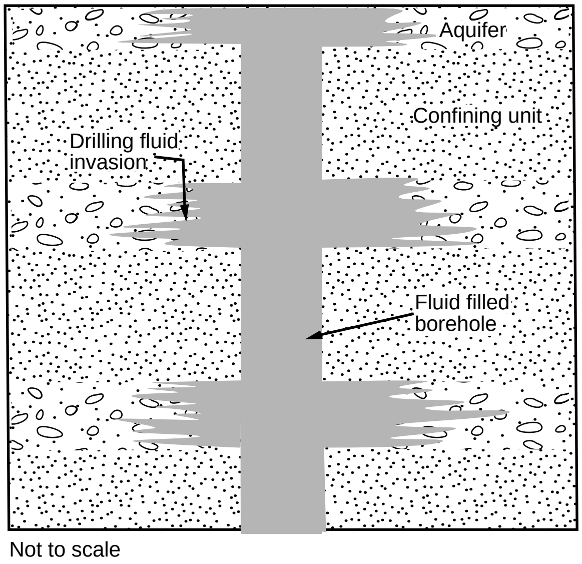

Figure 7. *Invasion of drilling fluid into adjacent aquifers.*

Common drilling fluids include potable water; water with additives either of clay (usually bentonites or "mud"), clay mixtures (amended bentonite), bentonite, or polymers (chemical foams); and compressed air. Some bentonite drilling additives contain petroleum or other organic compounds, and some drillers add diesel fuel to bentonite. Additives modify fluid characteristics (such as density or viscosity) in order to address a change in borehole or geologic conditions during drilling. The chemical composition of unamended bentonite is discussed under "Well Completion." Drilling additives in contact with potable-water aquifers must meet the requirements of National Sanitary Foundation (NSF) Standard 60-1988. Compressed air introduced into the drill stem also can be used to enhance circulation of the drilling fluid and can help move cuttings to the surface (Driscoll, 1986, p. 291), but must be filtered adequately to avoid introducing significant quantities of oil (ASTM, 1995b, D-5782-95).

Residues from drilling fluids can alter sample chemistry. Potential effects on water chemistry from "pure" (unamended) bentonite result primarily in changes in the major ion chemistry of ground water from the well (Aller and others, 1989, p. 104). If well development has insufficiently removed residues of bentonitic drilling fluids, the exchange of cations in the clay matrix with possible organic and inorganic constituents occurring in ground water could result in data showing lower or higher constituent concentrations. Other effects of drilling-fluid contamination on ground water can be indicated by elevated concentrations of sulfate, chloride, phosphate, and organic carbon; metals; sorbed organic compounds; an altered cation exchange capacity, pH, and chemical oxidation demand (Claassen, 1982; Keely and Boateng, 1987a, p. 301; T.E. Imbrigiotta, USGS, written commun., 1991). Polymeric drilling fluids contain organic compounds that enhance biologic degradation of the drilling fluid (Aller and others, 1989, p. 104), but this biologic activity can cause long-term variations in the chemistry of ground-water samples that could be difficult to reverse.

The drilling fluid must be removed after drilling. A poorly designed and improperly controlled drilling-fluid process results in invasion of mud to geologic materials that can cause damage to the borehole and to cores (W.E. Teasdale, written commun., 1996), as well as affecting the chemical composition of ground-water samples collected from the well (Claassen, 1982, p. 11). If a proper mud-control program is not implemented, fluid removal can involve an intensive and repetitive effort during well development (Claassen, 1982).

Lubricants

Some well-construction methods require equipment lubrication (table 15). Lubricants introduced to the subsurface can affect the chemistry of samples obtained from the borehole or well, and their use must be documented. Drilling methods that require air compressors most often require oil lubrication. Oil-free compressors usually are only available if special arrangements have been made. Use of high-efficiency, in-line filters in the compressor intake and discharge ports also can reduce downhole contamination from oil, but does not prevent it. Use of lubricants often can be avoided or minimized by a skilled driller. Synthetic lubricants, such as Teflon, can be selected that produce distinct identifying GC/MS signatures (J.A. Farrar, written commun., 1996).

Description of Well-Construction Methods

Applications, limitations, advantages, and disadvantages of various drilling and other well-construction methods are summarized in this section in relation to their use for environmental studies in general and water-quality studies in particular. The methods described include auger, rotary, and cable-tool drilling; heavy-duty casing drivers used in conjunction with rotary drilling; jet and jet percussion drilling; and direct push and vibration systems.

The suitability of a construction method depends on study- and site-specific characteristics, such as the nature of geologic materials encountered (unconsolidated, partly consolidated, or consolidated) drilling depth, data-collection objectives, and equipment limitations. Different construction methods cause different degrees of mechanical damage and possible contamination to aquifers in the vicinity of the borehole (Aller and others, 1989, p. 231; Shuter and Teasdale, 1989, p. 85). The degree of mechanical damage can affect the quality of geologic samples and depends on the materials being drilled, in addition to the drilling and sampling methods employed (see “Geologic Materials”). The degree of chemical contamination affects the quality of water samples (see “Drilling Fluids” and “Lubricants”). Well-construction methods that temporarily case the borehole during well construction and that control or avoid penetration of a drilling fluid into subsurface materials are preferable for water-quality studies.

Logs are kept during well construction by the driller and study geologist or hydrogeologist (fig. 15, page 89). The driller's log is a field record that describes the general types of materials observed, their depth intervals, general water-bearing characteristics and other properties of the ground-water system, and major well-construction details. The driller also should keep a record of drilling-equipment response, drilling rate, borehole stability, loss or gain of drilling fluid in the borehole, and changes in drilling-fluid temperature and conductivity (Driscoll, 1986; Shuter and Teasdale, 1989). The study geologist or hydrogeologist ordinarily prepares a detailed description of subsurface materials by constructing a lithologic log and (or) geologic log and well-completion diagram (fig. 16, page 91), which is generated from direct observation, geologist’s log, driller’s log, borehole-geophysical logs of physical, chemical, and mineral properties, and laboratory analyses.

Auger drilling

Power augers used for drilling wells include (1) hollow-stem, continuous-flight augers; (2) solid-stem, continuous-flight augers; and (3) bucket augers (tables 16a-c). Hand augers can be manual or power assisted (table 16d).

Auger-drilling methods usually are limited to drilling through unconsolidated or partly consolidated material. The borehole is advanced by pushing and rotating at low velocity the initial auger-column assembly into the ground. As drilling proceeds, auger flights (or kelly rods, when buckets are used) are added to the drill stem. The continuous auger flights carry drill cuttings to the surface. Auger methods normally do not use a drilling fluid. However, auger drilling tends to plaster fine-grained material encountered during drilling onto the borehole wall as cuttings are transported upward by the auger flights. Oil or grease commonly are used to aid separation of the auger flights during their removal from the borehole. These lubricants can bias analyses of organic compounds. Teflon lubricant is a common alternative to oil or grease. Alternatively, lubricant can be avoided entirely by inserting a string (“wicking”) between the flights to aid in their separation after drilling.

The hollow-stem auger is preferred for construction of shallow (<150-ft or ~45-m deep) monitoring wells because no drilling fluid is used and samples of unconsolidated materials (or ground water) can be collected as drilling progresses. Hollow-stem augers are equipped with core barrels for collecting continuous samples of unconsolidated materials. Collection of cores with an auger system is a more rapid and efficient sampling method than other methods of coring or sampling.

Auger drilling using a screened hollow-stem system is designed to allow analysis of water or gas samples for target constituents during drilling. Collection of real time data allows for accurate placement of the well screen at the desired depth based on water chemistry (see also “Direct-push systems and vibration drilling”). Information and procedures for screened hollow-stem auger drilling are available from U.S. Department of Energy (1994).

Rotary drilling using water or water-based fluid

In this section rotary drilling methods using water with or without mineral and chemical additives are grouped together and include direct rotary (also called forward rotary), reverse and dual-wall reverse

Table 16a. *Auger drilling: hollow-stem continuous-flight power auger*

[1 foot = 0.3048 meter; 1 inch = 2.54 centimeters]

Hollow-stem power-auger drilling pushes and rotates auger flights through geologic materials and serve as a temporary casing through which well casing and screen can be installed (Comment 1).

Applications	Limitations
• Drilling in unconsolidated materials, and weathered, and soft or partly consolidated rock units. • Continuous coring of geologic materials is possible through a hollow stem; for example, split-barrel or thin-wall samplers (Comment 2). • Geologic materials are returned as cuttings and on auger flights. • Ground-water samples can be collected during drilling using a screened hollow-stem auger method (Comment 2). • Estimate of depth to water table. • Lithologic logging (cuttings or cores) or geologic logging (from cores).	• Drilling is difficult in saturated, unconsolidated materials; in units that contain very coarse gravel, cobbles, or boulders, or in very dry, fine materials (for example, playa-lake deposits) • Borehole is limited to depths generally less than 150 feet. • Precise depth of origin of samples returned by auger flight or cuttings is difficult to determine. • Maximum borehole diameter is to about 18 inches.

Advantages	Disadvantages
• Precludes use of fluids during drilling under most circumstances (Comment 3). • Hollow-stem auger acts as a casing and facilitates installation of well casing and avoids contamination of hydrogeologic units (Comment 1). • Continuous samples of ground water can be collected during drilling by using the screened-auger method (Comment 2). • Use of lubricants can be avoided. • Drilling is moderately rapid. • Equipment is relatively mobile and widely available. • Method relatively inexpensive.	• Heaving of saturated sands into augers during drilling can be a problem (often it is necessary to wash out materials that have surged or been forced up into the hollow stem during drilling). • Cross contamination of ground water between zones along borehole wall can occur by upward vertical mixing of ground water or cuttings.

Comments

1. Hollow-stem augers are more effective than solid-stem augers for well construction because the hollow auger flights serve as a temporary casing to prevent caving and sloughing of loose borehole materials. The temporary casing also prevents cross contamination among hydrogeologic units.

2. Geologic materials cannot be sampled if the screened hollow-stem method is used. Direct-push methods such as hydropunch can be used in front of auger drilling during pauses in drilling to collect samples of water or geologic materials.

3. In cases where water-bearing silts or sands are penetrated, the addition of water or drilling mud to the hollow-auger column might be needed to inhibit piping of these materials into the auger flights.

Table 16b. *Auger drilling: solid-stem, continuous-flight power auger*

[1 foot = 0.3048 meter; 1 inch = 2.54 centimeters]

<table>
<tr><td colspan="2">Solid-stem, continuous-flight power-auger drilling is a rapid and effective method for drilling materials for which borehole collapse is not a problem (Comment 1).</td></tr>
<tr><th>Applications</th><th>Limitations</th></tr>
<tr><td>• Drilling in unconsolidated materials, and weathered, and soft-rock units (Comment 1).
• Geologic materials are returned as cuttings and on auger flights (Comment 2).
• Estimate of depth to the water table.
• Lithologic logging from cuttings (Comment 2).</td><td>• Presence of cobbles or boulders can result in “auger refusal,” and impede or halt drilling. Difficult drilling in very dry, fine materials (for example, playa deposits).
• Borehole is limited to depths generally less than 150 feet in geologic materials not subject to collapse.
• Cuttings are not always returned by augers. Cuttings returned on the auger flight may not be representative of the aquifer at the depth interval targeted.
• Casing diameter generally is limited to 5 inches or less; auger diameters available up to about 14 inches.</td></tr>
<tr><th>Advantages</th><th>Disadvantages</th></tr>
<tr><td>• Precludes use of drilling fluids.
• Use of lubricants can be avoided.
• Drilling is moderately rapid.
• Equipment is relatively mobile and widely available.
• Method is relatively inexpensive.</td><td>• Casing cannot be advanced (Comment 1).
• Borehole can collapse before well is set (Comment 1).
• Filter pack and annular seal may be difficult to emplace because of borehole collapse or irregularly shaped borehole.</td></tr>
<tr><th colspan="2">Comments</th></tr>
<tr><td colspan="2">1. A casing is installed in the open borehole after pulling the auger flights from the borehole. Under saturated conditions, a borehole usually will collapse upon auger removal; sometimes it is possible to push the casing through the collapsed materials by using drill-rig hydraulics while rotating the casing with a wrench.
2. Use of a split-barrel or thin-walled sampler is possible, provided the borehole does not collapse. For each sample, the entire string of auger flights is pulled out of the borehole and the sampler is driven through the bottom of the borehole.</td></tr>
</table>

Table 16c. *Auger drilling: power bucket auger*

[1 foot = 0.3048 m; 1 inch = 2.54 centimeters]

Power bucket auger drilling produces a large-diameter borehole; a drill rig with a bucket attached to a Kelly bar rotates and pushes the bucket into the ground.	
Applications	**Limitations**
• Drilling in unconsolidated materials, and weathered, and soft-rock units. • Geologic materials are returned as a mixture of cuttings in the bucket. • Accurate estimate of depth to the water table. • Installation of multiple sensors or multiple monitoring wells in a single borehole (Comment 1). • Lithologic logging (from cuttings).	• Drilling is confined to unconsolidated or partly consolidated materials without boulders. • Borehole is limited to depths generally less than 150 feet in geologic materials not subject to collapse and above the water table (Comment 2). • Maximum borehole diameter is about 4 feet.
Advantages	**Disadvantages**
• Precludes use of drilling fluids, under most circumstances (Comment 2). • Use of lubricants can be avoided. • Equipment is mobile. • Drilling is moderately rapid. • Method is relatively inexpensive.	• Casing cannot be advanced. • Cross contamination of ground water along borehole wall can occur. • Borehole collapse can occur during augering, particularly when borehole is below the water table or in poorly cohesive materials. • Heavy equipment required.
Comments	
1. Examine considerations under “Well Design” before deciding to construct several wells in a single borehole. 2. Drilling in sand below the water table is difficult, but not impossible, if hole is kept full of water or a water-based drilling fluid.	

Table 16d. *Auger drilling: hand auger, with or without power assistance*

[1 foot = 0.3048 meter; 1 inch = 2.54 centimeters]

Hand-auger drilling is a relatively laborious method of turning and pushing a hand-auger barrel attached to short extension rods into the ground either manually or with the assistance of a small electric or gasoline power unit. The auger is removed from the borehole when the auger head is full of geologic materials, the auger head is emptied, and the process is repeated (Comment 1).

Applications	Limitations
• Drilling in shallow, unconsolidated materials that maintain cohesiveness—for example, organic soils, clay, silt, and sand (Comment 2).	• Drilling is impeded in stiff clays or poorly sorted sands and is difficult to impossible in materials containing appreciable coarse gravel, cobbles, boulders, or in cemented or compact materials such as caliche or roots.
• Geologic materials returned in auger head (Comment 3).	• Hand auger without power assistance: drilling limited to depths of about 10 to 15 feet in geologic materials not subject to collapse.
• Accurate estimation of depth to water table (Comment 4).	• Hand auger with power assistance: drilling limited to depths up to about 70 feet in geologic materials not subject to collapse.
• Lithologic logging (from materials in auger head).	• Maximum borehole diameter is about 6 inches.

Advantages	Disadvantages
• Avoids use of drilling fluids.	• Casing cannot be advanced.
• Use of lubricants can be avoided.	• Borehole subject to collapse during augering, particularly when borehole is below the water table or is in poorly cohesive materials.
• Equipment is highly mobile and widely available (Comment 5).	
• Generally is considered the least expensive drilling method.	• Hand augering is very labor intensive; power assistance lessens labor requirements.

Comments

1. The auger head is emptied by tapping on it using a rubber mallet so as not to damage the auger head.
2. Successful hand augering requires maintaining an open hole; thin-walled casing can be used to case the borehole as the auger is advanced.
3. Sampler barrels can be used to obtain geologic materials from the open hole after auger assembly is removed.
4. A common procedure is to auger to the water table, remove the auger, and then drive a well point several feet below the water table.
5. Permits easy access and use in remote study sites where drill-rig access is difficult because of topographic, environmental, or other logistical concerns.

SAFETY NOTE: Heat generated from friction between auger flights and earth materials can enhance volatilization of organic compounds. If present, exposure to volatile organic compounds rising from the well during augering **can pose a health hazard** to personnel leaning over the borehole.

rotary, and wireline rotary drilling (tables 17a-d). Direct air-rotary drilling is classified separately under air-rotary drilling (Ruda and Bosscher, 1990). A common rotary drilling technique is to combine mud- and air-rotary drilling: first mud is circulated while drilling through the unconsolidated units; then air is used when consolidated or partly consolidated materials are encountered (Driscoll, 1986, p. 295). Reverse-circulation drilling sometimes uses air to assist with the process, but not as the primary fluid. Casing drivers can be fitted to rotary rigs to drill the borehole and drive casing simultaneously (see "Air-rotary drilling and casing-driver systems").

Most rotary drilling is accomplished with a drill rig by rotating and applying axial pressure on a drill string and bit, while maintaining circulation of a drilling fluid. Water-based drilling fluids serve to cool and lubricate the drill bit. The drilling fluid carries cuttings from the drilling operation to land surface. The drilling fluid is recirculated after being discharged to a pit or series of pits or a mechanical desilter, where the cuttings settle and (or) are separated from the fluid.

- In direct-rotary drilling, water is mixed with bentonite and other viscosity-building additives to produce the drilling fluid ("mud") needed to remove drill cuttings. The drilling fluid is circulated down the inside of the drill stem, out the drill bit, and back up the annulus formed between the drill stem and borehole wall.
- In reverse-circulation rotary drilling, additives seldom are mixed with water to increase viscosity, but low concentrations of polymer additives are added occasionally to reduce friction and water loss. Water loss can become a significant problem in permeable materials (Ruda and Bosscher, 1990). The drilling fluid is circulated down the annulus formed between the borehole wall and the drill stem and up the inside of the drill stem (Dricoll, 1986, p. 291; Ruda and Bosscher, 1990, p. 4-12). The reverse-circulation rotary drill rig can produce larger boreholes compared to direct-rotary drilling.
- Dual-wall, reverse-rotary drilling utilizes an outer tube that acts as a temporary casing during drilling. For some well construction, a third casing is driven over the dual wall prior to removing the dual wall string. Circulation of drilling fluid is contained between the two walls of the dual-wall pipe or casing and only contacts the borehole walls near the bit.
- Wireline-rotary drilling uses a drilling rod with an enlarged inside diameter. The outer large-diameter drill rod acts as a temporary casing. Fluid circulates between the borehole wall and the outer rod, and is focused at the drill bit. This can cause greater borehole damage than other rotary methods unless circulation pressure and drilling-fluid volume and viscosity are carefully monitored and maintained.

Air-rotary drilling and casing-driver systems

Air is used as the primary drilling fluid in two direct rotary methods: direct air rotary and down-the-hole air hammer (table 18) (Ruda and Bosscher, 1990, pp. 4-12—4-14). Either method can be combined with a casing-driver system.

- In direct air-rotary drilling, the air stream cools the drill bit and delivers cuttings to ground surface. The air is forced down the drill pipe using a large compressor. Chemical additives, such as foam surfactant, can be added to the air stream to increase efficiency. Direct air-rotary drilling is effective for hard to softer consolidated materials, such as quartzite, schist, limestone, sandstone, and shale.
- Down-the-hole (DTH) air hammer systems circulate air through the bit face and up the casing, reducing contact with the borehole wall. Cuttings from the bottom of the hole can be collected when either air, or air with foam, are used as the drilling fluid. DTH hammers are operated with a pneumatic drill at the end of the drill pipe which strikes the rock rapidly while the pipe is rotated. Rotation of the bit helps achieve even penetration, which results in straighter holes. DTH require a rock-cutting oil-type lubricant that must be continuously introduced in the air stream to prevent seizure of the hammer bit from/due to heat and dust generated during its operation. Air compressors are most often used to power the casing hammer and to accomplish drilling-fluid circulation. DTH is especially effective for very hard consolidated material, such as basalt, granite, quartzite, and gneiss and is not effective in silty and clayey materials.
- The term "casing driver" is used in this report for direct air-rotary drilling that combines heavy-duty casing drivers with air-rotary and down-the-hole air hammer units (Rudda and Bosscher, 1990, use the term "drill-through-casing-driver" method). Casing-driver systems (such as ODEX) are heavy-duty

Table 17a. *Rotary drilling: direct rotary with water-based fluid*

[1 inch = 2.54 centimeters]

<table>
<tr><td colspan="2">**Direct-rotary drilling with water-based fluid** circulates a water-based drilling fluid through the inside of the drill stem that returns through the annulus (Comment 1). This method can be combined with simultaneously driven casing (Comment 2).</td></tr>
<tr><th>Applications</th><th>Limitations</th></tr>
<tr><td>• Drilling in unconsolidated materials, including bouldery till and coarse stratified deposits, and in consolidated materials (unlimited depth for environmental studies).
• Coring of unconsolidated and consolidated materials—for example, split-barrel, thin-wall, wireline, and other core-barrel samplers (Comment 3).
• Cuttings are returned in drilling fluid.
• Lithologic logging (from cuttings or cores) or geologic logging (from cores).</td><td>• Drilling is difficult in geologic materials with large boulders.
• Borehole diameter usually is 12 inches or less (maximum is about 24 inches).</td></tr>
<tr><th>Advantages</th><th>Disadvantages</th></tr>
<tr><td>• Casing advance can be used to minimize contamination (Comment 4).
• Borehole usually is accessible for geophysical logging before casing is installed.
• Annulus between well casing and borehole wall can be readily filter packed and grouted.
• Drilling is rapid and readily accomplished.
• Equipment is widely available.</td><td>• Drilling fluid can alter or contaminate ground water, circulating contaminants from one part of borehole throughout the borehole (Comments 1, 4).
• Drilling fluid penetration into the borehole wall can prevent complete development of the well.
• Lubricants used during drilling can contaminate subsurface materials.
• Location of water table and water-bearing zones during drilling can be difficult to detect, unless temporary casing is advanced.
• Circulation of drilling fluid often is lost or difficult to maintain in fractured rock or gravel units, unless temporary casing is advanced (Comment 4).
• Additional equipment needed to install well casing. Mobility could be limited.</td></tr>
<tr><th colspan="2">Comments</th></tr>
<tr><td colspan="2">1. The water-based drilling fluid usually is a water-bentonite mixture. Retention of drilling fluid in an aquifer can cause elevated concentrations of organic and inorganic constituents.
2. Direct-rotary drilling with a simultaneously driven casing enables drilling in materials that otherwise could collapse; eliminates the problem of lost drilling-fluid circulation; eliminates uncertainty regarding the originating depth interval of geologic materials.
3. Samples of consolidated materials are collected by casing through the overburden to allow passage of core sampler to the consolidated zone.
4. Use of a temporary casing minimizes the loss of circulation in porous materials and reduces cross contamination among hydrogeologic units.</td></tr>
</table>

Table 17b. *Rotary drilling: reverse circulation with water*

[1 inch = 2.54 centimeters]

Reverse-circulation drilling circulates water downward through the annulus, between the drill string and borehole wall, through the drill bit, and back up the inside of the drill string. Water without additives normally is used as the drilling fluid, occasionally with air to assist circulation (Comments 1, 2).

Applications	Limitations
• Drilling in unconsolidated materials and in soft consolidated materials (without depth limitation for environmental studies). • Can be used for large-diameter boreholes. • Samples of unconsolidated materials using split-barrel, thin-wall, wireline samplers. • Samples of consolidated materials using wireline or other core-barrel samplers. • Cuttings from return in drilling fluid.	• Drilling through cobbles and boulders and through igneous and metamorphic rocks may be difficult to impossible (Comment 3). • Well diameter generally is 8 inches or less. • Borehole diameter usually is 30 inches or less for environmental purposes.

Advantages	Disadvantages
• Disturbance to hydrogeologic units is minimized. • Borehole is accessible for geophysical logging before installation of casing. • Large-diameter borehole permits easy installation of well casing, filter pack, and annular seals between well and borehole wall. • Drilling is rapid and readily accomplished. • Equipment is widely available. • Method is relatively inexpensive.	• Large quantities of non-native water usually are required during drilling and can be a cause of contamination between depth intervals. • Use of air or other drilling fluids and additives can contaminate ground water and geologic materials and circulate contaminants found in one interval throughout the borehole. • Drilling fluid can result in additional well development effort. • Lubricants used during the drilling process can contaminate ground water and geologic materials. • Drilling equipment is large and heavy, making site access and mobility potentially difficult.

Comments

1. Air is used to enhance fluid circulation and help transport cuttings to the surface, but not as a primary drilling fluid. Drilling fluid can consist of clear water; water mixed with minor concentrations of clay or polymers; water and air; or water and air and minor concentrations of additives.

2. Bentonite clay is added to clear water only if it is needed to increase fluid density and viscosity in order to carry cuttings to the surface. Because of this, mud control and mud contamination is much less a concern than in direct-rotary drilling. Large volumes of non-native water are required, compared with direct rotary and are a potential source of contamination.

3. Cobbles can be removed with “clam shell” or “orange peel” equipment.

Table 17c. *Rotary drilling: dual-wall reverse circulation*

[1 foot = 0.3048 meter; 1 inch = 2.54 centimeters]

Dual-wall reverse circulation is an effective method for drilling water-quality monitoring wells because contamination and disturbance to the subsurface is reduced by the presence of a temporary casing in the borehole. Drilling fluid is circulated between the inner and outer (dual) walls and cuttings are returned through the inner tube (Comment 1).

Applications	Limitations
• Drilling in unconsolidated, partly consolidated, and consolidated materials. • Coring of geologic materials (split-barrel, thin-wall, and wireline samplers). • Cuttings are returned in drilling fluid: can identify originating depth. • Good yield estimates of water-bearing zones. • Lithologic and geologic logging from cuttings or cores.	• Depths from 1,200-1,400 feet in unconsolidated materials and to 2,000 feet in consolidated material (Comment 2). • Borehole diameter usually is 10 inches or less. • Casing diameter is 1 to 2 inches if installed through dual-wall casing. • Well diameter generally is 6 inches or less if a dual-wall drill stem is not used.

Advantages	Disadvantages
• Circulation of drilling fluid is contained within the dual-wall pipe. This reduces contamination among depth intervals and other problems (Comments 3 and 4). • Outer casing of dual-wall drilling pipe seals off contaminated intervals. • Outer casing of dual-wall drilling pipe prevents collapse of borehole wall during drilling. • Drilling is rapid and readily accomplished. • Equipment is widely available.	• Drilling fluids can cause subsurface contamination (Comments 3 and 4). • Lubricants used during the drilling process can contaminate ground water and geologic materials. • Borehole is not accessible for many geophysical logs. • Extraction of casing can cause smearing of borehole wall with silt or clay encountered during drilling. • Emplacement of filter pack and annular seals can be difficult.

Comments

1. Dual-wall reverse-circulation drilling has similar advantages to the casing-advancement techniques used in direct-rotary drilling: drilling is readily accomplished in unconsolidated materials that ordinarily would collapse during the drilling process or before casing installation (Driscoll, 1986, p. 302).

2. System works best to 600 feet but greater depths are achieved using booster compressors.

3. Use of a temporary casing minimizes the loss of circulation in porous materials. The casing seals off contaminated intervals, reduces cross contamination among hydrogeologic units, and prevents clogging of aquifer materials at the borehole. Temporary casing eliminates uncertainty of whether or not aquifer-material and ground-water samples originate from the hydrogeologic unit(s) being drilled rather than from elsewhere along the borehole.

4. The only contact of the drilling fluid with the borehole wall occurs near the drill bit. Drilling fluid can consist of air, air plus water, air plus water plus surfactants, or water with clay or polymers.

Table 17d. *Rotary drilling: wireline*

[1 inch = 2.54 centimeters]

Wireline rotary drilling uses special drilling rods with enlarged inside diameter and specially designed diamond or carbide bits. Wireline methods include direct rotary wireline with water-based fluid (Comment 1a) and casing advancement with or without air or other drilling fluids (Comment 1b).

Applications	Limitations
• Used primarily for drilling consolidated materials, but applicable for unconsolidated materials, including gravel and cobble deposits (unlimited depth for environmental studies). • Large-diameter casing allows borehole testing such as packer testing and geophysical logging at selected intervals (Comment 2). • Continuous coring (Comment 3). • If fluid is used, originating depth of cuttings can be identified. • Lithologic loggings (from cuttings or cores) or geologic logging (from cores).	• Drilling fluids and polymer additives are required under some conditions. • Borehole diameter is usually 6 inches or less (maximum diameter is about 24 inches).

Advantages	Disadvantages
• Large-diameter rods provide temporary casing for borehole testing or installation of well or other monitoring device. • Casing-advancement technique can be used to minimize contamination (Comment 1b). • Air can be used instead of water-based fluid for drilling consolidated materials. • Well casing can be installed through hollow wireline casing; annulus between well casing and borehole wall can be filter packed and sealed. • Drilling is rapid and readily accomplished.	• Drilling fluid and polymer additives can alter or contaminate ground water, circulating contaminants from one part of borehole throughout the borehole (Comments 1, 3). • Plugging or hydraulic fracturing of borehole wall can occur if drilling rate is too rapid or the circulating air pressure is increased excessively. • Drilling fluid use can hamper or prevent complete development of the well. • Circulation of drilling fluid often is lost or difficult to maintain in fractured, weathered, or extremely porous units, unless casing is advanced). • Drill bit can be sandlocked or plugged in saturated cohesionless materials.

Comments

1a. Direct rotary wireline drilling with water-based drilling fluid is applicable if fluid circulation can be maintained. The water-based drilling fluid usually is a water-bentonite mixture. Retention of drilling fluid in an aquifer can cause elevated concentrations of organic and inorganic constituents.

1b. Casing-advancement wireline drilling enables high penetration rates in all types of consolidated and unconsolidated materials, prevents borehole collapse, minimizes the loss of circulation in fractured or porous materials, seals off contaminated intervals, and minimizes cross contamination among hydrogeologic units.

2. Core-barrel assembly must be removed before inflatable borehole packer(s) are run on the wireline system.

3. A pilot bit is replaced with a core-barrel assembly for sampling in consolidated or unconsolidated materials, or the coring assembly can be used to advance the borehole. Boreholes drilled by the wireline method usually require greater well-development effort than cable-tool drilled holes.

SAFETY NOTE: Method can enhance volatilization of organic compounds and release considerable dust at land surface. Inhaling volatile organic compounds and drilling dust **can pose a health hazard.**

Table 18. *Air-rotary drilling and casing-driver systems*

[1 inch = 2.54 centimeters]

Direct air-rotary drilling circulates compressed air (Comments 1, 2). **Down-the-hole (DTH) air hammer drilling** uses a pneumatic hammer bit that rapidly strikes the rock as the drill bit is rotated, pulverizing the rock and increasing the drilling rate (Comments 1, 3)**.**

Applications	Limitations
• Drilling in partly consolidated and consolidated geologic units (unlimited depth for environmental studies) (Comments 1, 2). • Hammer method facilitates penetration in hard rock units and in poorly consolidated gravel and cobble layers in alluvial deposits. • Coring of unconsolidated and consolidated material; for example, split barrel, thin-wall, wireline, and other core-barrel samplers (Comment 4). • Cuttings returned in air stream. Accurate correlation between cuttings and depth interval. • Can estimate yields of water-bearing zones and location of water table. • Lithologic logging (from cuttings or cores) or geologic logging (from cores).	• Method is not applicable for unconsolidated aquifers (Comments 1, 2). • Water, foam, or other fluid must be injected once saturated zone is encountered. • Borehole diameter is 24 inches or less for direct air rotary. • Borehole diameter is 12 inches or less for down-the-hole air hammer. • Location of water-bearing zones during drilling can be difficult to detect, unless hammer method is used.

Advantages	Disadvantages
• Casing advancement can be used (casing-driver system) (Comment 1). • Borehole is accessible for geophysical logging before construction of well. • Annulus formed between well casing and borehole wall can be filter packed and sealed readily. • Drilling is rapid and readily accomplished. • Well development is relatively easy. • Equipment is widely available.	• Air and foam can contaminate and alter ground-water chemistry. Aeration of anoxic ground water can induce local changes in ground-water chemistry. (Comment 5). • Potential cross contamination of hydrogeologic units along borehole. • Circulation of drilling fluid often is lost or difficult to maintain in fractured rock or gravel units. • Lubricants used during the drilling process can contaminate subsurface systems. • Air hammer can alter hydraulic properties of the rock near the borehole by opening new fractures. • Additional equipment required for temporary casing: high cost with larger hole diameters.

Comments

1. Direct air-rotary or DTH drilling, in combination with a casing-driver system, can be used for many subsurface conditions and is necessary for drilling soft, friable rock.
2. Direct air-rotary drilling relies on the stability and cohesiveness of subsurface materials.
3. The DTH hammer must be continuously lubricated with oil injected into the air stream. Type of oil, oil-injection rate, location of injection in borehole, quantity injected, and chemical makeup of oil should be documented.
4. Consolidated materials are collected by casing through the overburden.
5. An air stream carries hydrocarbons to subsurface. Hydrocarbon input can be reduced, but not eliminated, by placing filters in the compressor intake port and on the discharge port. Air stream can strip volatile compounds from the subsurface. A foam surfactant or viscosifiers can be added to the air stream to enhance drilling speed and removal of cuttings. Foam additive reduces loss of air into geologic units, but can affect ground-water chemistry.

SAFETY NOTE: Heat generated from friction between drill rods and earth materials can enhance volatilization of organic compounds that are carried in the air stream and released at the surface. If present, exposure to volatile organic compounds **can pose a health hazard** (Barcelona and others, 1985, p. 27-28).

drill systems used most commonly in combination with down-the-hole air hammers (and less commonly with rotary rock bits or wireline) for rapid construction of wells in materials which are difficult to drill by other methods, or where casing is required to maintain drilling-fluid circulation or to protect the borehole integrity (W.E. Teasdale, written commun., 1996). The use of a protective casing reduces potential contamination of overlying materials from lower hydrogeologic materials and allows for detailed sampling and testing of material at the base of the borehole. Casing-driver systems achieve high drilling rates in most unconsolidated materials and are effective in hard and soft consolidated materials.

A technique used to enhance drilling speed and the removal of cuttings is to add a foam surfactant and possibly carboxyl methyl cellulose (CMC) to the air stream. Viscosifiers, or “stiff foam” refers to a foam containing film-strengthening materials such a polymers and bentonite. The foam reduces air penetration into the aquifer (Driscoll, 1986, p. 297), and the vicosifier enhances the cuttings-carrying capability of the air stream (W.E. Teasdale, written commun., 1996). The air discharged from the compressor must be filtered, as it could contain hydrocarbons that affect ground-water quality (Aller and others, 1989, p. 89).

Cable-tool drilling

Cable-tool drilling is accomplished by repeatedly lifting and dropping a weighted drill bit that is suspended from a cable (table 19). The repeated dropping and rotating of the bit loosens and breaks up materials at the bottom of the borehole. Periodically, the drill bit is removed from the borehole and the slurry of water and cuttings at the bottom of the borehole is removed with a bailer. Although no drilling fluids are used with the cable-tool method, water must be present in the borehole for the bailer to remove the cuttings.

When drilling in unconsolidated materials, a temporary casing is simultaneously driven during drilling to prevent borehole collapse. This reduces the potential for cross contamination of hydrologic units in the borehole by sealing off each section as it is drilled. This method also eliminates uncertainty of the depth interval from which samples of geologic materials and ground water originate. The percussion effect can alter the physical characteristics of subsurface materials.

Jet-wash and jet-percussion drilling

Jet drilling is accomplished by pumping water under pressure down a small-diameter pipe fitted with a jet-wash drill bit (table 20). Subsurface materials are loosened by the drill bit and by the jetting action of the drilling fluid as it exits the drill bit. The drilling fluid carries the cuttings to the surface in the annulus formed between the drill string and borehole wall. The drill string also should be rotated by hand to increase the rate of drilling.

Jet-percussion drilling is the same as jet-wash drilling except that the drill string is repeatedly lifted and dropped as the drilling proceeds in order to further loosen subsurface materials. Lifting and dropping the drill string can be done by hand with small drilling rigs; with larger drilling rigs it usually is done mechanically.

If drilling in materials that are subject to borehole collapse, a temporary casing can be advanced simultaneously with the jetting. Once jetting to the required depth is complete, the drill string is extracted and the well is constructed in the borehole (or in the temporary casing). Alternatively, the well can be constructed by putting the jetting assembly inside the well casing and jetting the well into the subsurface (Driscoll, 1986, p. 489).

Because of the damage caused to the borehole, jet-wash and jet-percussion methods usually are not recommended for constructing water-quality monitoring wells.

Direct-push systems and vibration drilling

Wells or temporary sampling installations can be constructed without excavation of a borehole by using a direct-push system or vibration (also called “resonance”) drilling. Direct-push systems and vibration drilling incorporate rapidly expanding technologies that also have been developed for use with instrumentation for subsurface screening and on-site analysis of hydrologic, geochemical, and geologic data. Cone penetrometers, for example, often are used in conjunction with direct-push systems or vibration drilling to delineate zones of high permeability in aquifers and other characteristics of subsurface materials (Robertson and Campanella, 1984; Smolley and Kappmeyer, 1991; Chiang and others, 1992). The laser-induced fluorescent penetrometer senses petroleum hydrocarbons in unconsolidated materials (Lieberman and others, 1991). Some cone penetrometer systems incorporate chambers for collection of water-quality samples.

Table 19. *Cable-tool drilling*

[1 foot = 0.3048 meter; 1 inch = 2.54 centimeters]

<table>
<tr><td colspan="2">Cable-tool drilling is a laborious method that involves lifting and dropping a cable tool to break up and loosen geologic materials at the bottom of the borehole, normally while simultaneously driving a temporary casing.</td></tr>
<tr><th>Applications</th><th>Limitations</th></tr>
<tr><td>• Drilling in unconsolidated materials, but can be used for consolidated materials. Drilling possible in most types of subsurface conditions, including cobbles, boulders, and cavernous or fractured rock.
• Coring of geologic materials with split-barrel sampler (Comment 1).
• Cuttings returned in bailer (Comment 2).
• Excellent for detecting thin water-bearing intervals.
• Excellent for estimating yield of water-bearing intervals.
• Lithologic logging (from cuttings or cores) or geologic logging (from cores).</td><td>• Limited to shallow installations (around 200 feet) if drilling open borehole for well with filter-pack and annular-seal completion; otherwise, depth to almost 5,000 feet.
• Low penetration rates when drilling fine-grained materials.
• Borehole diameter usually is 8 inches or less for environmental studies.</td></tr>
<tr><th>Advantages</th><th>Disadvantages</th></tr>
<tr><td>• Avoids use of drilling fluids and associated problems of subsurface contamination and loss of fluid circulation.
• Low potential for cross contamination of ground water at one depth interval from other intervals.
• Advance of temporary casing maintains borehole stability and reduces cross contamination.
• Well can be completed within temporary casing (see Comment 3).
• Method allows for easy installation and precise placement of casing.
• Well development is relatively easy.
• Small rig size allows for drilling where site access can be a problem with other drilling methods.</td><td>• The percussion action damages physical properties of the hydrogeologic units.
• Borehole geophysical logging may not be possible unless there is water in the casing.
• Heaving of unconsolidated materials into bottom of casing can be a problem.
• Removing the temporary casing can cause difficulties in emplacing an effective filter pack and annular seal.
• Drilling rate can be slow.</td></tr>
<tr><th colspan="2">Comments</th></tr>
<tr><td colspan="2">1. Recovery of geologic samples excellent over entire depth of drilling.
2. Fluid is added to the bottom of the hole to make a slurry for sampling with a bailer.
3. After drilling is completed, well casing, filter pack, and annular seals can be installed inside the temporary casing before the casing is extracted.</td></tr>
</table>

Table 20. *Jet-wash and jet-percussion drilling*

[1 foot = 0.3048 meter; 1 inch = 2.54 centimeters]

Jet-wash drilling loosens subsurface materials with the drill bit and by the jetting action of the drilling fluid as it exits the drill bit. The drilling fluid carries cuttings to the surface.
Jet-percussion drilling loosens subsurface materials be repeatedly lifting and dropping the drill stem as drilling proceeds.

Applications	Limitations
• Drilling in unconsolidated (silt and sand) materials. • Coring of geologic materials with split-barrel sampler. • Cuttings are returned in fluid. • Lithologic logging from cuttings or cores, or geologic logging from cores (Comment 1).	• Presence of gravel, cobbles, or boulders impede drilling. • Jet-wash drilling limited to depths of 25 to 50 feet or less, depending on materials encountered. • Jet-percussion drilling limited to depths of 50 feet or less. • Borehole diameter usually is 4 inches or less for environmental purposes.

Advantages	Disadvantages
• Precludes use of drilling clays and polymers. • Advance of temporary casing maintains borehole stability and reduces cross contamination. • Well can be completed within temporary casing (Comment 2). • Method allows for precise placement of a well. • Equipment is highly mobile and widely available. • Drilling is rapid and readily accomplished. • A minimal amount of equipment is required.	• Jet-percussion drilling can cause compaction or otherwise alter physical characteristics of hydrologic units. • Use of non-native water can affect ground-water quality when temporary casing is not used. • Ground water from different depth intervals can mix with materials from different depth intervals as they are carried to the surface when temporary casing is not used. • Ground water at one depth interval can be contaminated by ground water from other intervals. • Borehole can collapse before setting the well when a temporary casing is not used. • Temporary casing can cause problems with the emplacement of a filter pack and annular seal. • Large quantities of water are required during drilling.

Comments
1. There is a good correlation between samples of geologic materials with the depth interval when casing is advanced during jetting. 2. After drilling is completed, a well casing, filter pack, and annual seal can be installed inside the temporary casing before the casing is extracted.

Direct-push systems produce relatively small (less than 4-in. diameter), shallow (~100-ft or ~30-m) wells and are used only for unconsolidated materials. Vibration drilling produces larger diameter (8 in. or ~20 cm or greater), deeper (about 500-ft or at least 150-m) boreholes and can be used for consolidated, partially indurated, or bouldery and cobbley materials, as well as for unconsolidated materials.

Direct-push systems.—Direct-push methods often are classified as sampling systems rather than as a well-construction method. Direct-push systems are being used primarily to perform rapid site reconnaissance in unconsolidated materials to guide the placement of wells. Direct-push methods generally result in temporary installations from which samples of ground water or geologic materials are collected or analyzed, but sometimes permanent installations are completed if State and local regulations governing the construction of monitoring wells have been met. Direct-push systems also are used to collect samples or complete well construction after an initial length of borehole has been excavated using either vibration or a conventional drilling method.

Drive points and small-diameter hollow rods can be installed using direct-push systems in unconsolidated materials at relatively shallow depths for (1) single sampling events in discrete intervals, (2) incremental sample collection throughout drilling, and (3) installation of temporary or permanent wells (table 21) (J.A. Farrar, written commun., 1995). Direct-push systems use either combinations of percussion and resonance driving, with or without static force; static force using hydraulic penetrometer, vibratory, or drilling equipment; or incremental drilling combined with direct-push water-sampling techniques. Use of truck-mounted hydraulic, drive, or vibratory equipment requires considerably less labor than manual installation.

Three types of wells installed using direct-push systems include:

- A simple drive-point piezometer or sampler that is pushed or driven to the desired depth and left in place for sample collection.
- A drive point that is pushed or driven to a specified depth and used to collect a water sample, then subsequently pushed (or driven) to greater depths and used to collect samples at those depths.
- A drive-point casing that is pushed or driven to a specified depth, after which a multilevel sampler (for example, fig. 5c) is lowered through the casing and the casing is withdrawn. This allows the geologic materials to collapse around the sampler, which can be left in the ground.

The well must be constructed with a long enough column of overburden materials to ensure an adequate annular seal above the well screen. If an adequate seal is not obtained, standard well-completion procedures are required. Direct-push systems are designed with a single-wall or double-wall casing. Single-wall casing systems are used for rapid advancement to the depth of interest. As the well screen or sampler is pushed (or driven) through geologic materials, a zone of compaction forms around the rods, which helps to form a natural seal of native materials above the drive point or sampler screen. If a double-tube system is used, the installation requires placement of an annular seal (see "Well Completion") when the outer rods are removed. The advantage of double-wall casing is that it can be used to collect samples at known depths as the outer casing is advanced.

A variety of materials are available in different design configurations to address monitoring problems. Well screens that are protected with a retractable riser during casing advancement should be used for water-quality studies. Protected screens also have an advantage of protecting the screened area from exposure to ground water until the depth of interest is reached, as well as protecting the screen from physical damage. Discrete or continuous cores of geologic materials can be collected, but the coring equipment must be pulled back and replaced with the well point or ground-water sampler for temporary or permanent construction of the well. Direct-push systems do not produce cuttings.

Vibration drilling.—Vibration drilling, also termed resonance drilling, involves a dual (double-tube) casing and simultaneous use of high-frequency vibrations (50 to 200 hertz) and low-speed rotation coupled with downpressure to drill a borehole while taking continuous core samples of unconsolidated and most consolidated materials (table 22). The core barrel is advanced ahead of the outer casing in increments that can range from 1 to 30 ft (~0.3 to ~9 m). The outer casing usually is advanced dry, but air, water, or water-based drilling fluids can be applied depending on the type of materials encountered, borehole depth, and sample-collection objectives or other requirements. The well-casing, screen, and well-completion materials are installed through the outer drilling casing, after which the outer casing is vibrated out of the borehole. This vibration enhances emplacement of the filter packs and annular seals between the borehole wall and well casing.

The vibration method normally is used to construct a permanent monitoring well. Vibration drilling also provides the capability to collect samples with direct-push coring equipment and to sample soil vapors and ground water.

Table 21. *Direct-push systems*

[1 foot = 0.3048 meter; 1 inch = 2.54 centimeters]

Direct-push installation systems use push or drive force to install temporary or permanent wells. Rapid installation allows for rapid site reconnaissance. Ground-water quality can be monitored with depth, continuously, or at discrete intervals.

Applications	Limitations
• Drilling in unconsolidated (silt and sand) materials. • Installation of small-diameter wells or temporary sampling devices to screen for water-quality and hydrologic properties. • Concurrent use of direct push with mobile laboratory allows rapid real-time monitoring and assessment of ground-water-quality or hydrologic data. • Continuous or discrete cores of unconsolidated materials to 4 feet in length. • Sampling screens available in large or small diameter sizes—large-diameter screen used for collection of nonaqueous phase liquid substances (NAPLS).	• Penetration not possible in hard, consolidated materials and can be difficult or impossible in soft rock (claystones and shales); in coarse materials such as gravel, cobbles, and boulders; and in caliches (Comment 1). • Normally used for a temporary installation. • 40-feet or less depth for hand-pushed or driven wells. • 100-feet or less depth using power-driven or direct-push equipment. • Well diameter is 2 inches or less. • No drill cuttings generated for use for lithologic logging.
Advantages	**Disadvantages**
• Precludes use of drilling fluids and lubricants. • Ground-water samples and samples of subsurface materials can be collected at multiple locations per day (depending on site characteristics and depth requirements). • Minimizes disturbance of subsurface geochemistry disturbance to field site also is minimal because equipment is relatively lightweight. • Avoids need to dispose of subsurface fluids and materials. • Well-development and purging efforts are relatively small and rapid, if using protected well screen. • Well screens can be emplaced without exposure to overlying materials. Double-tube systems allow easy sealing above the well screen. • Equipment is highly mobile, allowing good site accessibility. • Drive or push method is rapid.	• Singular sampling event—usually not suitable for repeated or long-term monitoring. • Small-diameter drive pipe or casing generally precludes conventional borehole-geophysical logging. • Casing and drive point are constructed of steel (Comment 2). • Drive points yield relatively low rates of water; ground-water sample volume is small. • Turbidity usually is high in water samples. • Well screen can become clogged during driving, making well development difficult, if using an unprotected well screen. • Drive methods can cause compaction or otherwise alter physical characteristics of subsurface units.

Comments

1. If a well is to be pushed or driven into unconsolidated materials that are overlain by cemented or consolidated materials, vibratory or conventional drilling methods can be used to penetrate the overlying formation and then direct push or drive is used to construct a well at the interval of interest.

2. Because of the force and pressure applied to direct-push devices, the sampler body and sampler tip typically are composed of steel, stainless steel, or other metal alloys. Well-screen materials are available in stainless steel, rigid PVC, PTFE, PE, and PP. The user should consider if screens or tips left in the well will leach materials that can bias concentrations of the constituents to be analyzed for the study.

Table 22. *Vibration drilling*

[1 foot = 0.3048 meter; 1 inch = 2.54 centimeters]

Vibration drilling: dual-cased drilling system that uses high-frequency mechanical vibration to take continuous core samples and advance a borehole for permanent well installation (Comment 1).

Applications	Limitations
• Drilling in unconsolidated and consolidated materials, and through boulders, wood, concrete, and other construction debris. • Can obtain large-diameter, continuous, and representative cores of unconsolidated and consolidated materials (Comment 2). • Used with equipment to monitor ground-water and vapor chemistry. • Used with direct-push equipment for environmental monitoring. • Can estimate aquifer yield.	• Limited to 500-foot depth. • No geologic logging using cuttings. • Borehole diameter is 12 inches or less (Comment 3).

Advantages	Disadvantages
• Normally avoids use of drilling fluids and lubricants and disposal of subsurface fluids and materials. • Casing is advanced. • Minimal disturbance of subsurface geochemistry. • Concurrent use with direct push with mobile laboratory allows real-time monitoring and assessment of ground-water quality or hydrologic data. • Easily adapted to conventional wireline core drilling, fluid-rotary drilling, or down-the-hole hammer drilling methods. • Reduction in waste disposal from drill cuttings. • Drilling is more rapid than other methods, with the exception of dual-wall reverse circulation. • Equipment is highly mobile, allowing good site accessibility.	• Drilling and sampling in consolidated materials requires addition of water or air or both to remove cuttings (Comment 2). • Some types of borehole-geophysical logs are not possible when water-based fluid is not used.

Comments

1. Vibration drilling, with some variations, is also referred to as sonic, rotasonic, sonicore, and ResonantSonic drilling.
2. Method produces few cuttings.
3. Optimal bit diameter is 8 inches or less for boreholes more than 100 feet deep.

Well Completion

Well completion primarily consists of backfilling and sealing the annular space between the borehole wall and the installed well screen and casing. At the end of well completion, an outer casing usually is installed, along with a surface seal, to protect the well. The basic purpose of well completion is to ensure

- that the hydraulic head measured in the well is that of the aquifer targeted for study,
- only the aquifer targeted for study contributes water to the well, and
- the annular space is not a vertical conduit for water and contaminants.

The four major elements of well completion are (1) installation of the primary filter pack around the well screen, if a well screen is used and a filter pack is required; (2) installation of a secondary filter pack above the primary filter pack; (3) installation of the annular seal(s); and (4) installation of a surface seal, protective casing, and cover around the well at land surface. Figure 3 illustrates these major elements for a well with a filter-packed well screen installed in unconsolidated materials.

Objectives and considerations for each of the elements of well completion are discussed below. Ordinarily, these elements are followed in sequence and are the steps that comprise well completion. However, completion practices can differ considerably among wells, depending on geologic materials, well design, and method of well drilling or construction. Each element of well completion might be modified or even omitted in some situations. For example, completion of a well might not require placement of either the primary and secondary filter packs. Completion of a well in consolidated materials in which one well casing extends from above the open interval (no well screen installed) to land surface could require only an annular and surface seal. Also, some steps of well completion are not possible, such as installation of filter packs and annular seals for wells pushed or driven through unconsolidated materials.

STANDARD PROCEDURE: SEAL THE ANNULAR SPACE BETWEEN THE BOREHOLE WALL AND WELL CASING ABOVE THE FILTER PACK(S) TO ENSURE THAT THE SAMPLE WATER IS ONLY FROM THE TARGETED INTERVAL.

Specific details of well completion require knowledge and consideration of hydrogeologic factors, including depth to the water, to the top of the aquifer of interest, and to the zone in the aquifer to be monitored; and the nature of materials that make up the aquifer and those that overlie the aquifer (for example, unconsolidated, partly consolidated, or consolidated materials). Other site-specific factors include whether or not consolidated materials are fractured or have openings caused by dissolution; water-level fluctuations; whether the vertical head gradient is downward, upward, or fairly uniform with depth; and if the aquifer is confined or unconfined.

Documentation of the methods and materials used for well completion is required. This documentation includes a field log of the methods used, conditions encountered, and a diagram of the completed well (fig. 16, page 91). The well-completion diagram indicates borehole depth and diameter; if cased, the type, diameter, length, and materials used for the well casing and screen; the number of wells installed in the borehole; the locations and lengths of screened or open intervals; if emplaced, the materials, length, and thickness of filter packs, annular and surface seals; and, if used, the characteristics of the protective casing.

To prevent contamination of water in the borehole, pumps, tremie pipes, or other equipment used downhole during well completion must be properly employed and decontaminated. Additional information about well completion can be found in Driscoll (1986) and ASTM (1992). Compliance with Federal, State, and local regulations for well completion is mandatory.

Filter Packs

Two filter packs are installed in the annular space surrounding and immediately above the well screen: the primary filter pack and the secondary filter pack. Each fulfills different objectives and should be designed accordingly.

Primary filter pack

The primary filter pack (also called a sand, gravel, or filter pack) is a cylindrical envelope of material that backfills the annulus around the well screen to retain and stabilize geologic materials from the hydrogeologic unit (fig. 3). Primary filter-pack grain size and gradation are designed to permit only the finest grains to enter the screen during development, resulting in relatively sediment-free water in samples collected after development. The length of the filter pack also is an important consideration. The primary (or secondary) filter pack(s) must not intersect multiple water-bearing units that otherwise would not be screened, and must not cross confining units. Intersection of multiple water-bearing units can result in an artificial vertical hydraulic connection along the annulus between these units (fig. 8). The hydraulic connection could result in waters of different chemistry mixing with water from the aquifer targeted for sampling.

A primary filter pack generally contains a grain size greater than that of the aquifer material in the vicinity of the screen. ASTM (1992) provides filter (sand) pack mesh sizes that are applicable for several sizes of screen openings. In those situations where a well is constructed and completed in one phase, filter-pack material must be purchased and their grain-size characteristics analyzed before soil samples are collected. The recommended procedure, however, is to collect soil samples during drilling and use the results of analysis of the soil sample grain-size characteristics to determine filter pack size (table 23). In this situation, the selection of a filter pack size is based on the grain-size distribution of the aquifer material and filter-pack material, and the uniformity coefficient of the filter-pack material. For example, Driscoll (1986, p. 722) recommends that the grain-size distribution curve for the filter pack be selected by multiplying the 70-percent retained size of the finest stratum to be screened by 3 or 4; and that the filter pack selected has a uniformity coefficient ranging from 1 to 3. ASTM (1992, p. 127) recommends that a filter pack be selected that has a 30-percent finer grain size than that corresponding to about 4 to 10 times the 30-percent finer grain size of the stratum being screened, and that the filter pack selected has a uniformity coefficient of less than about 2.5.

The primary filter pack can affect the chemistry of water passing through or residing in it and should consist of relatively inert material. For this reason, a filter pack should consist primarily of quartz grains, contain no limestone or other calcareous materials such as shell fragments, and contain no organic material such as wood fragments or lignite.   As an alternative, filter-

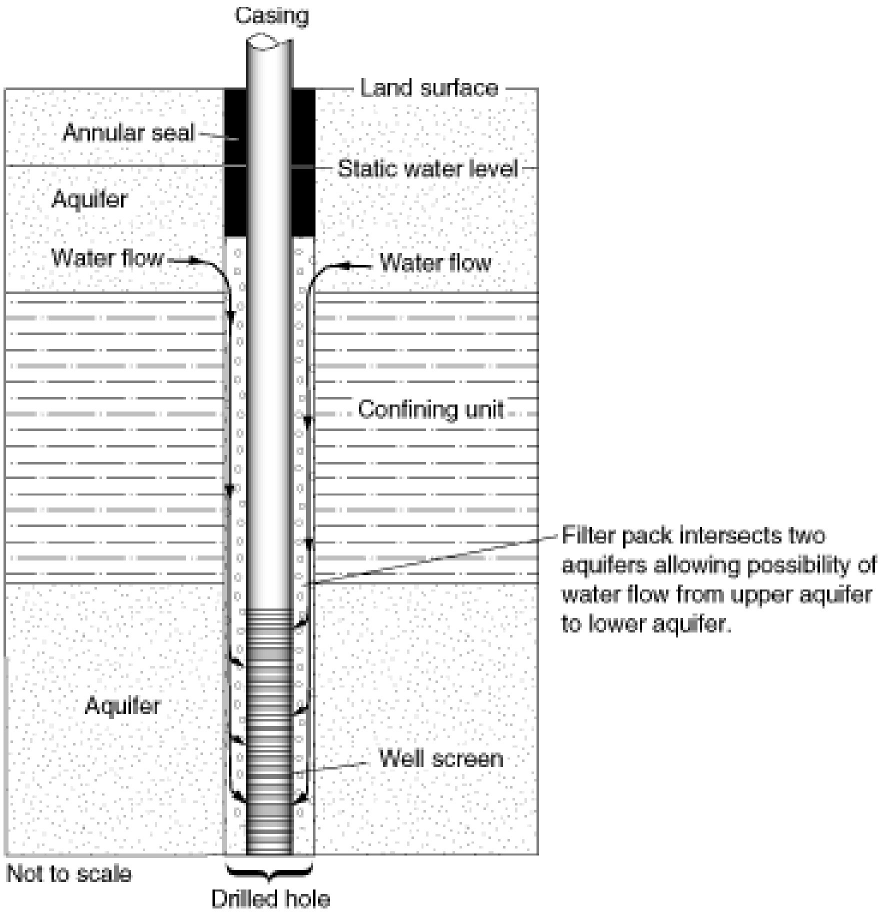

Figure 8. *Long filter pack can lead to uncertainty about the source of water to a well.*

Table 23. *Recommended primary filter (sand) pack size for common screen slot sizes (modified from ASTM, 1992, p. 128)*

Size of screen opening, in millimeters (inches)	Slot number	Filter (sand) pack mesh size designations
0.125 (0.005)	5	100
0.25 (0.010)	10	20 to 40
0.50 (0.020)	20	10 to 20
0.75 (0.030)	30	10 to 20
1.0 (0.040)	40	8 to 12
1.5 (0.060)	60	6 to 9
2.0 (0.080)	80	4 to 8

pack material of known chemistry, such as glass beads, could be used (ASTM, 1992). It is not recommended that native materials brought to the surface during the drilling process be used in a filter pack. This material could contain contaminants or could become contaminated during its extraction or at land surface. By returning potentially contaminated material to the borehole, one risks contamination of the aquifer. Additional reasons for not using native materials as a filter pack are: (1) it usually is not possible to return material in the exact order in which it was extracted, and (2) replaced earth materials do not readily compact to their original state.

A common method of placement of a primary filter pack is to insert a string of small-diameter pipe, called a tremie pipe, in the annulus between the casing and the borehole down to a depth that is at or below the bottom of the screen. The filter-pack material is funneled through the tremie around the screen. The annulus is backfilled slowly from the bottom up to a distance above the top that is equivalent to about 20 percent of the screen length or 2 ft above the top of the screen, whichever is greater (ASTM, 1992). If the well is deep and no secondary filter pack will be installed, this distance should be increased accordingly to prevent seepage of sealant to the screened interval (see discussion under “Secondary filter pack”). Use of the tremie pipe reduces bridging of the annulus by the filter pack, and also reduces the tendency for selective sorting of the filter pack by grain size as it falls through the water down the annulus.

An alternative to completing the well with an externally introduced filter pack is to allow collapse of the native materials around the well screen and casing. This method is applicable only if the native unconsolidated materials in the screened interval will collapse around the well to form a filter pack and result in a well that yields sediment-free water in samples collected after the well is developed.

The installation of a filter pack can be difficult or impossible when installing a well in karst or highly fractured consolidated materials because of the size and configuration of void spaces at the borehole (ASTM, 1992, p. 127). A filter pack might not be necessary or desirable to use under these conditions. In some cases, the installation of a filter pack could plug water-bearing fractures from which ground-water samples need to be obtained.

Secondary filter pack

The secondary filter pack (fig. 3) has a finer grain size than the primary filter pack, and is placed above the primary filter pack. The secondary filter pack prevents material used for the overlying annular seal from infiltrating and clogging the primary filter pack and affecting water chemistry adjacent to the screen. A secondary filter pack also can be used between different types or sections of annular seals (ASTM, 1992, p. 124).

The secondary filter pack should consist of relatively inert material, similar to the material used for the primary filter pack. Uniformly graded fine sand that completely passes through a No. 30 U.S. Standard sieve, and where less than 2 percent of this sand by weight passes through a 200 U.S. Standard sieve (ASTM, 1992, p. 129) or sand sold for plaster or mortar.

The depth of the borehole to the well screen is an important consideration in determining the length of the secondary filter pack. As the depth of the well and the length of the column of sealant increase, the penetration of sealant into the filter pack also commonly increases. Penetration of the sealant into the filter pack should be limited to less than a few inches to prevent contact with water in the screened or open interval (Hardy and others, 1989). For shallow wells, a length of secondary filter pack of about 1 to 2 ft (~0.3 to ~0.6 m) commonly is recommended (Hardy and others, 1989, p. 16; ASTM, 1992, p. 129, figs. 2 and 3). For deep wells, however, a secondary filter pack of 10 ft (~3 m) or longer could be required to prevent material used for the annular seal from seeping through the filter pack to the well screen; for wells 1,000 ft (~300 m) or greater, up to 60 ft (~18 m) of filter pack could be required (J. Izbicki, USGS, written commun., 1995).

The method of placement of the secondary filter pack is similar to that for placement of the primary filter pack: a tremie pipe is inserted in the annulus of the borehole to the top of the primary filter pack and the secondary filter-pack material is funneled slowly through the tremie. Depending on the viscosity or other properties of drilling fluid being used for well installation, emplacing the secondary filter pack through a tremie by gravity flow might be problematic because the filter-pack material might not be dense enough to sink through the drilling fluid in the tremie. Emplacement of slightly coarser materials through the tremie could be tried. Alternatives to a secondary filter pack include use of a cement basket placed immediately above the screened interval. This alternative method can have substantial effects on ground-water chemistry, and needs to be evaluated relative to study objectives (Claassen, 1982, p. 16; Driscoll, 1986, p. 325). If conditions make placement of a secondary filter pack impractical, another alternative is to extend the primary filter pack up the annulus to a minimum of about 5 ft (~1.5 m) above the top of the screen. The primary and (or) secondary filter pack must not intersect multiple water-bearing units that otherwise would not be screened, and must not cross confining units, as discussed earlier under “Primary filter pack.”

Well Seals

Two types of well seals are installed above the filter pack: the annular seal and the surface seal. Annular seal(s) provide a plug of dense material above the filter pack to prevent the annulus from being a conduit through which water from higher unit(s) can enter and contaminate the screened hydrogeologic unit. The surface seal prevents surface runoff down the annulus of the well. The most common sealant materials are described at the end of this section in “Characteristics of bentonite and cement as well seals.”

Annular seal

An annular seal is installed to prevent vertical flow of water within the annular space between the well casing and borehole wall. Ordinarily, the annular seal consists of a slurry of sealant (such as bentonite or cement) that is pumped or tremie-piped up the annulus from the top of the secondary filter pack (fig. 3). The distance between the bottom of the seal and the top of the well screen is an important consideration that was discussed under “Filter Packs.” At a minimum, a 3- to 5-ft (~0.9- to ~1.5-m) seal overlying the filter pack is required to ensure proper well completion. The annulus can be sealed to just below the frost line, the position of which depends on factors such as climate and geographic location.

An ideal seal material must develop strength quickly and bond to the well casing, it must seal the annulus between the borehole wall and casing, and should be chemically inert, permanent, stable, and resistant to deterioration (Moehrl, 1964). Failure of a seal usually results from a poor bond between the sealant and the borehole wall, the well casing, or both; from bridging of the sealant during placement; or from swelling or shrinking of the sealant over time.

Native materials at the site or cuttings returned from the borehole during drilling are not recommended as annular seals, although they commonly are used because they are readily available and inexpensive. Native materials might be contaminated or have become contaminated during drilling. Because these materials likely would not have adequate sealing properties, there would be no assurance that the annulus would be sealed. It is probable that the water-bearing units surrounding the native-material seal will be more compacted and have a lower hydraulic conductivity than the seal itself, thus providing hydraulic connection between aquifers and preferential flow along the annulus of the well.

Discussions of characteristics of annular seals and methods of placement can be found in detail in Driscoll (1986) and ASTM (1992).

Surface seal

The surface seal prevents surface runoff down the annulus of the well and, in situations in which a protective casing around the well is needed, holds the protective casing in place (figs. 3 and 9). The surface seal usually is constructed with its top surface sloping

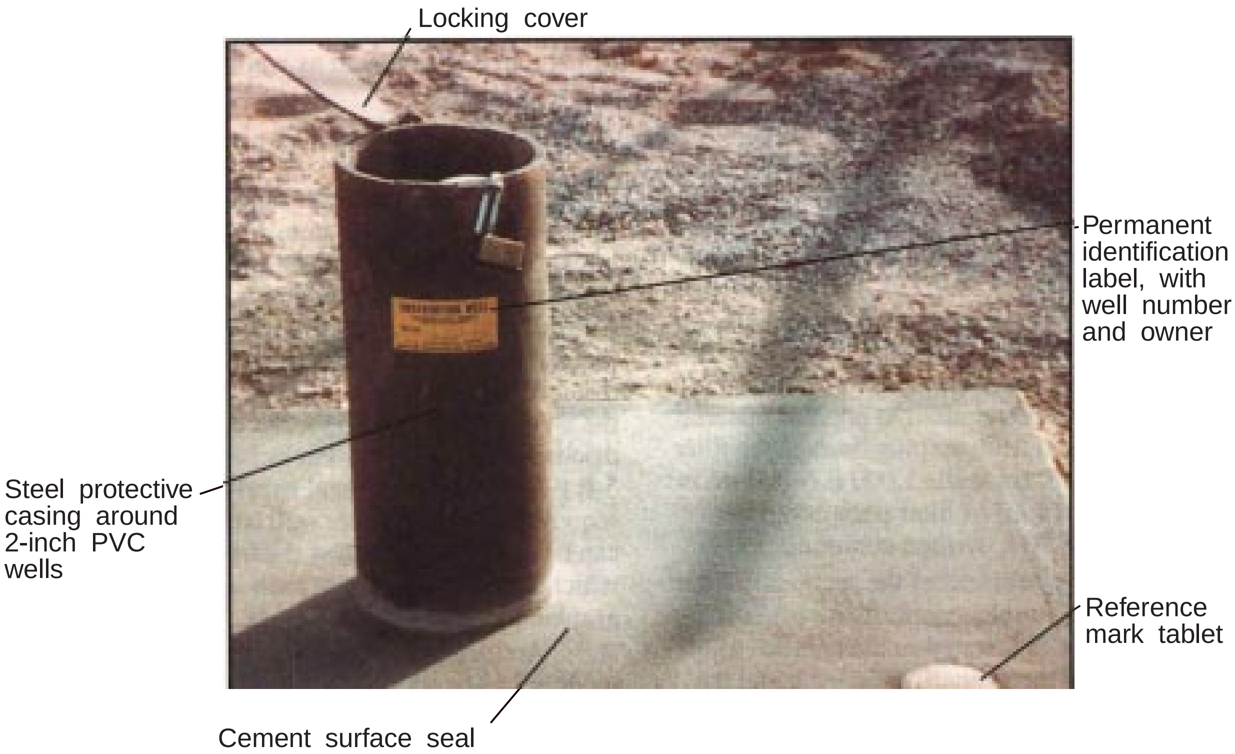

Figure 9. *A cement surface seal and protective casing at a monitoring well. Photograph by Ron G. Fay, 1989.*

slightly downward away from the well casing to transport runoff from precipitation away from the well casing and annular space around the well. It is useful for the well identification to be imprinted permanently into the top of the surface seal during construction of the surface seal; for example, by using a reference mark tablet (see Kennedy, 1990, fig. 12a). A cement surface seal is preferred because of the possibility of bentonite desiccation and the need for strength to protect the well from physical damage. The depth of installation of a surface seal can range from several feet to several tens of feet below land surface, must be below the frost line, and should comply with Federal, State, and local regulatory agencies' specifications for surface seals.

Characteristics of bentonite and cement as well seals

Bentonite generally is recommended for use as an annular seal and cement generally is recommended for a surface seal. Cement, or mixtures of cement and bentonite, are also used as annular seal materials. The primary consideration for choice of sealant is that it would have little or no effect on the water-quality constituents of interest, should sealant infiltrate the filter pack to the well screen.

Bentonite is a hydrous aluminum silicate composed primarily of montmorillonite (table 24). Chemical analysis of a sodium montmorillonite by one manufacturer indicates the following compositions as oxides (percentages approximate): SiO_2 (55.4 percent), Al_2O_3 (20.1 percent), Fe_20_3 (3.7 percent), Na_20 (2.8 percent), $Mg0$ (2.5 percent), K_20 (0.6 percent) and $Ca0$ (0.5 percent). In addition to its relatively inert chemistry (relative to cement), bentonite has two properties that make it an effective annular seal: when hydrated, it expands in volume from 10 to 15 times its dry volume and it has a low hydraulic conductivity that ranges from about 1×10^{-7} to 1×10^{-9} cm/sec (Aller and others, 1989, p. 194).

Bentonite is available as pellets, granules, and powder. The best method of emplacement of bentonite is as a slurry made from quick-setting powder that is pumped into the annulus through a tremie pipe. Installing a seal often is attempted by pouring the dry pellets

Table 24. *Characteristics of bentonite and cement as annular seals*[1]

[Information from Claassen (1982), Gillham and others (1983), Driscoll (1986), Aller and others (1989), Hardy and others (1989), and ASTM (1992); ~, approximately]

BENTONITE

(A hydrous aluminum silicate composed primarily of montmorillonite with pH ranging from 8.5 to 10.5)

Advantages:

- Readily available and inexpensive.
- Several options for placement of the bentonite exist. The best method, however, is as a slurry made from a quick-setting powder, which is pumped into the annular space through a tremie pipe.
- If it remains saturated, it remains plastic and will not crack.
- Expands 10 to 15 times the dry volume when hydrated.
- Low hydraulic conductivity (about 1×10^{-7} to 1×10^{-9} centimeters per second).

Disadvantages:

- Effectiveness of seal is difficult to assess.
- Complete bond to casing is not assured.
- If it is not pumped into the annulus as a slurry, bentonite can stick to the walls of the annulus and bridge the annulus because of rapid hydration.
- Because of desiccation, bentonite generally is not an effective annular seal in the unsaturated zone (and is a poor surface seal).
- Can affect the chemistry of the surrounding ground water by cation exchange of Na, Al, K, Mg, Ca, Fe, and Mn from the bentonite with other cations in the ground water.
- Sets with a pH between 8.5 and 10.5, which can affect the chemistry of surrounding ground water that differs in pH.
- Most bentonites contain about 4-6 percent organic matter, which could affect the concentration of some organic constituents in ground water.
- Bentonite can react with high-salinity ground water and not set properly, resulting in a poor annular seal.

CEMENT

(Composed of calcium carbonate, alumina, silica, magnesia, ferric oxide and sulfur trioxide with pH ranging from 10 to 12)

Advantages:

- Readily available and inexpensive.
- Can assess continuity of placement using temperature or acoustic-bond logs.

Disadvantages:

- Requires mixer, pump, and tremie pipe for placement.
- Generally, cleanup required exceeds that required for bentonite.
- Contamination can be introduced to borehole by the pump.
- Failure of the cement to form a seal can occur because of premature or partial setting, insufficient column length, voids or gaps in the column, or excessive shrinkage.
- Neat cement (cement and water) will shrink during the curing process, which could result in a poor seal between the cement and the casing or the borehole wall (Aller and others, 1989, p. 196).
- Heat of hydration during curing can deform or melt thermoplastic casing such as PVC in a 2-inch (~5 centimeter) annulus filled with cement as temperature rises to about 35-45°F (Smith, 1976; Driscoll, 1986, p. 324).
- Additives to the cement that compensate for natural shrinkage can cause an increase in pH, dissolved solids, and temperature of the ground water during the curing process. The increased pH can cause precipitation of calcium and bicarbonate ions from ground water that has a pH less than that of cement.
- Soluble salts in the cement can be leached by the ground water, thereby increasing the concentrations of calcium and bicarbonate in the ground water.
- Cement can cause unusually high values of pH in ground-water-quality samples.
- Most cement will react with high-sulfate ground water and deteriorate.

[1] Native materials at the site or cuttings returned from the borehole during drilling are commonly used as annular seals but are not recommended because they might be contaminated and likely would not have the properties required to seal the annulus adequately.

or granules of bentonite down the annulus. Because bentonite hydrates rapidly, a major problem with this method is that the bentonite can stick to the borehole wall or casing and ultimately bridge the annulus far above its intended location of emplacement. This bridging occurs more readily with the granules of bentonite, but is also can occur with the pellets. Uneven hydration of pellets can lead to air pockets and pathways for downward movement of water.

In some situations, use of one chemical type of bentonite is preferable over another. For example, of the two types of bentonite commonly used for annular seals (sodium bentonite and calcium bentonite), calcium bentonite is recommended in high-calcium environments because shrinkage from long-term calcium-for-sodium ion exchange is reduced; sodium bentonite, however, generally has greater expandability (Aller and others, 1989, p. 194).

Bentonite slurry has a relatively high pH of between 8.5 and 10.5 and has a high cation-exchange capacity. Thus, bentonite can affect the chemistry of ground water it contacts by the exchange of sodium, aluminum, and manganese cations from the bentonite for cations in the ground water.

Cement mixed with clean water in a proportion of 1 ft^3 (~23.3 L) of cement to about 5 gal (~19 L) of water is used for well seals. Aller and others (1989, p. 196) describes five general types of Portland cement: Type I is suitable in most environments for use in well completion. Type II is used for situations in which moderate sulfate resistance or moderate heat of hydration is required. Type III is used when a quick setting, strong seal is required. Type IV is used for situations in which low heat of hydration is required. Type V is used for situations in which high sulfate resistance is required.

Sealing the annular space with cement usually is done by pumping the cement into the annulus through a tremie pipe. The method of placement is similar to that for placement of the filter packs and the short bentonite seal: a tremie pipe is inserted into the annulus of the borehole to the top of the underlying filter pack or short bentonite seal and the cement is pumped slowly through the tremie. Experiments indicate no significant penetration of cement into a fine-grained filter pack composed of uniform sand with grain size finer than 0.025 in. (0.6 mm), or into nonuniform sand with a hydraulic conductivity less than 400 ft/d (122 m/d or ~0.14 cm/sec) (Driscoll, 1986, p. 325).

Factors that can contribute to failure of a cement seal include premature or partial setting of the cement; insufficient seal length; voids or gaps in the seal column, usually caused by contact of the casing with the borehole wall or by the presence of washouts; excessive shrinkage of the cement; and collapse of the casing (Driscoll, 1986, p. 330). Two important steps can be taken to minimize the possibility of a cement seal failure: (1) position the tremie pipe near the bottom of the annulus and withdraw it slowly as cement fills the void—this minimizes bridging of the annulus by the cement; and (2) complete placement in one continuous operation.

The heat of hydration during curing of neat cement (cement and water) can deform or melt thermoplastic casing such as PVC. For example, if cement fills a 2-in. (~5-cm) annulus, the heat produced during hydration results in a temperature rise of about 35 to 45°F (~1.7 to 7.2°C) (Smith, 1976; Driscoll, 1986, p. 324).

Chemically, cement is composed of calcium carbonate, alumina, silica, magnesia, ferric oxide and sulfur trioxide, and has a pH that ranges from about 10 to 12. Claassen (1982, p.16) describes some of the possible effects of cement on water chemistry. Neat cement will shrink during the curing process and this shrinkage can result in a poor seal between the cement and the casing or the borehole wall. Additives can compensate for this natural shrinkage of cement, but cause a substantial increase in pH, dissolved solids, and temperature during the curing process. The increased pH can cause precipitation of calcium and bicarbonate ions from the ground water that has a lower pH than that of the cement. Alternatively, if the pH decreases during pumping of ground water past the cement seal, soluble salts in the cement can be leached, thereby increasing the concentrations of calcium and bicarbonate in the ground water.

Protective Casing

A protective casing commonly is installed around a well to protect it from damage and to prevent unauthorized access to the well. The protective casing is emplaced during installation of the surface seal and must extend below the frost line (ASTM, 1992). One design for a protective casing consists of a steel casing with a vented, lockable protective cover (figs. 3 or 9) and a weep hole. The weep hole is about 0.25-in. in diameter, drilled through the protective casing about

6 inches above ground level. This hole permits condensation to drain out of the annular space between the protective casing and the well casing. It also allows water from a well that occasionally flows under artesian conditions to escape from between the protective casing and the well. ASTM (1992, p. 132) also suggests that coarse sand, pea gravel, or both be placed in the annular space between the protective casing and the well to prevent entry and nesting of insects through the weep hole.

Flush-mounted casing is used to complete wells that are level with or slightly below land surface. These wells are installed in areas such as parking lots where a well that extends above land surface is impractical. Several factors to consider when using flush-mounted casing have been suggested by Michael Lico (U.S. Geological Survey, written, commun., 1996) and John Mullaney (U.S. Geological Survey, written commun., 1996).

(1) Access to well.

- The well must be located where access can be assured. For example, flush-mounted wells should not be installed at the end of cul-de-sacs or edges of parking lots where they could be buried by snowbanks.
- Flush-mounted protective casing can be problematic if installed in a low-lying area or an area that receives surface runoff. Standing water or runoff can infiltrate the annulus of the well or flow down the inside of the well casing. Standing water in flush-mounted protective casings can freeze in winter, which makes gaining access to the well difficult and time consuming.

(2) Construction of flush-mounted casing.

- The steel manhole casing must have a bolted or locked manhole cover.
- The cement surface seal needs to extend well below the frost line to prevent heaving of the well and the protective casing, and breaching of the surface seal.
- Drain holes drilled around the bottom of the protective casing will help drain standing water (drain holes are essential for wells in low lying areas).
- To prevent standing water from infiltrating the well, use a well cap that has a rubber gasket to seal the well or use a locking or nonlocking pressure plug. Note that these seals can prevent air pressure inside the well casing from equilibrating with atmospheric pressure, which can affect the water level for a period of time, even after removal of the well cap.

(3) Difficulty in finding the well.

- Document the well location in the field folder using distances that were measured between several permanent and easily identified points and the well.
- Use a metal detector to locate the steel manhole casing.

Well Development

Well development helps restore the aquifer at the screened or open section of the well to its original condition. Well installation can cause a decrease in aquifer permeability, changes in aquifer stratification, and aquifer contamination by drilling fluids. Redevelopment of a well is required when there is a buildup of sedimentation in the well or clogging of the aquifer or well screen over time.

Restoring the physical characteristics of the aquifer to its pre-drilled condition is necessary to ensure a good hydraulic connection between the well and the aquifer, to increase well capacity, and to remove fine-grained material from the aquifer near the well screen that might otherwise enter the well and cause excessive pump wear or might bias water analyses. These are achieved by removing loose material introduced during drilling, loosening or redistributing native materials compacted by the installation process, and removing fine-grained material from the vicinity of the well screen.

Restoring the chemical quality of the ground water to its pre-drilled condition is necessary to ensure that the water-quality samples collected will be representative of native ground water. This is achieved by removing drilling fluids and other foreign materials that could penetrate the aquifer. The efficacy of well development to remove foreign materials is evaluated by monitoring turbidity and other field measurements throughout the development process. Measuring turbidity as the well is developed is a requirement of some regulatory and military agencies.

Well development is documented by recording on field forms the method(s) used and time required for development; equipment used; static water level; estimate of volume of water removed; the visual appearance (clarity) of the discharge water; well characteristics such as depth of the well, well diameter, and depth to the screened or open interval; and measurement of turbidity and other field parameters, such as specific electrical conductance and pH (fig. 17). Information also can be collected during well development to evaluate requirements that will be needed for purging the well prior to sample collection. After pumping, the rate of recovery and time required for recovery of the water level can be used to estimate the time required for purging. For example, if the recovery rate of the water level in the well is slow even after development, it might be necessary to plan to purge the well a day or several hours before sample collection. The recovery time also can be used to determine the pumping rates for purging, and to determine if an alternative method of pumping is required. In addition, wells can be screened for selected contaminants during development (see “Field screening during development”).

STANDARD PROCEDURE: SELECT A DEVELOPMENT METHOD THAT AVOIDS INTRODUCTION OF AIR, FOREIGN WATER, OR CHEMICALS TO THE AQUIFER DURING DEVELOPMENT, IF POSSIBLE.

STANDARD PROCEDURE: MONITOR FIELD PARAMETERS, SUCH AS TURBIDITY, DURING DEVELOPMENT.

Selected Methods

The general approach to development involves dislodging and moving fine-grained material and drilling fluid out of the aquifer and into the well, and then from the well itself, until pre-drilling conditions in the aquifer are restored. The six methods of well development described briefly in this section, in order of recommended use, include bailing; mechanical surging; pumping or overpumping, with backwashing; indirect eduction; backwashing; and jetting and surging with water or air.[8] Often, combinations of these six methods are used. For example, after bailing, the well might be pumped, during which field parameters are measured. Well development methods can introduce contaminants to the subsurface; therefore, the best techniques are those that avoid injection of air, foreign water, and chemicals (for example, deflocculation or dispersing agents, acids, surfactants, and disinfectants) into the aquifer. The methods are described in order of recommended use for restoring the chemical quality of the ground water to its pre-drilled condition.

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[8] Detailed discussion of these and other methods of well development can be found in many references, including Driscoll (1986), Gass (1986), Shuter and Teasdale (1989), and Roscoe Moss Company (1990). General well-development techniques that are appropriate for obtaining water samples representative of ground water also are presented in Claassen (1982), Aller and others (1989), and ASTM (1992, p. 132-133).

Although methods differ substantially in principle and in equipment, the following four development practices apply in most situations (ASTM, 1992, p. 132-133):

- Well development is initiated gently.
- The degree of agitation is increased slowly as flow is established through the intake portions of the well.
- A time limit is not imposed on development; rather, development ends only after development objectives are met.
- Combinations of different development methods could be required to completely develop the well.

The duration of well development varies in accordance with the method of drilling employed, the characteristics of the subsurface materials to which the well is open, construction details of the well and the depth to water level and the height of the water column in the well. The time required to develop a well also depends on development objectives. When the primary objective is to remove drilling artifacts that affect ground-water chemistry, the criteria to assess development are to include (1) removal from the well of the estimated volume (or a multiple of that volume) of drilling fluid that was lost to the aquifer; (2) turbidity—less than 5 NTUs (Nephelometric Turbidity Units) or the known background value for that aquifer (generally no greater than 25 NTUs); and (3) stability—of water-quality measurements in at least five sequential samples of the discharge (fig. 17). Field measurements of water quality collected during development (fig. 17) can be used as a criterion to determine when development objectives have been met. For example, field measurements aid in assessing the effectiveness of the removal of contaminants introduced during drilling. A graph of turbidity or conductivity (specific electrical conductance) measurements over time can help decide when water pumped from a well sufficiently represents original conditions (Claassen,1982).

Bailing

A simple bailer consists of a small-diameter pipe, several feet long, with a check valve at the bottom. The bailer is lowered down the well until it hits the water surface and enters the water column. The impact of the bailer on the water surface initially forces water from the well into the aquifer. The bailer fills with water and is withdrawn from the water column. The withdrawal of the bailer causes water to flow from the aquifer back into the well. Repetition of this procedure loosens and removes fine-grained material, such as silt and clay, and drilling fluid, from the aquifer adjacent to the open or screened intervals of the well, and removes sediment suspended in the well itself.

Bailing is an effective method of well development in relatively clean, permeable aquifers (Aller and others, 1989, p. 237). An advantage of this method over several other commonly used methods is that no air or foreign water is added to the well. Vigorous bailing, however, can collapse the well casing or screen.

Mechanical surging

Mechanical surging, commonly used with cable-tool, auger, and mud-rotary rigs, is similar in principle to bailing. A simple surge block (a short cylindrical device with a diameter that is slightly smaller than the inside diameter of the well casing) is lowered through the water column. The surge block is designed to allow some water to bypass it on the downward stroke; however, the downward motion also forces water from the well into the aquifer. As the surge block is pulled up through the water column, the upward movement induces water to flow from the aquifer back into the well. Repeating this procedure loosens and removes fine-grained material from the aquifer adjacent to the screen or open intervals of the well and cleans the well screen (if used). Loose materials in the well subsequently are removed using a bailer or pump.

Mechanical surging minimizes the stress to the aquifer by uniformly distributing the force applied over the open interval of the well; surging therefore reduces invasion or disturbance of the aquifer, but often it is adequate to develop a well (Shuter and Teasdale, 1989, p. 87). Problems that can be encountered if surging is too vigorous include collapse of the well casing or screen and induction of excessive amounts of loose materials into the well. Both could lock the surge block. As in the case of bailing, an advantage of mechanical surging over several other methods is that no air or foreign water is added to the well during development.

Pumping or overpumping, with backwashing

Repetitive cycles of pumping or overpumping, with backwashing, can be effective methods of well development. Pumping induces water, fine-grained material, and drilling fluid to flow from the aquifer into the well. Backwashing helps prevent bridging of fine-grained material in the filter pack around the well and cleans the well screen (Shuter and Teasdale, 1989). During overpumping, water is withdrawn from the well at a rate that substantially exceeds the ability of the aquifer to deliver water (Aller and others, 1989, p. 242). The effect of overpumping is to remove fine-grained material and drilling fluid from the aquifer in excess of that which would be removed at lower pumping rates used later; for example, during water-quality sampling. Backwashing occurs when the pump is shut off, if there is no antibacksiphon valve on the pump. Once the pump is shut off, the water in the pump line falls back into the well, causing an outward surging of water into the aquifer.

As in the case of bailing and mechanical surging, an advantage of the pumping with backwashing method over other commonly used methods is that no air or foreign water that might affect the quality of ground water is added to the well during development. However, even backwashing done with water pumped from the aquifer can potentially affect ground-water chemistry (see “Backwashing”).

Indirect eduction

Indirect eduction (Anderson, 1984; Driscoll, 1986; Hardy and others, 1989, p. 17) uses air to discharge water through an eduction line. The eduction line is a rigid pipe or flexible tube about 1/2 the diameter of the well. The bottom of the eduction line is placed at the center of the well screen, and an air line is placed inside the eduction line to a depth equivalent to about 1/3 the length of the static water column above the screen. Air is pumped intermittently into the eduction line to create a downward surge of water into the well and out into the aquifer. Although indirect eduction uses air to develop the well, it is designed to avoid introducing air into the aquifer. This reduces the possibility of air affecting ground-water chemistry (Hardy and others, 1989, p. 17). Because the air stream could contain lubricants from the compressor, it is recommended that the air stream be filtered before injection.

Backwashing

Backwashing alone is sometimes used for well development. In backwashing, a pump is used to inject water into the well and out into the aquifer. For wells that are constructed with a well screen and filter pack, the flow through the screen washes and cleans the screen, and helps reduce bridging of fine-grained material in the filter pack around the well screen.

Backwashing can work well in some situations, such as in an auger-drilled hole where the aquifer has collapsed and a well point has been driven or washed into the collapsed material. In this situation, backwashing could lift the collapsed material in a suspended slurry. Upon gradual decrease in the rate of backwashing, the coarser-grained material in the slurry will settle back around the well screen, first creating a coarse-grained filter pack (Shuter and Teasdale, 1989, p. 86).

Because backwashing commonly uses foreign water for injection, the chemistry of the ground water can be affected. Even if the water injected was originally pumped from the same aquifer, the chemistry of the injected water can change before reinjection. For example, gases in the water can volatilize; anoxic water can be oxygenated; or the dissolved-oxygen concentration can increase, which could cause precipitation of chemical species, such as iron and manganese as hydroxides, and affect the concentration of these and pH. Also, backwashing without subsequent pumping of the well in most situations is not a good technique for well development because fine-grained material and drilling fluid are not drawn into the well and removed (Shuter and Teasdale,1989, p. 86).

Jetting and surging with water or air

Jetting and surging requires injection of either water or air into the well. The injection of the air or foreign water can alter the chemistry of the ground water in the vicinity of the well screen. It is extremely difficult to quantitatively determine the effects of the air or foreign water on the chemistry of the ground water. Consequently, if a well is to be used to sample ground water, methods of development that employ injection of air or foreign water are avoided, unless no alternative method is possible.

If no method other than jetting and surging with either water or air is possible, steps can be taken to reduce, and possibly quantify, the effects of injection of the water or air (Aller and others, 1989, p. 232). If water is injected, the chemistry of the ground water can change simply because of mixing of the two water types and complex chemical reactions also can occur. Consequently, at the very least, both the volume and chemical quality of the injection water is documented. Ideally, water of similar chemical composition to that of the ground water is injected. Even if the water injected was originally pumped from the same aquifer, however, the water chemistry can change before reinjection.

Injection with air during development can cause several problems that are difficult to prevent or quantify. The air forced into the aquifer can cause chemical reactions between the air and ground water. Air-ground water contact can occur for a longer period of time than the time required for development because air can become trapped in the aquifer. Trapped air also can cause an air lock, which can reduce flow to the well.

The air stream also contains lubricants from the compressor and must be filtered before injection. Collecting water-quality samples during development to analyze for compressor oil and lubricants and to measure dissolved-oxygen concentrations can aid in assessing some of the effects of well development with air.

Field Screening During Development

Characteristics of the chemistry of well water can be screened during development using immunoassay tests, gas chromatography, and spectrophotometers to analyze samples in the field. Field screening during development can be useful in planning for sample collection. For example, these data can help to determine the order in which wells in a network are to be sampled by identifying wells with highly contaminated water. The highly contaminated wells would be sampled at the end of a sampling round, thereby lowering the risk of cross contamination between wells or among samples by contaminated sampling equipment. In addition, this information would be used to alert the laboratory doing the chemical analyses and prevent hazards to personnel and fouling of laboratory equipment. Field screening also can be used to identify sites where extra care will be required when decontaminating sampling equipment, and where safety, such as health concerns, could be an issue during pumping and sampling.

Well Disposition

At the end of a study, options need to be considered for the disposition of a well: the well can be maintained, ownership can be transferred, or the well can be destroyed (abandoned).

- USGS procedure and policy for release of an observation (or monitoring) well to the land owner are provided in WRD Memorandum 87.017.
- USGS procedure and policy for abandoning a well, stated in WRD Memorandum 88.021, is that the well be plugged and filled according to State law. If no State law exists, the casing is cut off at 2 ft (~0.6 m) below ground surface and filled with grout from the bottom to the casing cut-off; then the excavation is filled with native material. If allowed by State law, another option is to pull the casing from the ground; this is an expensive process which usually exceeds the salvage value of the casing. If the casing is pulled, however, the open hole must be grouted according to State law.

Federal, State, and local regulations might not allow certain types of installations (such as direct push) to be permanent monitoring wells, and the installation is removed immediately after use. In this case, the need for backfilling the annulus after removal is assessed on the basis of the size of the annulus, ground-water quality, and the potential for movement of contaminants from land surface to ground water or among water-bearing units. For example, a small-diameter direct-push borehole, such as a cone penetrometer hole that is 1.4 to 1.5 in. (36 to 38 mm) in diameter, would require no backfilling if the hole naturally closes or caves sufficiently to reduce water transmission. Backfill grouting of small diameter holes that do not naturally cave in is difficult and expensive. Nevertheless, grouting the hole is required because surface and cross contamination between aquifers could be possible if an annulus is left open.

For test holes in which no well is installed, the hole is abandoned according to Federal, State, or local regulations. If the test hole collapses naturally, a minimum requirement for backfilling is to seal the surface of the hole to prevent hazards to those at the surface and to eliminate direct movement of surface contaminants to ground water. In cases where the test hole remains open, the hole must be completely backfilled. Grouting can displace ground water from the hole to the surface. If the ground water is contaminated, State law could require this water to be collected and disposed of properly.

MANDATORY: FOLLOW STATE REGULATIONS WHEN A WELL IS ABANDONED.

EXAMPLES OF FORMS CITED IN THIS REPORT

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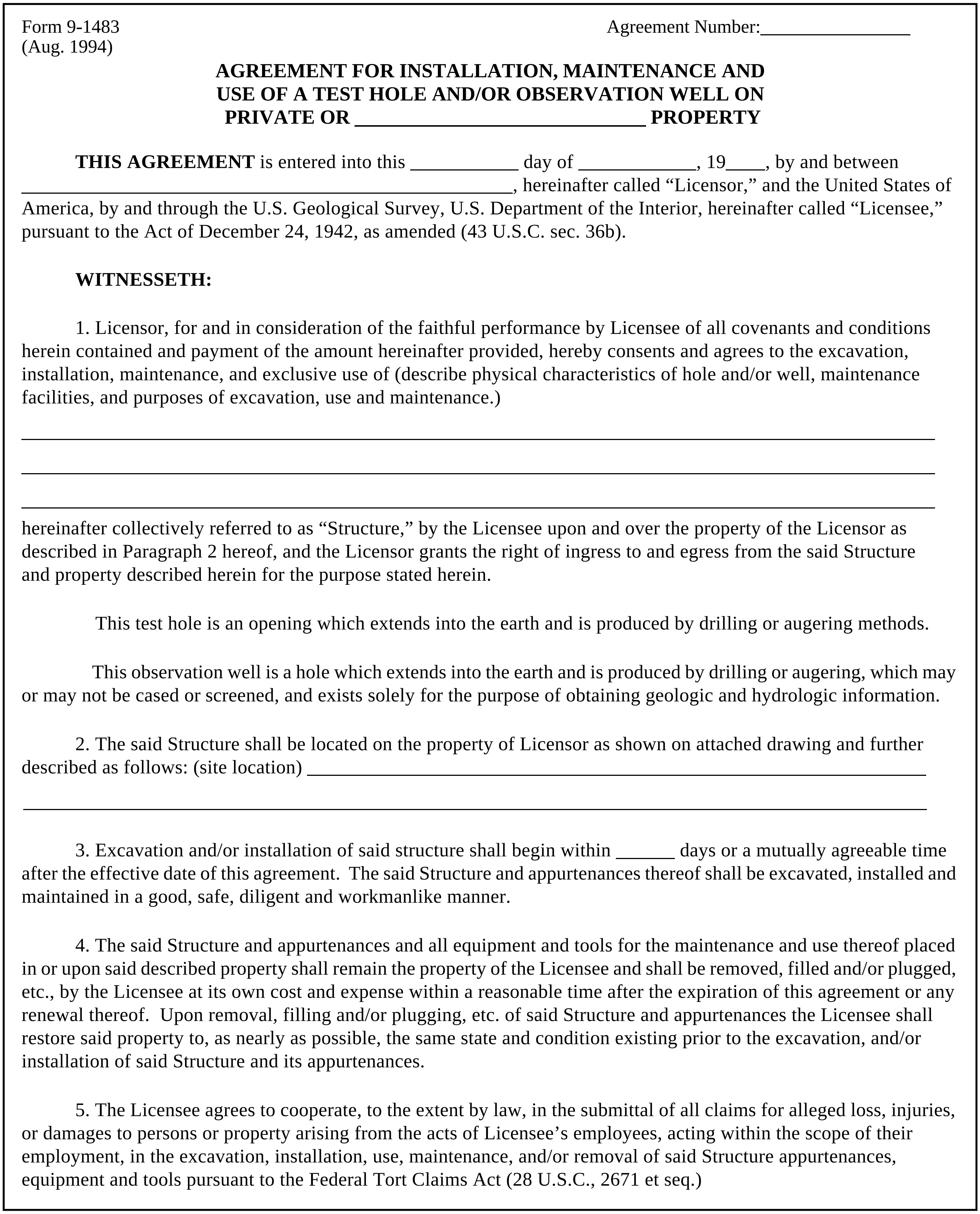


Form 9-1483
(Aug. 1994)

Agreement Number:________________

AGREEMENT FOR INSTALLATION, MAINTENANCE AND USE OF A TEST HOLE AND/OR OBSERVATION WELL ON PRIVATE OR ______________________________ PROPERTY

THIS AGREEMENT is entered into this ___________ day of ____________, 19____, by and between ____, hereinafter called “Licensor,” and the United States of America, by and through the U.S. Geological Survey, U.S. Department of the Interior, hereinafter called “Licensee,” pursuant to the Act of December 24, 1942, as amended (43 U.S.C. sec. 36b).

WITNESSETH:

1. Licensor, for and in consideration of the faithful performance by Licensee of all covenants and conditions herein contained and payment of the amount hereinafter provided, hereby consents and agrees to the excavation, installation, maintenance, and exclusive use of (describe physical characteristics of hole and/or well, maintenance facilities, and purposes of excavation, use and maintenance.)

____

____

____

hereinafter collectively referred to as “Structure,” by the Licensee upon and over the property of the Licensor as described in Paragraph 2 hereof, and the Licensor grants the right of ingress to and egress from the said Structure and property described herein for the purpose stated herein.

This test hole is an opening which extends into the earth and is produced by drilling or augering methods.

This observation well is a hole which extends into the earth and is produced by drilling or augering, which may or may not be cased or screened, and exists solely for the purpose of obtaining geologic and hydrologic information.

2. The said Structure shall be located on the property of Licensor as shown on attached drawing and further described as follows: (site location) ____

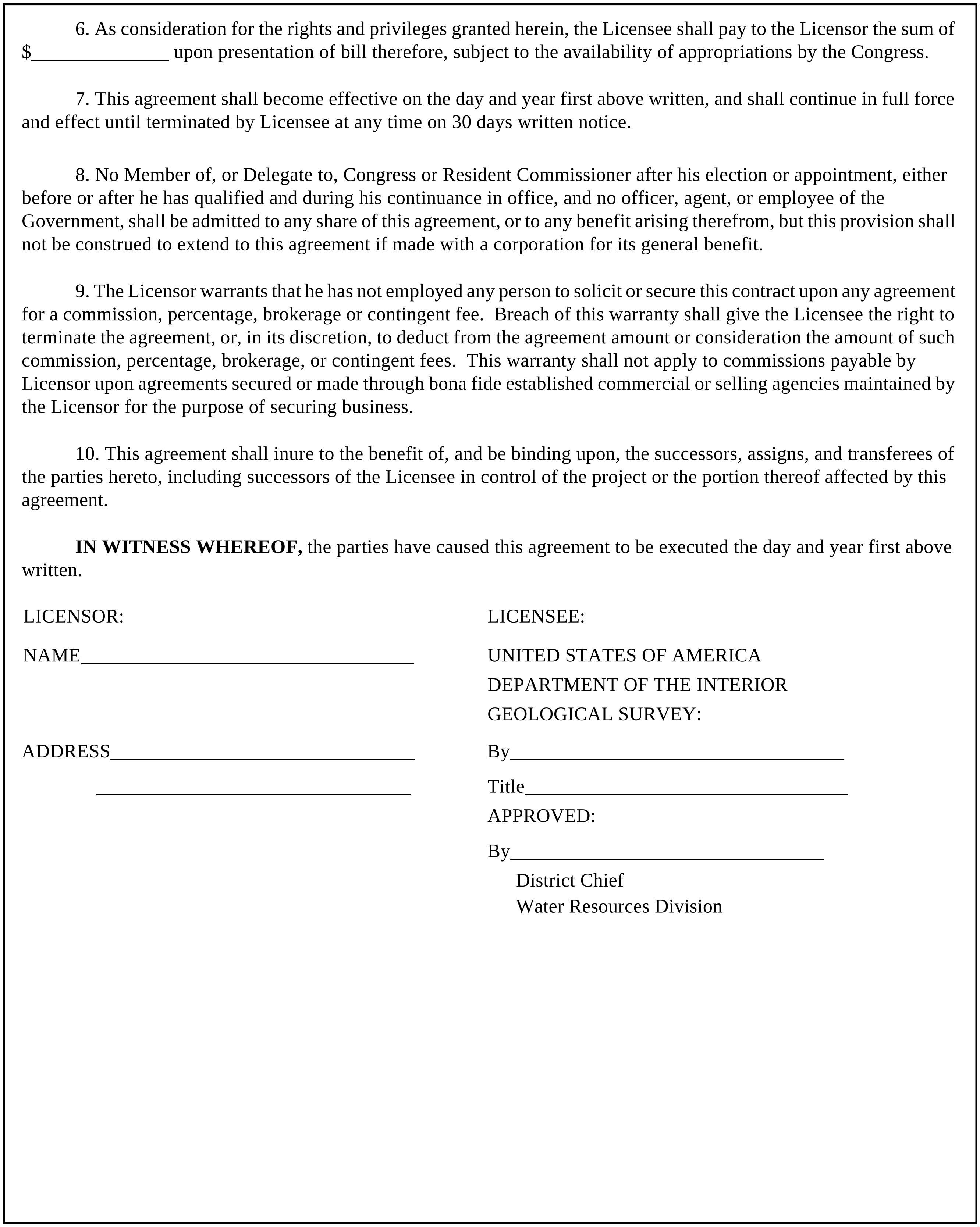
____

3. Excavation and/or installation of said structure shall begin within ______ days or a mutually agreeable time after the effective date of this agreement. The said Structure and appurtenances thereof shall be excavated, installed and maintained in a good, safe, diligent and workmanlike manner.

4. The said Structure and appurtenances and all equipment and tools for the maintenance and use thereof placed in or upon said described property shall remain the property of the Licensee and shall be removed, filled and/or plugged, etc., by the Licensee at its own cost and expense within a reasonable time after the expiration of this agreement or any renewal thereof. Upon removal, filling and/or plugging, etc. of said Structure and appurtenances the Licensee shall restore said property to, as nearly as possible, the same state and condition existing prior to the excavation, and/or installation of said Structure and its appurtenances.

5. The Licensee agrees to cooperate, to the extent by law, in the submittal of all claims for alleged loss, injuries, or damages to persons or property arising from the acts of Licensee’s employees, acting within the scope of their employment, in the excavation, installation, use, maintenance, and/or removal of said Structure appurtenances, equipment and tools pursuant to the Federal Tort Claims Act (28 U.S.C., 2671 et seq.)

Figure 10a. *Reproduction of Form 9-1483 (Aug. 1994), “Agreement for Installation, Maintenance and Use of a Test Hole and/or Observation Well on Private or _____ Property.”*



6. As consideration for the rights and privileges granted herein, the Licensee shall pay to the Licensor the sum of $_______________ upon presentation of bill therefore, subject to the availability of appropriations by the Congress.

7. This agreement shall become effective on the day and year first above written, and shall continue in full force and effect until terminated by Licensee at any time on 30 days written notice.

8. No Member of, or Delegate to, Congress or Resident Commissioner after his election or appointment, either before or after he has qualified and during his continuance in office, and no officer, agent, or employee of the Government, shall be admitted to any share of this agreement, or to any benefit arising therefrom, but this provision shall not be construed to extend to this agreement if made with a corporation for its general benefit.

9. The Licensor warrants that he has not employed any person to solicit or secure this contract upon any agreement for a commission, percentage, brokerage or contingent fee. Breach of this warranty shall give the Licensee the right to terminate the agreement, or, in its discretion, to deduct from the agreement amount or consideration the amount of such commission, percentage, brokerage, or contingent fees. This warranty shall not apply to commissions payable by Licensor upon agreements secured or made through bona fide established commercial or selling agencies maintained by the Licensor for the purpose of securing business.

10. This agreement shall inure to the benefit of, and be binding upon, the successors, assigns, and transferees of the parties hereto, including successors of the Licensee in control of the project or the portion thereof affected by this agreement.

IN WITNESS WHEREOF, the parties have caused this agreement to be executed the day and year first above written.

LICENSOR:

NAME___________________________________

ADDRESS________________________________
____

LICENSEE:

UNITED STATES OF AMERICA
DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY:

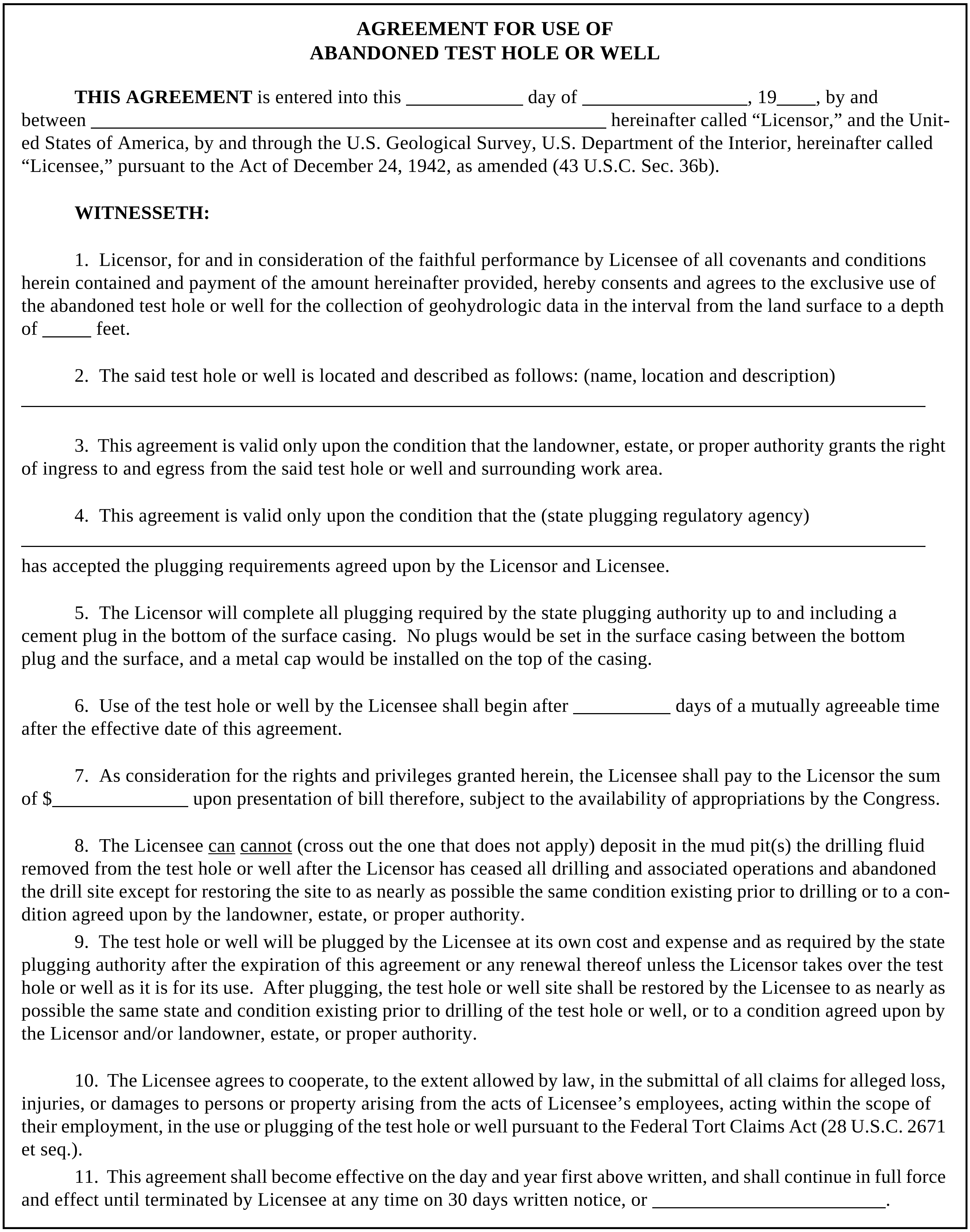
By___________________________________

Title___________________________________

APPROVED:

By_________________________________
District Chief
Water Resources Division

Figure 10a. *Reproduction of Form 9-1483 (Aug. 1994), "Agreement for Installation, Maintenance and Use of a Test Hole and/or Observation Well on Private or _____ Property"--Continued.*



AGREEMENT FOR USE OF ABANDONED TEST HOLE OR WELL

THIS AGREEMENT is entered into this ____________ day of _________________, 19____, by and between ____ hereinafter called “Licensor,” and the United States of America, by and through the U.S. Geological Survey, U.S. Department of the Interior, hereinafter called “Licensee,” pursuant to the Act of December 24, 1942, as amended (43 U.S.C. Sec. 36b).

WITNESSETH:

1. Licensor, for and in consideration of the faithful performance by Licensee of all covenants and conditions herein contained and payment of the amount hereinafter provided, hereby consents and agrees to the exclusive use of the abandoned test hole or well for the collection of geohydrologic data in the interval from the land surface to a depth of _____ feet.

2. The said test hole or well is located and described as follows: (name, location and description)

____

3. This agreement is valid only upon the condition that the landowner, estate, or proper authority grants the right of ingress to and egress from the said test hole or well and surrounding work area.

4. This agreement is valid only upon the condition that the (state plugging regulatory agency)

____

has accepted the plugging requirements agreed upon by the Licensor and Licensee.

5. The Licensor will complete all plugging required by the state plugging authority up to and including a cement plug in the bottom of the surface casing. No plugs would be set in the surface casing between the bottom plug and the surface, and a metal cap would be installed on the top of the casing.

6. Use of the test hole or well by the Licensee shall begin after __________ days of a mutually agreeable time after the effective date of this agreement.

7. As consideration for the rights and privileges granted herein, the Licensee shall pay to the Licensor the sum of $______________ upon presentation of bill therefore, subject to the availability of appropriations by the Congress.

8. The Licensee can cannot (cross out the one that does not apply) deposit in the mud pit(s) the drilling fluid removed from the test hole or well after the Licensor has ceased all drilling and associated operations and abandoned the drill site except for restoring the site to as nearly as possible the same condition existing prior to drilling or to a condition agreed upon by the landowner, estate, or proper authority.

9. The test hole or well will be plugged by the Licensee at its own cost and expense and as required by the state plugging authority after the expiration of this agreement or any renewal thereof unless the Licensor takes over the test hole or well as it is for its use. After plugging, the test hole or well site shall be restored by the Licensee to as nearly as possible the same state and condition existing prior to drilling of the test hole or well, or to a condition agreed upon by the Licensor and/or landowner, estate, or proper authority.

10. The Licensee agrees to cooperate, to the extent allowed by law, in the submittal of all claims for alleged loss, injuries, or damages to persons or property arising from the acts of Licensee’s employees, acting within the scope of their employment, in the use or plugging of the test hole or well pursuant to the Federal Tort Claims Act (28 U.S.C. 2671 et seq.).

11. This agreement shall become effective on the day and year first above written, and shall continue in full force and effect until terminated by Licensee at any time on 30 days written notice, or ________________________.

Figure 10b. *Sample of form for agreement for use of abandoned test hole or well.*

12. No Member of or Delegate to Congress or Resident Commissioner after his election or appointment, either before or after he has qualified and during his continuance in office, and no officer, agent, or employee of the Government, shall be admitted to any share of this agreement, or to any benefit arising therefrom, but this provision shall not be constructed to extent to this agreement if made with a corporation for its general benefit.

13. The Licensor warrants that he has not employed any person to solicit or secure this contract upon any agreement for a commission, percentage, brokerage, or contingent fee. Breach of this warranty shall give the Licensee the right to terminate the agreement, or, in its discretion, to deduct from the agreement amount or consideration the amount of such commission, percentage, brokerage, or contingent fees. This warranty shall not apply to commissions payable by Licensor upon agreements secured or made through bona fide established commercial or selling agencies maintained by the Licensor for the purpose of securing business.

14. This agreement shall inure to the benefit of and be binding upon the successors, assigns, and transferees of the parties hereto, including successors of the Licensee in control of the project or the portion thereof affected by this agreement.

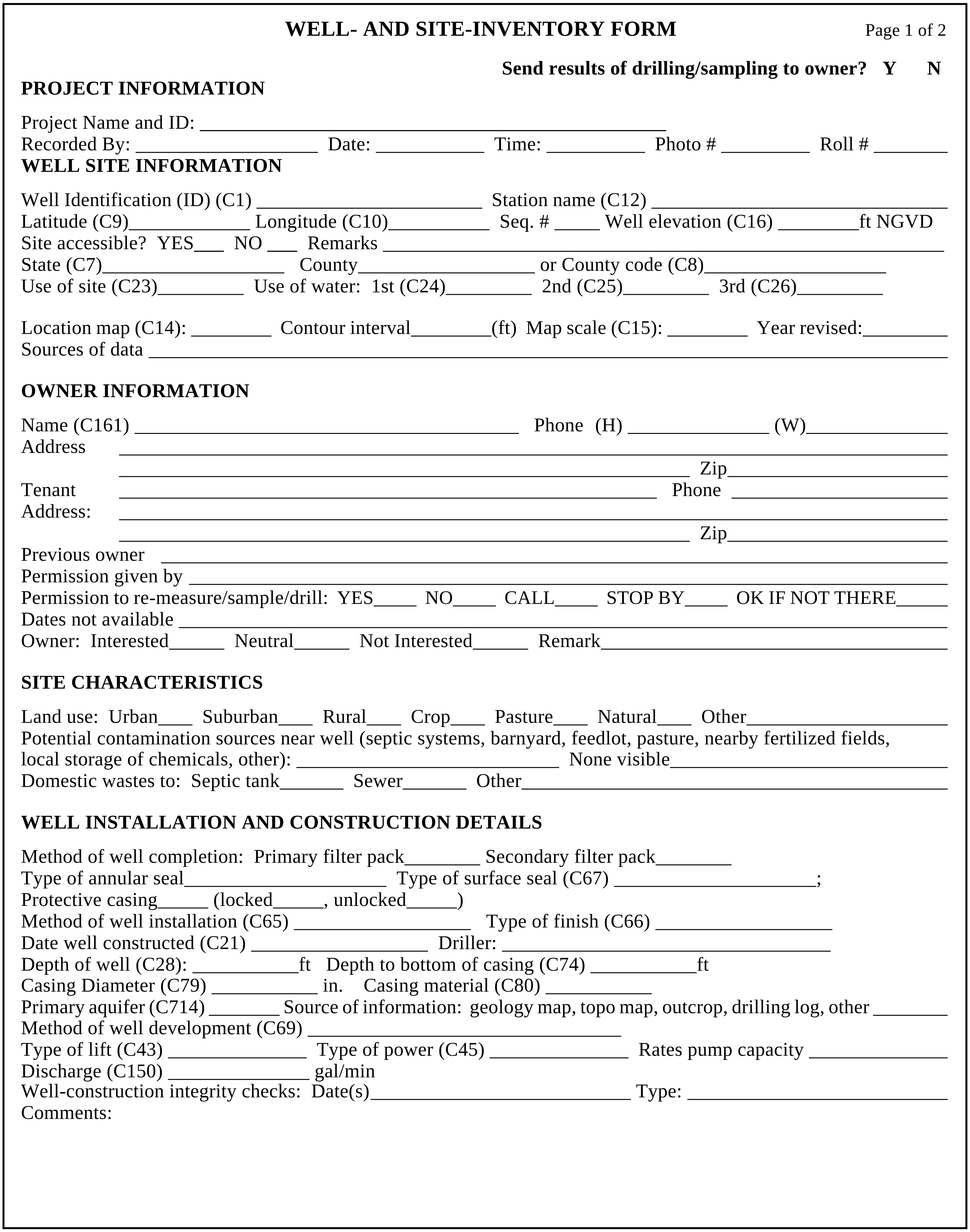
IN WITNESS WHEREOF, the parties have caused these presents to be executed the day and year first above written.

LICENSOR:
NAME___________________________________

ADDRESS________________________________
____
____

LICENSEE:
UNITED STATES OF AMERICA
DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY:
By___________________________________
Title_________________________________
APPROVED:
By________________________________
District Chief
Water Resources Division

Figure 10b. *Sample of form for agreement for use of abandoned test hole or well--Continued*



WELL- AND SITE-INVENTORY FORM Page 1 of 2

Send results of drilling/sampling to owner? Y N

PROJECT INFORMATION

Project Name and ID: ____________________
Recorded By: __________ Date: ________ Time: ________ Photo # ________ Roll # ________

WELL SITE INFORMATION

Well Identification (ID) (C1) ______________ Station name (C12) ______________
Latitude (C9)__________ Longitude (C10)__________ Seq. # _____ Well elevation (C16) ________ft NGVD
Site accessible? YES___ NO ___ Remarks ______________________________
State (C7)__________ County__________ or County code (C8)__________
Use of site (C23)________ Use of water: 1st (C24)________ 2nd (C25)________ 3rd (C26)________

Location map (C14): ________ Contour interval________(ft) Map scale (C15): ________ Year revised:________
Sources of data ______________________________

OWNER INFORMATION

Name (C161) ____________________ Phone (H) ____________ (W)____________
Address ______________________________
______________________________ Zip____________
Tenant ______________________________ Phone ____________
Address: ______________________________
______________________________ Zip____________
Previous owner ______________________________
Permission given by ______________________________
Permission to re-measure/sample/drill: YES_____ NO_____ CALL_____ STOP BY_____ OK IF NOT THERE_____
Dates not available ______________________________
Owner: Interested______ Neutral______ Not Interested______ Remark____________________

SITE CHARACTERISTICS

Land use: Urban____ Suburban____ Rural____ Crop____ Pasture____ Natural____ Other____________
Potential contamination sources near well (septic systems, barnyard, feedlot, pasture, nearby fertilized fields, local storage of chemicals, other): ______________ None visible______________
Domestic wastes to: Septic tank_______ Sewer_______ Other____________________

WELL INSTALLATION AND CONSTRUCTION DETAILS

Method of well completion: Primary filter pack________ Secondary filter pack________
Type of annular seal______________ Type of surface seal (C67) ______________;
Protective casing_____ (locked_____, unlocked_____)
Method of well installation (C65) ______________ Type of finish (C66) ______________
Date well constructed (C21) ______________ Driller: ____________________
Depth of well (C28): __________ft Depth to bottom of casing (C74) __________ft
Casing Diameter (C79) __________ in. Casing material (C80) __________
Primary aquifer (C714) ________ Source of information: geology map, topo map, outcrop, drilling log, other ________
Method of well development (C69) ____________________
Type of lift (C43) ____________ Type of power (C45) ____________ Rates pump capacity ____________
Discharge (C150) ____________ gal/min
Well-construction integrity checks: Date(s)______________ Type: ______________
Comments:

Figure 11. *Example of a well- and site-inventory form.*

WELL- AND SITE-INVENTORY FORM

Page 2 of 2

WATER LEVEL

Can water level be measured? YES_____ NO_____ Why not?_________________ If yes, method (C34)______

	Hold_______________	Hold_______________	Hold_______________
	Cut________________	Cut________________	Cut________________
	= __________________	= __________________	= __________________
	+/-mp______________	+/-mp______________	+/-mp______________
Water level, in ft below LS (C30 or C237)	__________________	__________________	__________________

Water-level status (C238): ____

SAMPLING INFORMATION

Can well be sampled? YES_____ NO_____ Why not?____
Sampling tap location: __________ Plumbing needed: __________ Holding tank: YES_____ NO_____ Size_____
Sample before tank? YES_____ NO_____
Water quality? Taste: _____ Odor: _____ Color: _____ Remarks: _____________________________________
Water treated? YES_____ NO_____ Type: Filtration_____ Softening_____ Other_________________________
Minimum rate at which pump in well can be operated: _________________gal/min

WATER-QUALITY FIELD MEASUREMENTS

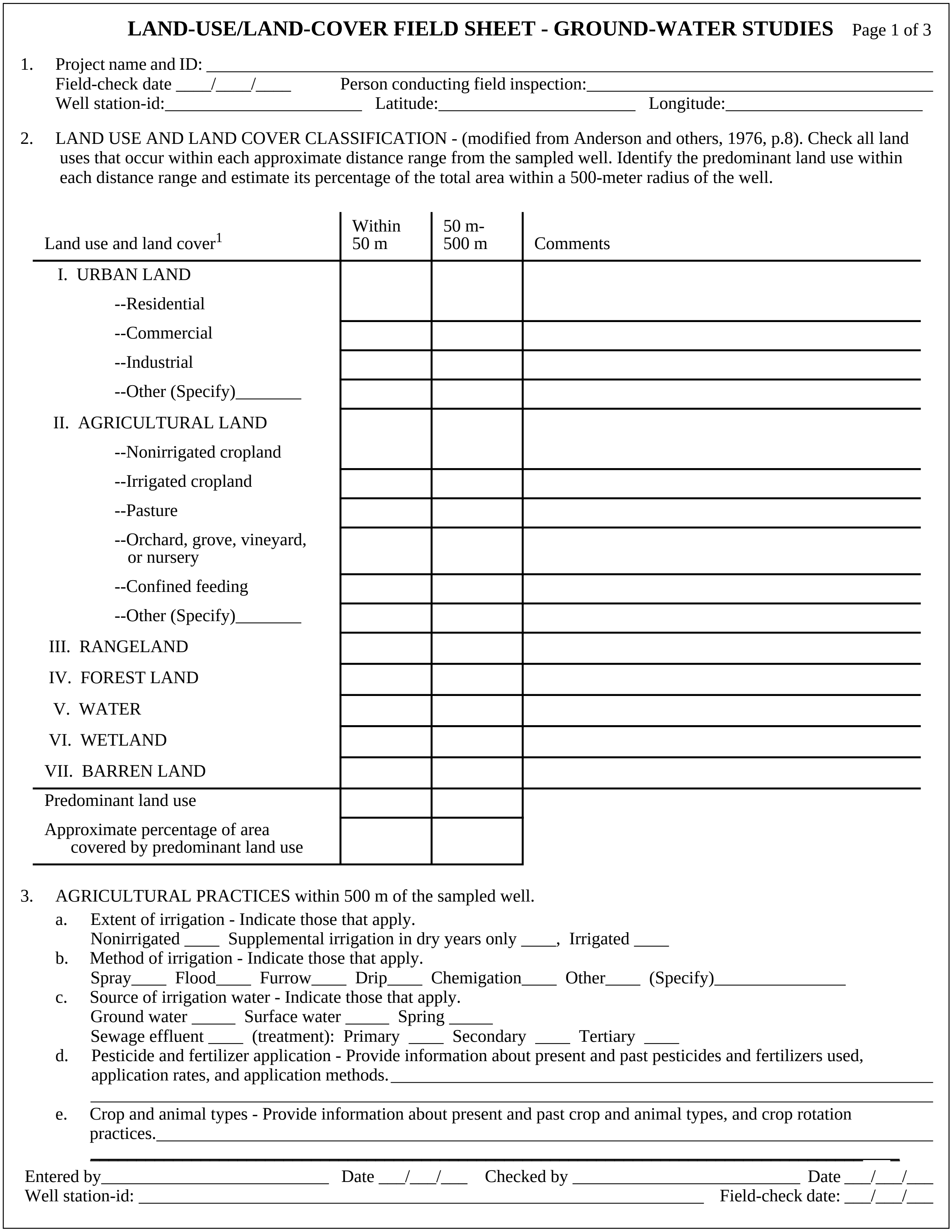
Location of sampling point____
00010 Temperature _______^{o}C 00095 Specific Electrical Conductance __________µS/cm
00400 pH _____________ 00300 Dissolved oxygen ___________mg/L 00076 Turbidity___________NTU
Other _____________________

AVAILABILITY OF ADDITIONAL INFORMATION (refer to Well Information Check List and include in inventory file):

Water-level records? YES_____ NO_____ Remarks ____
Pumping records? YES_____ NO_____ Remarks ____
Water-chemistry records? YES_____ NO_____ Remarks ____
Borehole geophysical logs? YES_____ NO_____ Type____
Surface geophysical surveys? YES_____ NO_____ Type____
Aquifer tests? YES_____ NO_____ Type____
Geologic materials samples? YES_____ NO_____ Type____
Land-use records for well vicinity (for example, pesticide and fertilizer application rates):

REMARKS AND SITE SKETCH (Township_________ Range_________ Section_________ Quarter_________):

Figure 11. *Example of a well- and site-inventory form--Continued*



LAND-USE/LAND-COVER FIELD SHEET - GROUND-WATER STUDIES Page 1 of 3

1. Project name and ID: ____
Field-check date ____/____/____ Person conducting field inspection:______________________
Well station-id:______________________ Latitude:______________________ Longitude:______________________

2. LAND USE AND LAND COVER CLASSIFICATION - (modified from Anderson and others, 1976, p.8). Check all land uses that occur within each approximate distance range from the sampled well. Identify the predominant land use within each distance range and estimate its percentage of the total area within a 500-meter radius of the well.

Land use and land cover[1]	Within 50 m	50 m-500 m	Comments
I. URBAN LAND			
--Residential			
--Commercial			
--Industrial			
--Other (Specify)________			
II. AGRICULTURAL LAND			
--Nonirrigated cropland			
--Irrigated cropland			
--Pasture			
--Orchard, grove, vineyard, or nursery			
--Confined feeding			
--Other (Specify)________			
III. RANGELAND			
IV. FOREST LAND			
V. WATER			
VI. WETLAND			
VII. BARREN LAND			
Predominant land use			
Approximate percentage of area covered by predominant land use			

3. AGRICULTURAL PRACTICES within 500 m of the sampled well.
   a. Extent of irrigation - Indicate those that apply.
   Nonirrigated ____ Supplemental irrigation in dry years only ____, Irrigated ____
   b. Method of irrigation - Indicate those that apply.
   Spray____ Flood____ Furrow____ Drip____ Chemigation____ Other____ (Specify)________________
   c. Source of irrigation water - Indicate those that apply.
   Ground water _____ Surface water _____ Spring _____
   Sewage effluent ____ (treatment): Primary ____ Secondary ____ Tertiary ____
   d. Pesticide and fertilizer application - Provide information about present and past pesticides and fertilizers used, application rates, and application methods.________________________________
   ____
   e. Crop and animal types - Provide information about present and past crop and animal types, and crop rotation practices.________________________________
   ____

Entered by__________________________ Date ___/___/___ Checked by __________________________ Date ___/___/___
Well station-id: ____ Field-check date: ___/___/___

Figure 12. *Example of a land-use and land-cover field sheet.*

LAND-USE/LAND-COVER FIELD SHEET - GROUND-WATER STUDIES

Page 2 of 3

4. LOCAL FEATURES - Indicate all local features that may affect ground-water quality which occur within each approximate distance range from the sampled well.

Feature	Within 50 m	50 m - 500 m	Comments
Gas station			
Dry cleaner			
Chemical plant or storage facility			
Airport			
Military base			
Road			
Pipeline or fuel storage facility			
Septic field			
Waste disposal pond			
Landfill			
Golf course			
Stream, river, or creek Perennial ___ Ephemeral ___			
Irrigation canal Lined ___ Unlined ___			
Drainage ditch Lined ___ Unlined ___			
Tile drains			
Lake Natural ___ Manmade ___			
Reservoir Lined ___ Unlined ___			
Bay or estuary			
Spring Geothermal (> 25^{o}C)___ Nongeothermal ___			
Salt flat or playa Dry ___ Wet ___			
Mine, quarry, or pit Active ___ Abandoned ___			
Oil well			
Major withdrawal well			
Waste injection well			
Recharge injection well			
Other ______________			

Figure 12. *Example of a land-use and land-cover field sheet--Continued.*

LAND-USE/LAND-COVER FIELD SHEET - GROUND-WATER STUDIES Page 3 of 3

5. LAND-USE CHANGES - Have there been major changes in the last 10 years in land use within 500 m of the sampled well?
Yes____, Probably____, Probably not____, No____ If yes, describe major changes.

____

____

____

____

____

____

6. ADDITIONAL COMMENTS - Emphasize factors that might influence local ground-water quality.

____

____

____

____

____

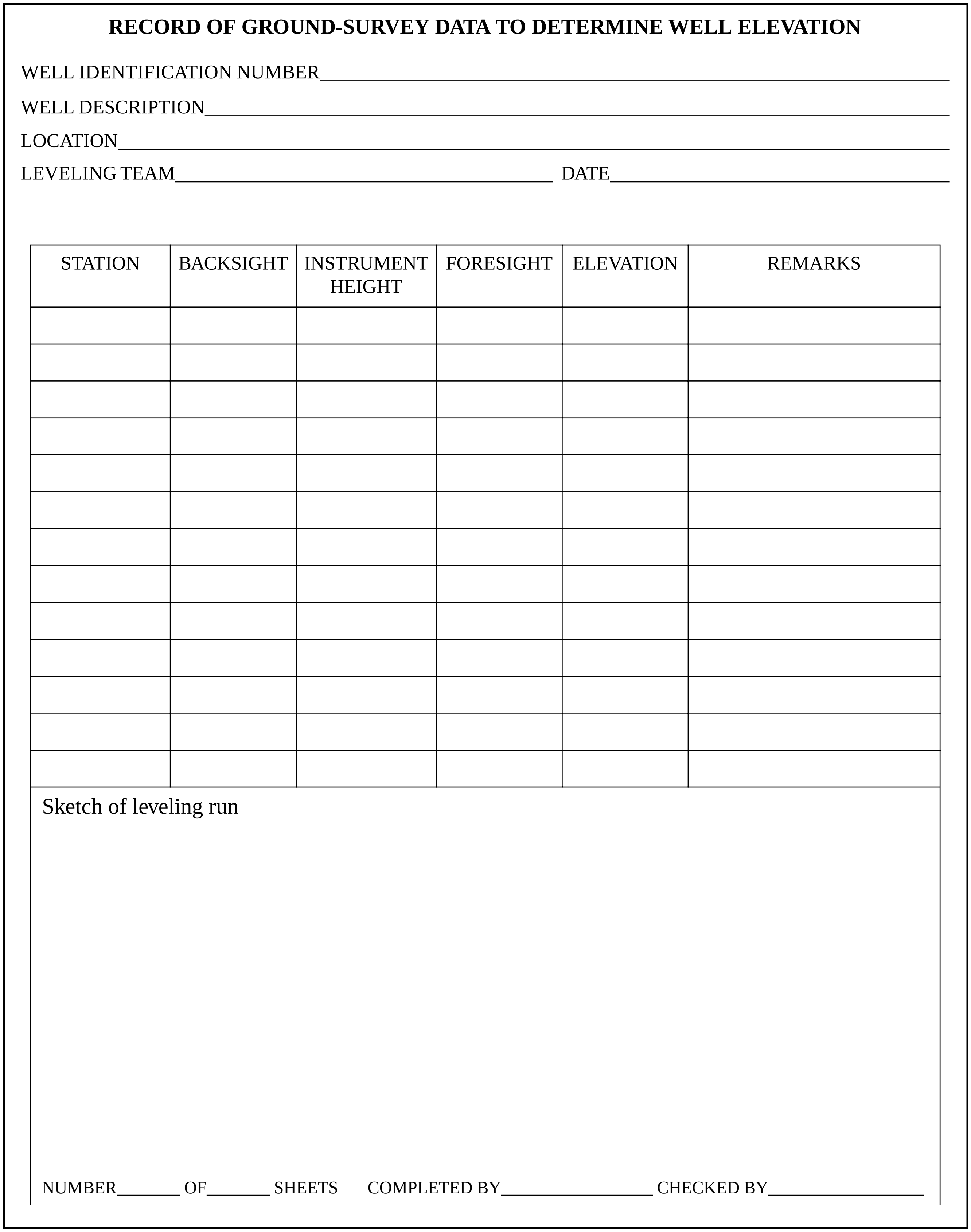
____

Remarks

---

[1] Quantitative data, such as the percentage of land use and land cover near a well, is required to establish relations between land use and ground-water quality.

Figure 12. *Example of a land-use and land-cover field sheet--Continued.*



RECORD OF GROUND-SURVEY DATA TO DETERMINE WELL ELEVATION

WELL IDENTIFICATION NUMBER______________________________

WELL DESCRIPTION______________________________

LOCATION______________________________

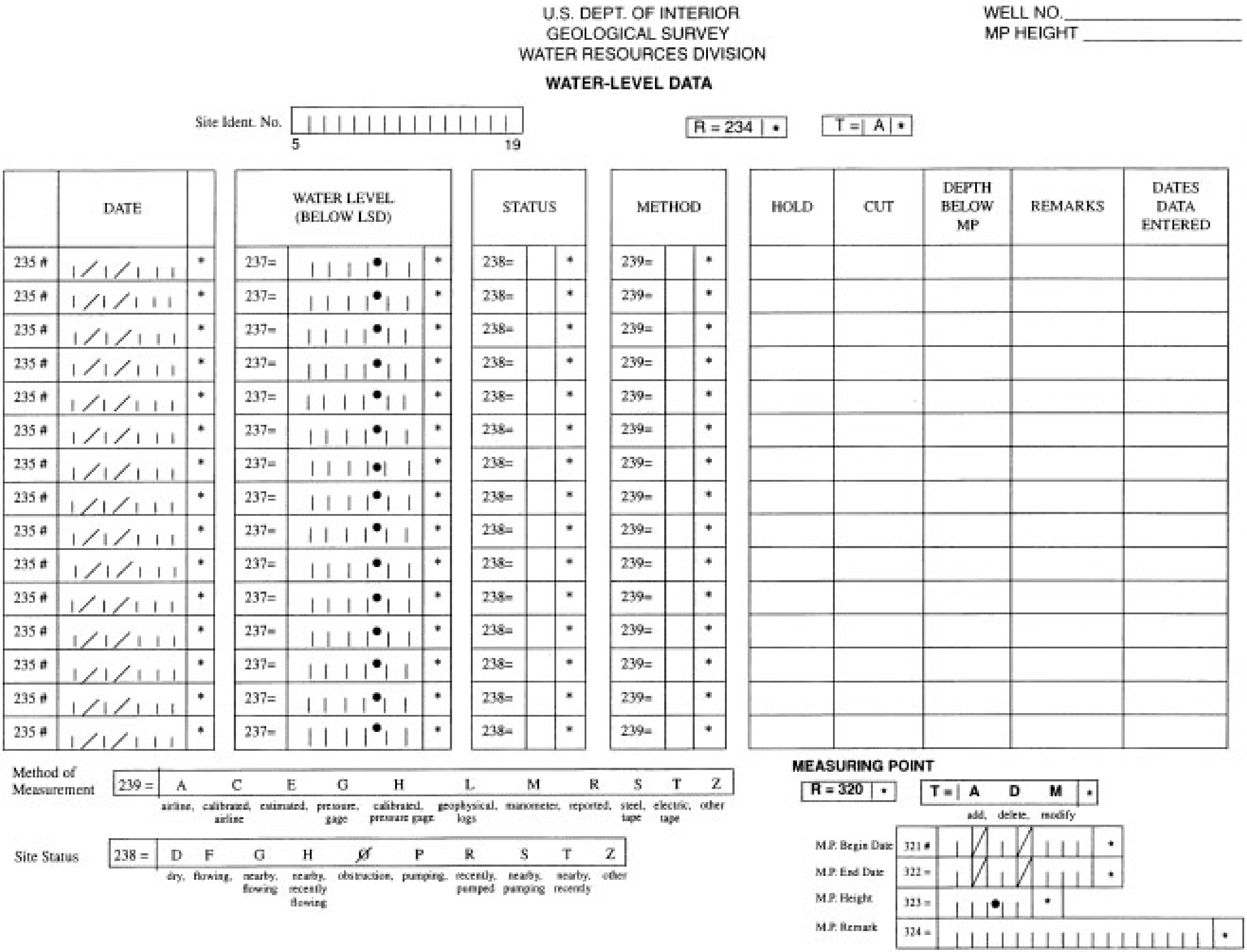
LEVELING TEAM____________________ DATE____________________

STATION	BACKSIGHT	INSTRUMENT HEIGHT	FORESIGHT	ELEVATION	REMARKS

Sketch of leveling run

NUMBER_______ OF_______ SHEETS COMPLETED BY________________ CHECKED BY________________

Figure 13. *Example of a form to record ground-survey data used to determine the elevation of a well.*



U.S. DEPT. OF INTERIOR
GEOLOGICAL SURVEY
WATER RESOURCES DIVISION

WELL NO.________________
MP HEIGHT ________________

WATER-LEVEL DATA

Site Ident. No. | | | | | | | | | | | | | | | 5 19

R = 234 | *

T = | A | *

	DATE		WATER LEVEL (BELOW LSD)			STATUS			METHOD			HOLD	CUT	DEPTH BELOW MP	REMARKS	DATES DATA ENTERED
235 #	/ /	*	237=	.	*	238=		*	239=		*					
235 #	/ /	*	237=	.	*	238=		*	239=		*					
235 #	/ /	*	237=	.	*	238=		*	239=		*					
235 #	/ /	*	237=	.	*	238=		*	239=		*					
235 #	/ /	*	237=	.	*	238=		*	239=		*					
235 #	/ /	*	237=	.	*	238=		*	239=		*					
235 #	/ /	*	237=	.	*	238=		*	239=		*					
235 #	/ /	*	237=	.	*	238=		*	239=		*					
235 #	/ /	*	237=	.	*	238=		*	239=		*					
235 #	/ /	*	237=	.	*	238=		*	239=		*					
235 #	/ /	*	237=	.	*	238=		*	239=		*					
235 #	/ /	*	237=	.	*	238=		*	239=		*					
235 #	/ /	*	237=	.	*	238=		*	239=		*					
235 #	/ /	*	237=	.	*	238=		*	239=		*					
235 #	/ /	*	237=	.	*	238=		*	239=		*					

Method of Measurement	239 =	A	C	E	G	H	L	M	R	S	T	Z
		airline,	calibrated, airline	estimated,	pressure, gage	calibrated, pressure gage	geophysical, logs	manometer,	reported,	steel, tape	electric, tape	other

Site Status	238 =	D	F	G	H	Ø	P	R	S	T	Z
		dry,	flowing,	nearby, flowing	nearby, recently flowing	obstruction,	pumping,	recently, pumped	nearby, pumping	nearby, recently	other

MEASURING POINT

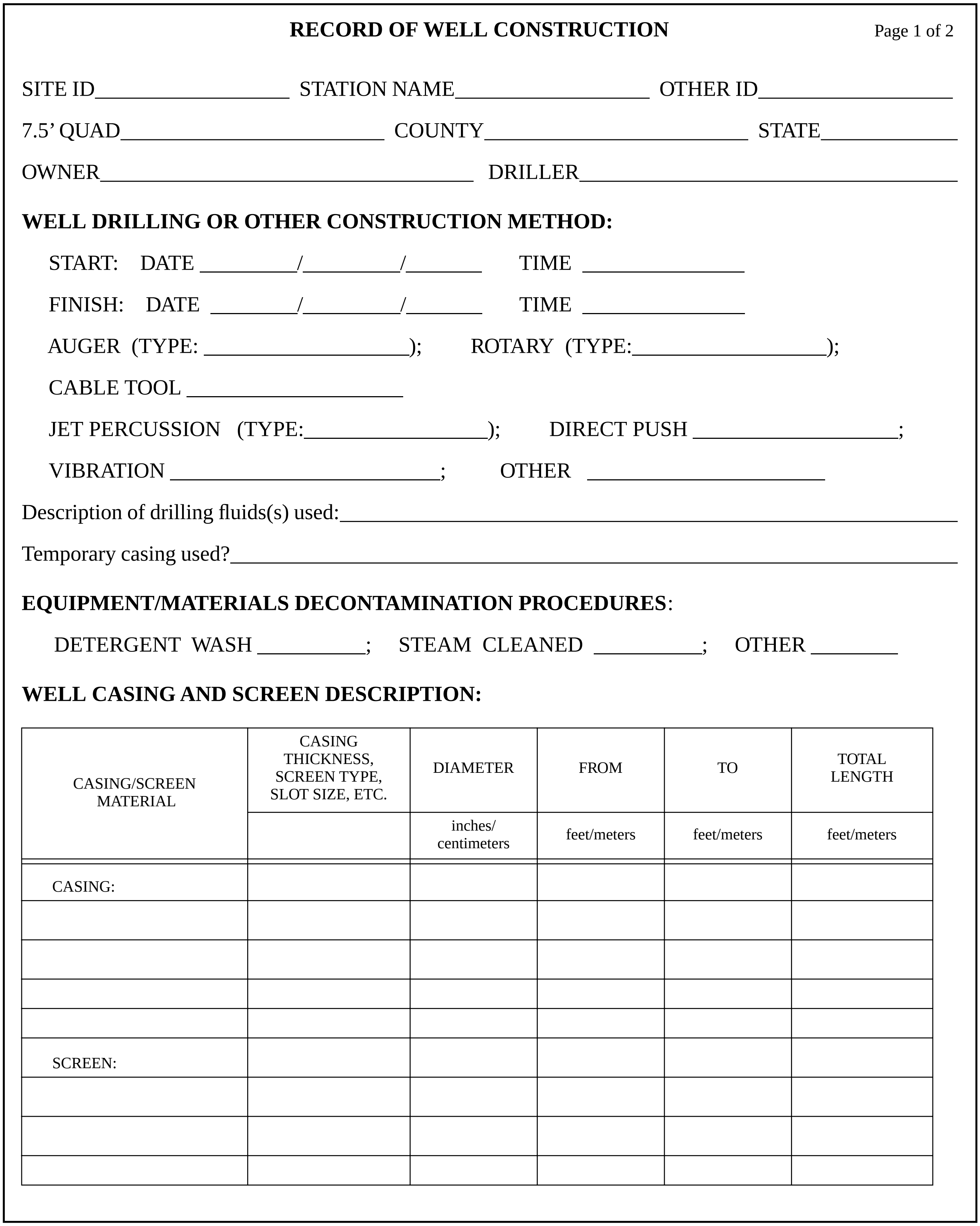
R = 320 | *

T = | A D M | *

add, delete, modify

M.P. Begin Date	321 #	/ /	*
M.P. End Date	322 =	/ /	*
M.P. Height	323 =	.	*
M.P. Remark	324 =		*

Figure 14. *Example of a form to record water-level data in a well.*



RECORD OF WELL CONSTRUCTION

Page 1 of 2

SITE ID__________________ STATION NAME__________________ OTHER ID__________________

7.5’ QUAD_________________________ COUNTY_________________________ STATE_____________

OWNER___________________________________ DRILLER____________________________________

WELL DRILLING OR OTHER CONSTRUCTION METHOD:

START: DATE _________/_________/_______ TIME _______________

FINISH: DATE ________/_________/_______ TIME _______________

AUGER (TYPE: ___________________); ROTARY (TYPE:__________________);

CABLE TOOL ____________________

JET PERCUSSION (TYPE:_________________); DIRECT PUSH ___________________;

VIBRATION _________________________; OTHER ______________________

Description of drilling fluids(s) used:____

Temporary casing used?____

EQUIPMENT/MATERIALS DECONTAMINATION PROCEDURES:

DETERGENT WASH __________; STEAM CLEANED __________; OTHER ________

WELL CASING AND SCREEN DESCRIPTION:

CASING/SCREEN MATERIAL	CASING THICKNESS, SCREEN TYPE, SLOT SIZE, ETC.	DIAMETER	FROM	TO	TOTAL LENGTH
		inches/ centimeters	feet/meters	feet/meters	feet/meters
CASING:					
SCREEN:					

Figure 15. *Example of a form to record well construction.*

RECORD OF WELL CONSTRUCTION

Page 2 of 2

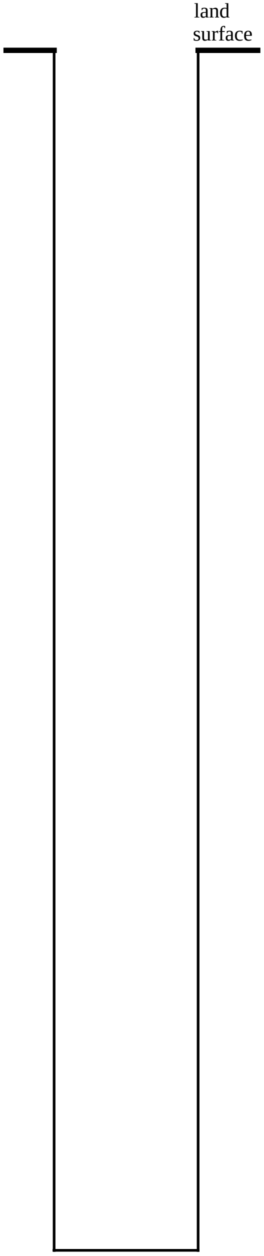
BOREHOLE DATA:

BOREHOLE DIAMETER: _____________ inches (or centimeters);

TOTAL DEPTH OF BOREHOLE: _____ feet (or meters);

APPROXIMATE DEPTH TO WATER: _________________ feet (or meters)

Illustrate thickness and types of lithologic materials



DESCRIPTION OF GEOLOGIC MATERIALS				FROM	TO	THICKNESS
LITHOLOGY	SORTING	COLOR	WET OR DRY	feet (or meters)	feet (or meters)	feet (or meters)

Figure 15. *Example of a form to record well construction--Continued*

RECORD OF WELL COMPLETION

Page 1 of 2

START WELL COMPLETION: DATE _____/_____/_____ TIME ______________

FINISH WELL COMPLETION: DATE _____/______/______ TIME ______________

COMPLETION ELEMENT	COMPLETION MATERIALS	AMOUNT (by weight or volume)	FROM feet (or meters)	TO feet (or meters)	TOTAL LENGTH feet (or meters)
PRIMARY FILTER PACK					
SECONDARY FILTER PACK					
ANNULAR SEALS					
SURFACE SEAL					
WELL PROTECTOR					

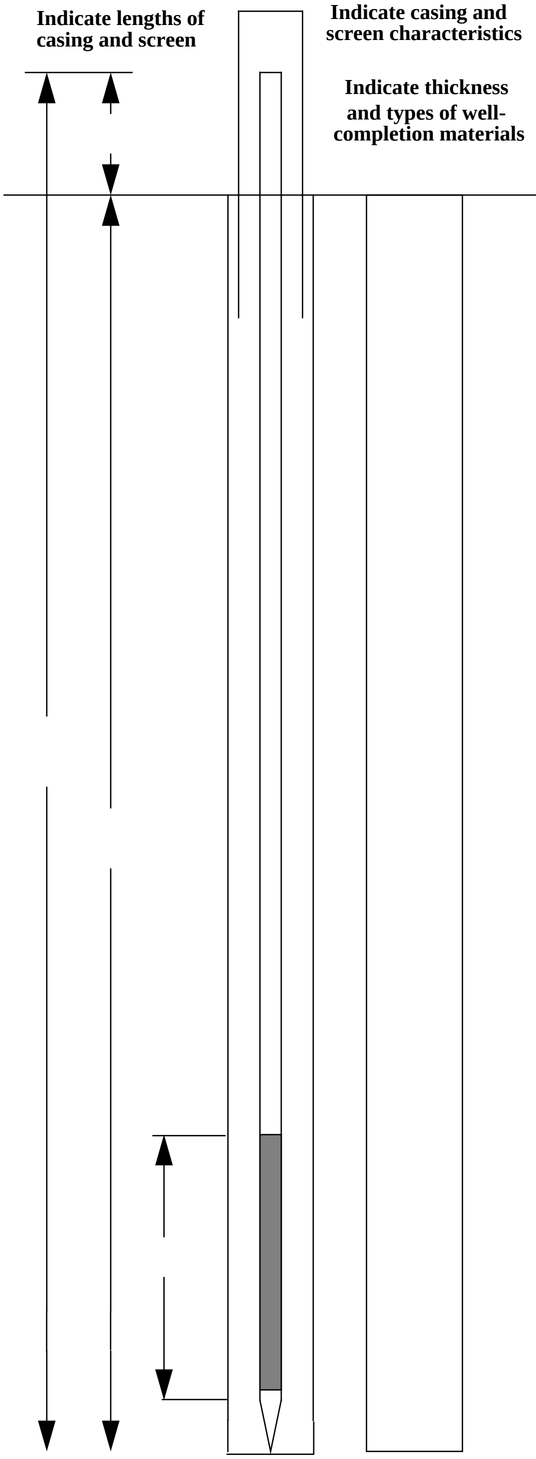
COMMENTS:

Figure 16. *Example of a form to record well completion.*

Page 2 of 2

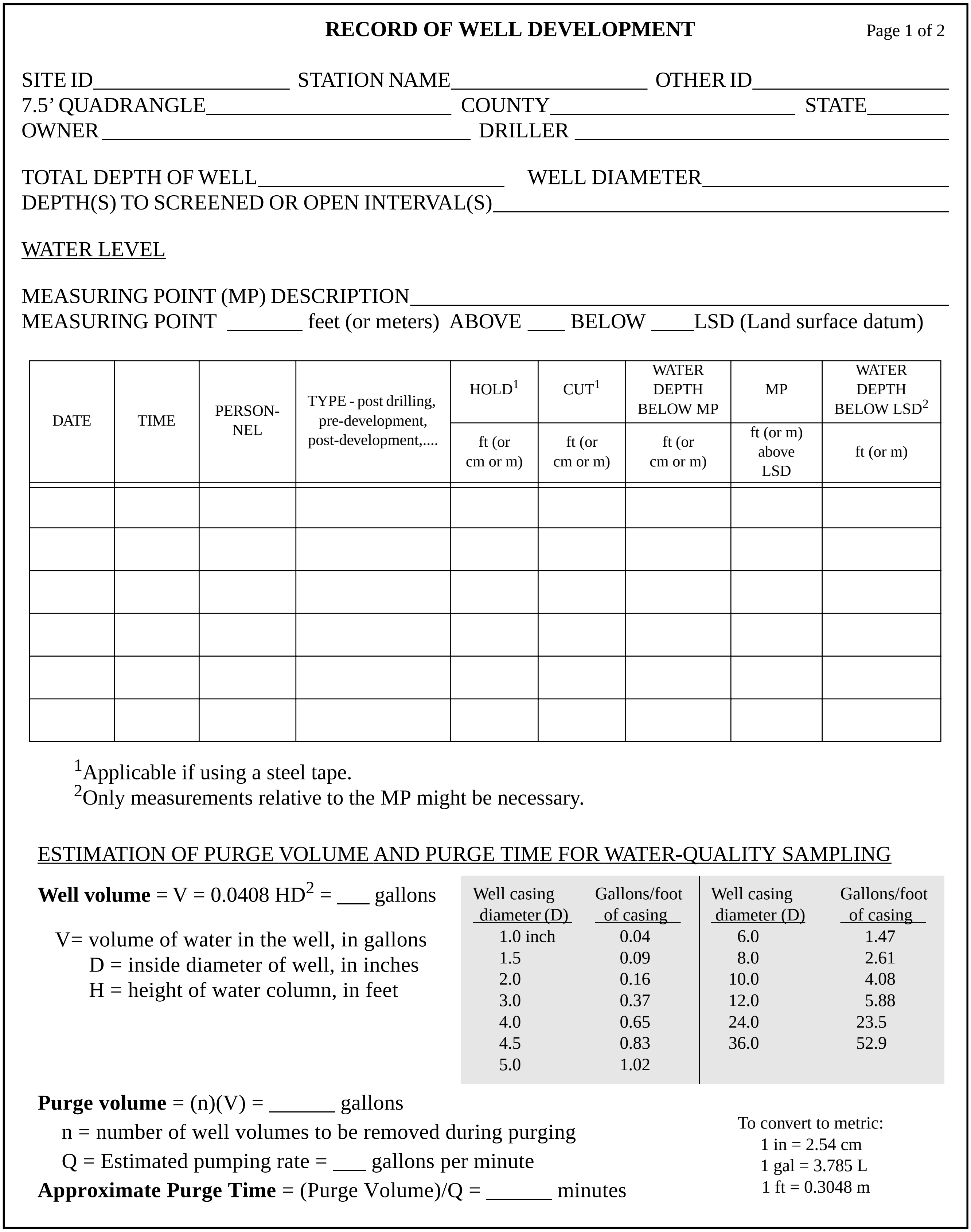
RECORD OF WELL COMPLETION: WELL-COMPLETION DIAGRAM (Single-well site)

SITE ID ______________________________ STATION NAME ______________________________
OTHER ID ______________________________
7.5’ QUAD ______________________________ COUNTY ____________________ STATE ____________
OWNER ______________________________ DRILLER ______________________________
Units used (circle one): feet / meters / other ____________



Notes

Figure 16. *Example of a form to record well completion--Continued.*



RECORD OF WELL DEVELOPMENT

Page 1 of 2

SITE ID__________________ STATION NAME__________________ OTHER ID__________________
7.5’ QUADRANGLE______________________ COUNTY______________________ STATE________
OWNER_________________________________ DRILLER ________________________________

TOTAL DEPTH OF WELL______________________ WELL DIAMETER______________________
DEPTH(S) TO SCREENED OR OPEN INTERVAL(S)____

WATER LEVEL

MEASURING POINT (MP) DESCRIPTION____
MEASURING POINT _______ feet (or meters) ABOVE ___ BELOW ____LSD (Land surface datum)

DATE	TIME	PERSONNEL	TYPE - post drilling, pre-development, post-development,....	HOLD[1]	CUT[1]	WATER DEPTH BELOW MP	MP	WATER DEPTH BELOW LSD[2]
				ft (or cm or m)	ft (or cm or m)	ft (or cm or m)	ft (or m) above LSD	ft (or m)

[1] Applicable if using a steel tape.
[2] Only measurements relative to the MP might be necessary.

ESTIMATION OF PURGE VOLUME AND PURGE TIME FOR WATER-QUALITY SAMPLING

Well volume = V = 0.0408 HD^2 = ___ gallons

V= volume of water in the well, in gallons
D = inside diameter of well, in inches
H = height of water column, in feet

Well casing diameter (D)	Gallons/foot of casing	Well casing diameter (D)	Gallons/foot of casing
1.0 inch	0.04	6.0	1.47
1.5	0.09	8.0	2.61
2.0	0.16	10.0	4.08
3.0	0.37	12.0	5.88
4.0	0.65	24.0	23.5
4.5	0.83	36.0	52.9
5.0	1.02		

Purge volume = (n)(V) = ______ gallons
n = number of well volumes to be removed during purging
Q = Estimated pumping rate = ___ gallons per minute
Approximate Purge Time = (Purge Volume)/Q = ______ minutes

To convert to metric:
1 in = 2.54 cm
1 gal = 3.785 L
1 ft = 0.3048 m

Figure 17. *Example of a form to summarize development of a well.*

RECORD OF WELL DEVELOPMENT

Page 2 of 2

Date: ____________________ By: ____________________________

SITE ID____________________ STATION NAME____________________ OTHER ID____________________

WELL DEVELOPMENT METHOD(S):

BAILING______; MECHANICAL SURGING______; INDIRECT EDUCTION______;
PUMPING/OVERPUMPING, AND BACKWASHING______; BACKWASHING______;
JETTING WITH WATER_____; JETTING WITH AIR_____; OTHER________________________________
PUMP DESCRIPTION____

TIME	TEMPER-ATURE	CONDUCTIVITY	pH	DISSOLVED OXYGEN	TURBIDITY	APPROX. PUMPING RATE	COMMENTS (INCLUDING CLARITY OF WATER AND SUCCESS OF DEVELOPMENT)
HR:MIN	^{o}C	µS/cm	units	mg/L	NTU (or FTU)	gal/min (or L/min)	

FIELD PARAMETERS NTU, Nephelometric Turbidity Units; FTU, Formazin Turbidity Units	**STABILITY CRITERIA** Allowable difference in sequential parameter values
pH	± 0.1 standard units
Temperature, in degrees Celsius (^{o}C)	± 0.2°C (thermistor)
Specific electrical conductance (SC), in microsiemens per centimeter at 25^{o}C (µS/cm)	± 5%, for SC ≤ 100 µS/cm ± 3%, for SC > 100 µS/cm
Dissolved-oxygen concentration, in milligrams per liter (mg/L)	± 0.3 mg/L
Turbidity (TU), in NTU (FTU ~ NTU)	± 10%, for TU < 100 NTU: ambient TU is <5 NTU for most ground-water systems (visible TU > 5 NTU)

Figure 17. *Example of a form to summarize development of a well--Continued*

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Internal Documents

The following documents are available in U.S. Geological Survey, Water Resources Division offices nationwide. Abstracts of the Water Resources Division Memorandums and a copy of the Office of Ground Water Technical Memorandum are available on the World Wide Web. The URL is http://wwwoper.er.usgs.gov/memos.

Water Resources Division Memorandums

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