TWDB Contract No. 2000012441
Final Report
Received: August 30, 2021

Final Report: Drilling and Logging the Ideal Exploratory Brackish Groundwater Well

Texas Water Development Board Contract No. 2000012441

Prepared for:

Texas Water Development Board

Prepared by:

Andrew Donnelly, P.G.

Marvin Glotfelty, P.G.

Russell Perry, P.G.

Mike Jacobs, P.G.

Elizabeth Bastien

T. Neil Blandford, P.G.

August 2021

This page is intentionally blank.

Final Report: Drilling and Logging the Ideal Exploratory Brackish Groundwater Well

Texas Water Development Board
Contract No. 2000012441

By

Andrew Donnelly, P.G.

Marvin Glotfelty, P.G.

Russell Perry, P.G.

Mike Jacobs, P.G.

Elizabeth Bastien

T. Neil Blandford, P.G.

Daniel B. Stephens & Associates, Inc.

August 2021

This page is intentionally blank.

Geoscientist Seals

The contents of this report, including figures and tables, document the work of the following Texas-licensed professionals:

Andrew Donnelly, P.G. No. 737
Mr. Donnelly was responsible for preparing the introduction, scale of investigation, and pre-drilling data collection report sections. He also provided overall project planning, project management, interaction with the TWDB, and report review.

STATE OF TEXAS
ANDREW C.A. DONNELLY
GEOLOGY
No. 737
LICENSED
PROFESSIONAL GEOSCIENTIST

8/24/21

Andrew C.A. Donnelly

Russell Perry, P.G. No. 735
Mr. Perry was responsible for preparing sections of the report describing the types of exploratory boreholes and wells, other drilling methods, well completion, well development, drilling costs, data collected during drilling, and miscellaneous issues. He also contributed to the geophysical logging and data collected after well completion sections.

STATE OF TEXAS
RUSSELL PERRY
GEOLOGY
735
LICENSED
PROFESSIONAL GEOSCIENTIST

8/25/21

Russell Perry

Mike Jacobs, P.G. No. 5980
Mr. Jacobs contributed to and reviewed the geophysical logging section.

Mike Jacobs

T. Neil Blandford, P.G. No. 1034
Mr. Blandford was responsible for senior project oversight and report review.

T. Neil Blandford

Table of Contents

List of Figures

List of Tables

List of Appendices

List of Acronyms and Abbreviations

°C	degrees Celsius
°F	degrees Fahrenheit
µmhos/cm	micromhos per centimeter
µs/ft	microseconds per foot
API	American Petroleum Institute
ARCH	air-rotary casing hammer
ASR	aquifer storage and recovery
BCWID	Brown County Water Improvement District
BEG	Bureau of Economic Geology
BFZ	Balcones fault zone
BRACS	[TWDB] Brackish Resources Aquifer Characterization System
BSEACD	Barton Springs/Edwards Aquifer Conservation District
COC	chain of custody
cps	counts per second
DBS&A	Daniel B. Stephens & Associates, Inc.
DR	dual rotary
GIS	geographic information system
GLF	[BEG] Geophysical Log Facility
gpm	gallon(s) per minute
gpm/ft	gallons per minute per foot
HPUWCD	High Plains Underground Water Conservation District
HSLA	high steel low alloy
K	hydraulic conductivity
KB	Kelly bushing
mg/L	milligrams per liter
mmhos/m	millimhos per meter
mV	millivolt(s)
NMR	nuclear magnetic resonance
ppm	parts per million
PVC	polyvinyl chloride
RRC	Railroad Commission of Texas

SC	specific capacity
SDR	submitted drillers report
SP	spontaneous potential
T	transmissivity
TDLR	Texas Department of Licensing and Regulation
TDS	total dissolved solids
TWDB	Texas Water Development Board
TWRSRS	Texas Well Report Submission and Retrieval System
USDOE	U.S. Department of Energy
USGS	U.S. Geological Survey

1 Introduction

According to the 2022 Texas State Water Plan (TWDB, 2021), the demand for water in Texas is projected to increase 9 percent from 2020 to 2070, while at the same time the existing Texas water supplies are expected to decrease by 18 percent. Due to limitations on the existing supplies of surface water and groundwater, new sources of water are needed to help meet this increasing demand. As discussed in *The Future of Desalination in Texas: 2020 Biennial Report on Seawater and Brackish Groundwater Desalination in Texas* (TWDB, 2020), brackish groundwater has been recognized as an important resource that can provide new supplies of water to reduce the demand on freshwater supplies and help meet a variety of water demands across the state.

Brackish groundwater is groundwater that contains total dissolved solids (TDS) concentrations between 1,000 and 10,000 milligrams per liter (mg/L) (Table 1-1). Total dissolved solids are the total concentration of ions and molecules dissolved in the water. In most cases, higher total dissolved solids concentrations are the result of increased sodium chloride content, which makes the water "salty", or more saline. Total dissolved solids content is referenced as salinity in some parts of this report. For reference, fresh water contains total dissolved solids concentrations less than 1,000 mg/L, while seawater contains total dissolved solids concentrations of approximately 35,000 mg/L. According to *A Desalination Database for Texas* (Nicot and others, 2006), feedwater for desalination plants using reverse osmosis technology typically has total dissolved solids concentrations less than 3,000 to 3,500 mg/L, although brackish groundwater exploration programs generally consider slightly saline (1,000 to 3,000 mg/L total dissolved solids) to moderately saline (3,000 to 10,000 mg/L total dissolved solids) useful for potential groundwater resource development.

Table 1-1. Groundwater salinity classifications.

Classification	Total Dissolved Solids (mg/L)
Fresh	0 to 1,000
Brackish - Slightly saline	1,000 to 3,000
Brackish - Moderately saline	3,000 to 10,000
Saline	10,000 to 35,000
Brine	Greater than 35,000

Modified from Winslow and Kister, 1956.

Brackish groundwater can be found across the state in a variety of aquifers. It has been estimated that approximately 2.7 billion acre-feet of brackish groundwater is present in the major and minor aquifers across Texas (LBG-Guyton, 2003), as shown in Figure 1-1. Many of the aquifers in Texas contain groundwater that is fresh closer to the surface, but transitions to brackish at greater depths. In some areas, even shallow groundwater can be primarily brackish. In several parts of the state, primarily in west, south, and north-central

Texas, fresh groundwater is rare, and the dominant quality of available groundwater is brackish, as shown in Figure 1-1.

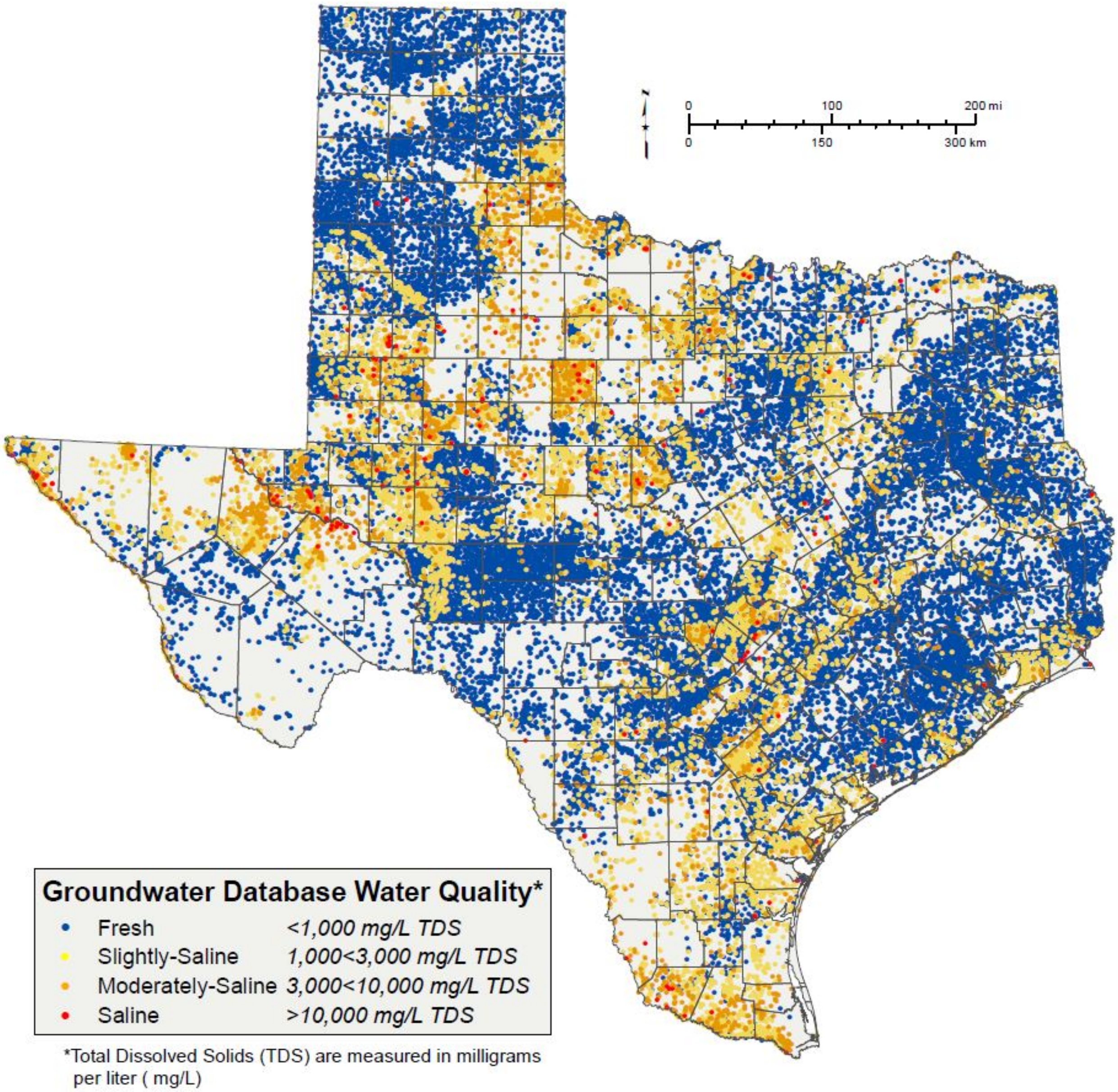


Figure 1-1. The distribution of groundwater quality in Texas (source: TWDB).

With the inception of the Texas Water Development Board (TWDB) seawater desalination program in 2005 and the brackish groundwater desalination program in 2009, the TWDB contracted to have a Brackish Groundwater Exploration Guidance Manual (LBG-Guyton, 2008) developed to provide guidance to stakeholders interested in developing water supplies in brackish aquifers. This guidance manual provides a broad overview of the development of brackish groundwater resources

In 2015, the 84th Texas Legislature passed House Bill 30, which directed the TWDB to identify and designate brackish groundwater production zones in aquifers across Texas to determine the amount of brackish groundwater that can be produced from these zones without impacting fresh water quality or availability, and to make recommendations on how to monitor the effects of the production of brackish groundwater from these zones.

In 2019, the 86th Texas Legislature passed House Bill 722, which established a permitting framework for the development of brackish groundwater supplies from the production zones identified in each of the state's major and minor aquifers. The brackish groundwater production zones may be local or regional in size, with the potential for moderate to high availability and productivity of brackish groundwater. House Bill 722 allows for groundwater conservation districts to adopt permitting rules applicable to the withdrawal of groundwater from TWDB-designated brackish groundwater zones. The permitting framework allows a minimum 30-year permit for (1) a municipal project designed to treat brackish groundwater to drinking water standards for the purpose of providing a public source of drinking water or (2) an electric generation project to treat brackish groundwater to water quality standards sufficient for the project needs.

These bills illustrate the importance of the development and use of brackish groundwater as a significant long-term component of water supplies in Texas in the coming decades. They also illustrate the need for a how-to resource document for drilling and logging exploratory wells to provide critical information and guidance to assist groundwater conservation districts and other stakeholders interested in determining if brackish groundwater may be a viable water resource to meet their specific needs.

As a result, the TWDB contracted Daniel B. Stephens & Associates, Inc. (DBS&A) to prepare a resource document focusing on the data collection aspect of drilling and logging the ideal exploratory brackish groundwater wells, to be written in a manner that provides guidance for district managers or board members, stakeholders, or other potential end users. The technical content will help optimize data collection efforts for mapping and modeling brackish groundwater production zones and for monitoring the impact of brackish groundwater production on adjacent aquifers.

This new resource document is an update and expansion of the existing Brackish Groundwater Exploration Guidance Manual (LBG-Guyton, 2008). The 2008 guidance manual had limited discussion on the development and implementation of a testing program to determine the physical characteristics of the aquifer, including groundwater quality and hydraulic characteristics of the aquifer. This resource document focuses on the types of exploratory wells that can be constructed, drilling methods that can be used to install a test well, geophysical logging techniques that can provide valuable information on the nature of the aquifer and groundwater contained in it, and how to test a well to determine aquifer characteristics and water quality so that development of the resource can be properly planned. This resource document is intended to provide a roadmap for the drilling and logging of the ideal exploratory brackish groundwater well. To implement an exploration program, it is imperative that expert consulting services and drilling contractors be engaged to provide the expertise necessary to properly test and evaluate a potential brackish groundwater resource.

2 Exploratory Boreholes and Wells

Exploratory boreholes and wells are borings drilled into the subsurface that can be used to obtain or expand knowledge of brackish groundwater resources. There are several types of boreholes and wells, as described in detail in Section 2.2. Data collection should always be performed before drilling exploratory boreholes or installing wells because (1) existing data may be sufficient to develop a conceptual model of the aquifer under consideration without additional boreholes/wells, (2) existing data may reduce and/or eliminate the need for expensive borehole/well installations, and (3) assessment of existing data may identify data gaps that can be used to optimize the selected location of new boreholes/wells if they are needed. Data collection prior to drilling is discussed more in Section 5.

While drilling exploratory boreholes, the well site geologist typically collects drill cuttings (particles of the subsurface geologic materials brought to the ground surface during the drilling process), and a lithologic log is prepared from the drill cuttings by examining and classifying the drill cuttings relative to the drilled depth.

A borehole geophysical survey is often conducted immediately after the exploratory borehole is drilled. The purpose of the geophysical survey is to complement the lithologic log and provide additional information on the density, porosity, salinity, and other physical properties of the geologic units and the fluids they contain, as discussed in detail in Section 7. Exploratory boreholes and wells can be used to collect groundwater samples for chemical analysis, and aquifer properties can be determined or estimated by performing hydraulic tests within brackish groundwater production zones. The aquifer properties are used to determine the well yield and the long-term effects, such as water level decline, that will occur from pumping the well.

2.1 Scale of Investigation

The scale of investigation is determined by the extent and depth of the brackish water resource being investigated and the time and resources available to the stakeholder. The scale of investigation will ultimately determine the number and types of exploratory boreholes or wells needed for the investigation. These well types, and their advantages and disadvantages, are discussed in this section.

The scale of a brackish groundwater investigation will be largely dependent upon the project budget and goals. In general, the fewer exploratory boreholes or wells needed to accomplish the project goals will correlate to lower costs. Greater depth of investigation will increase the required budget. For example, in some cases it may be possible that a single exploration well used in conjunction with pre-existing published local data might provide the necessary information to plan and successfully complete a brackish water development project. In other cases where existing data are limited or the study area is large, multiple exploratory wells might be needed to adequately characterize the resource and confirm that installation of a well field and water treatment facility is justified.

2.2 Types of Exploratory Boreholes/Wells

Brackish groundwater in Texas occurs in a wide variety of aquifers and at different depths. Therefore, the types of exploration boreholes or wells, construction methods, and testing approaches that may be used for brackish groundwater exploration are also variable. This section discusses the challenges and benefits for each type of exploration well. The type of well that can be installed will depend largely on the drilling method selected, as discussed in more detail in Section 3. The drilling methods selected depend on the type of geologic materials that will be penetrated, anticipated depth of the well, and other considerations such as artesian conditions or the presence of natural gas. Drilling companies with local brackish groundwater exploration experience are often a valuable source of information regarding effective drilling and well completion methods.

The terms “well,” “hole,” “borehole,” and “boring” are often used in a general sense to describe a void drilled in the earth to access groundwater or other resources like oil and gas. For purposes of this document, the terms “hole,” “borehole,” or “boring” refer to an uncased void in the earth created by drilling. In the spirit of consistency, we use the term “borehole,” as it better implies a void created using drilling methods. “Slim hole” is a driller’s term used to describe an exploration borehole drilled to obtain general geologic information about subsurface formations and aquifers in a relatively quick time frame where the deviation (crookedness) of the borehole is not a concern, as it will be plugged and abandoned once the geologic data is obtained (Glotfelty, 2019). “Pilot borehole” is a term used to describe a small diameter borehole drilled to provide a guide or pilot hole for a larger diameter drill string used to ream (widen) the borehole prior to installation of a well. Pilot boreholes are drilled as straight as possible so that the larger-diameter drill string will follow a straighter path downward while drilling; reasonably straight boreholes allow easier installation of well materials (e.g., casing and screen). A perfectly “straight” hole would be a perfectly vertical hole, and the term deviation refers to the extent to which a borehole deviates from vertical.

The term “well” refers to a borehole that has been stabilized with screen and casing such that unconsolidated materials like cobbles, gravel, sand, silt, and clay cannot cave in and block the borehole. Drillers often describe unconsolidated materials as “overburden.” The term “well” can also describe a borehole that has been drilled through consolidated materials (rock) like limestone, sandstone, and shale, where those materials would not be expected to cave into the borehole because the borehole stays open naturally without the need for screen or casing. Wells installed without screen and casing are often called “open hole wells,” and most have some type of casing installed near the surface (surface casing) to prevent loose materials in shallower zones from caving into the “open hole.” Surface casing is also used to protect shallow fresh groundwater from deeper (brackish) groundwater or to prevent unwanted contaminants from entering the well from the surface, such as seepage from a septic system or a surface chemical spill.

"Monitor wells" are constructed using the same methods as other wells, but are designed to allow the collection of water levels and/or water samples for chemical analysis. Piezometers are wells installed with short screens or open intervals specifically designed for monitoring water levels rather than water quality samples. Monitor wells and piezometers are not used for water supply purposes, and typically cannot produce significant quantities of water due to their small diameter. For purposes of consistency in this document, the term "wells" will include "monitor wells" and "piezometers."

The decision criteria used to select individual exploration borehole or well types depend largely upon the project budget, the abundance or scarcity of data from offset wells in the immediate area, formation types to be penetrated, the depth to target brackish groundwater production aquifers, and well site accessibility.

2.2.1 Exploratory Boreholes

A decision to drill exploratory boreholes instead of installing exploratory wells might be based on the need to obtain relatively quick, less expensive, raw data where other data for the study area are not available. Exploratory boreholes can be drilled through any type of geologic material and can be used to plan the construction design of future permanent exploratory wells or production wells, if needed.

Exploratory boreholes are primarily drilled to obtain lithologic data from drill cuttings and to obtain detailed formation information from the geophysical survey. A borehole is drilled to the target depth of investigation while the on-site geologist collects and examines drill cuttings. When drilling is complete, a geophysical survey is performed, an electronic file of the geophysical data is prepared, and a paper log of the geophysical survey (geophysical log) is generally printed on-site. A lithologic log prepared by the on-site geologist and the geophysical log are valuable tools used to characterize the brackish groundwater production potential of the geologic formations encountered.

Exploratory boreholes are typically drilled with a relatively small-diameter drill string (drill bit and drill pipe). "Small" is a relative term, as shallower boreholes can be drilled with a smaller-diameter drill string and deeper boreholes may require larger-diameter drill strings due to the increased downhole torque and stress that occur in deeper borings. Also, if a geophysical survey is desired, the borehole needs to be large enough to accommodate the geophysical survey tools. Exploration boreholes intended for geophysical logging are typically 6½ to 7⅞ inches in diameter, at a minimum, but can be smaller if drilled through consolidated rocks not subject to caving.

Exploratory boreholes are typically plugged and abandoned after logging is complete. The rapid and economic approach to drilling these small-diameter boreholes will accommodate the quick and relatively inexpensive collection of site-specific hydrogeologic data, but this process does not accommodate the drilling of a straight borehole. Therefore, exploratory boreholes are generally not reamed out for conversion to a test well, even if the collected subsurface data appear favorable for water production (Glotfelty, 2019).

Zonal testing, also known as depth-specific testing, can also be performed during the drilling of exploratory or pilot boreholes. The purpose of zonal testing is to collect data on water quality and/or aquifer properties at specific depths along the borehole. Estimates of the aquifer hydraulic conductivity can be obtained by conducting falling-head tests during zonal testing. For larger-diameter exploratory boreholes, sample intervals within the borehole can be isolated using bentonite clay seals. For smaller-diameter exploratory boreholes, however, there may not be enough space within the boring for the bentonite clay chips to be installed through a tremie pipe to form the necessary seals above and below the desired sample interval. In such cases, inflatable packers (called "straddle packers") are used to achieve the required isolation of the sample interval (Glotfelty, 2019). An expanded discussion of data collected during drilling is presented in Section 6.

The benefits of drilling test boreholes are that surface casing is typically not installed (but check with your local regulatory entity to confirm), and the borehole can be drilled and logged in a relatively short period of time without the need to convert the boring to a well by installing casing and screen. Test boreholes are therefore less expensive than other drilling investigation methods.

The challenge of installing a test borehole is that if it is installed in unconsolidated formation materials, the borehole may need to be conditioned with drilling mud or polymers to keep the borehole open long enough to perform a geophysical survey and zonal testing, and multiple borehole drilling iterations ("trips" in to and out of the borehole) may be required to ream the borehole of sloughed material in unstable formations. Borehole conditions generally deteriorate (the borehole side walls become less stable) with time, so reaming the borehole and logging can be time-critical to avoid excessive caving or borehole collapse. Geophysical logging, followed by zonal testing if conducted, are typically scheduled to occur immediately upon drilling the borehole to its target depth.

The general steps for installing an exploratory test borehole are as follows:

1. Drill borehole to maximum depth of investigation.
2. Perform geophysical survey, evaluate drill cuttings (lithology) and evaluate potential permeable zones and groundwater salinity zones favorable for brackish groundwater production (from geophysical log).
3. Perform zonal testing (if any).
4. Plug and abandon borehole.

The advantages and disadvantages of installing exploratory boreholes relative to exploration test wells are summarized in Table 2-1. A case study of an exploratory borehole installed within the Dockum Aquifer for the High Plains Underground Water Conservation District is presented in Appendix A.

Table 2-1. Advantages and disadvantages of exploratory boreholes relative to exploration test wells.

Advantages	Disadvantages
• Can be drilled relatively fast to obtain lithologic and geophysical data. • Surface casing may not be needed (check local regulations), and production casing/screen not used. • Can provide information for future exploration well or production well installation planning. • Zonal testing can be performed to evaluate potential production intervals. • Least expensive of all types of exploratory boreholes/wells.	• Borehole deviation is likely, which would prevent conversion to a well. • If drilled in unconsolidated materials, formation cave-in may prevent geophysical survey or zonal testing and may require multiple drilling cleanout trips.

2.2.2 Exploration Test Wells

Exploration test wells are boreholes converted to temporary or permanent wells through the installation of well materials that may include surface casing, production casing, screen, filter pack, bentonite seal, and grout. The boreholes for exploration test wells are typically larger in diameter than exploratory boreholes, as they must be large enough to accommodate surface casing and other well materials, and they must also be large enough to accommodate use of a tremie pipe used to install the well materials between the screen and casing and the borehole annulus. Exploration test wells can contain one casing string (casing and screen) or multiple casing strings. An example of the borehole size needed for an exploration test well might include a 14-inch-diameter borehole for the installation of 10-inch-diameter surface casing, and an 8-inch-diameter borehole below the bottom of the surface casing to accommodate a 4-inch-diameter casing string and screen. For deeper test wells, multiple successively smaller diameter casings may be required to isolate successively deeper zones from the screened interval of the well. Borehole diameters at shallower depths need to be larger than those at greater depths to accommodate well completion and testing activities that will be conducted in the deepest portion of the well.

2.2.2.1 Single-Zone Test Wells

Single-zone test wells are installed with one screen or open hole interval that intersects a single brackish groundwater production zone or a portion of a production zone. Single-zone test wells are required in situations where aquifer testing or sampling using exploratory boreholes in conjunction with zonal testing is not practical due to unstable borehole conditions (mostly found in unconsolidated formation materials), or where higher-quality groundwater samples or more accurate hydraulic testing data are desired, such as data obtained by performing an aquifer test.

Single-zone test wells can also be installed in consolidated formation materials where evaluation of open borehole conditions is desired. Test wells completed within open boreholes require isolation of upper and lower formations from testing; this isolation is generally achieved by plugging back the portion of the borehole below the test zone with Portland cement and installing/cementing permanent casing above the test zone.

Single-zone test wells can be installed to help prevent formation materials from entering the test interval; once the single-zone test well is installed and developed, aquifer testing and sampling can be performed at a later date, unlike exploratory boreholes, which typically require time-critical testing due to borehole sloughing concerns.

Single-zone test wells are the least complex well completion for a given situation, all other factors being equal. In some cases, surface casing and intermediate casing may be installed to control formation materials from caving or to isolate geologic zones of concern. For example, casing is used to isolate the open interval of the brackish aquifer well from overlying freshwater aquifers or geologic zones that contain oil or natural gas.

The general procedures for installing single-zone test wells in unconsolidated formation materials are illustrated in Figure 2-1, and are as follow:

1. Drill pilot borehole, perform geophysical survey, and install surface casing to isolate fresh groundwater (<1,000 mg/L total dissolved solids).
2. Extend pilot borehole through brackish groundwater zone to maximum depth of investigation.
3. Evaluate drill cuttings (lithology), perform second geophysical survey, and evaluate potential permeable zones and groundwater salinity zones favorable for brackish groundwater production (from geophysical log).
4. Plug back borehole to bottom of deepest potential production interval.
5. Install screen and casing.
6. Install filter pack and bentonite seal, with bentonite seal installed adjacent to formation materials with low hydraulic conductivity.
7. Install grout above the bentonite seal within the annulus extending into the bottom portion of the surface casing, or grout to the ground surface.
8. Develop well to promote formation yield.
9. Perform aquifer test.
10. Collect groundwater samples for chemical analysis.
11. Plug and abandon single-zone test well or retain for future hydrologic testing and/or use as a monitor well for routine groundwater sampling and analysis.

The general procedures for installing single-zone test wells in consolidated formation materials are illustrated in Figure 2-2, and are as follow:

1. Drill pilot borehole, perform geophysical survey, and install surface casing to isolate fresh groundwater.

2. Extend pilot borehole through brackish groundwater zone to maximum depth of investigation.
3. Evaluate drill cuttings, perform second geophysical survey, and evaluate potential permeable zones and groundwater salinity zones favorable for brackish groundwater production.
4. Plug back borehole to bottom of deepest potential production interval.
5. Install casing with bottom set above the production zone with no screen (open casing), and fill production zone with sand, grout casing, and subsequently wash (drill) out the sand.
6. Develop well to promote formation yield.
7. Perform aquifer test.
8. Collect groundwater sample for chemical analysis.
9. Plug and abandon single-zone test well or retain for future hydrologic testing and/or use as a monitor well for routine groundwater sampling and analysis.

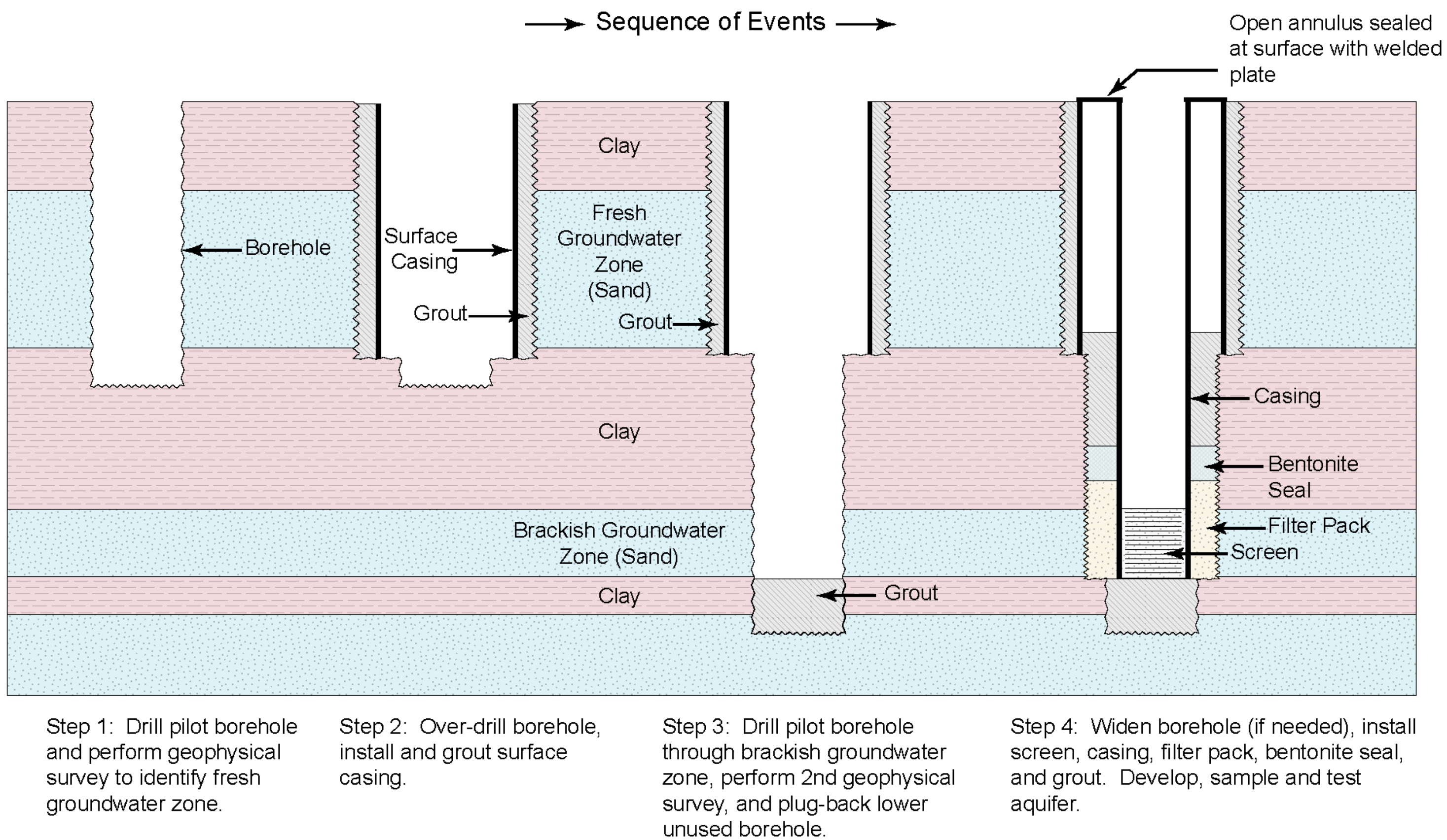


Figure 2-1. Construction sequence for single-zone test well in unconsolidated formations.

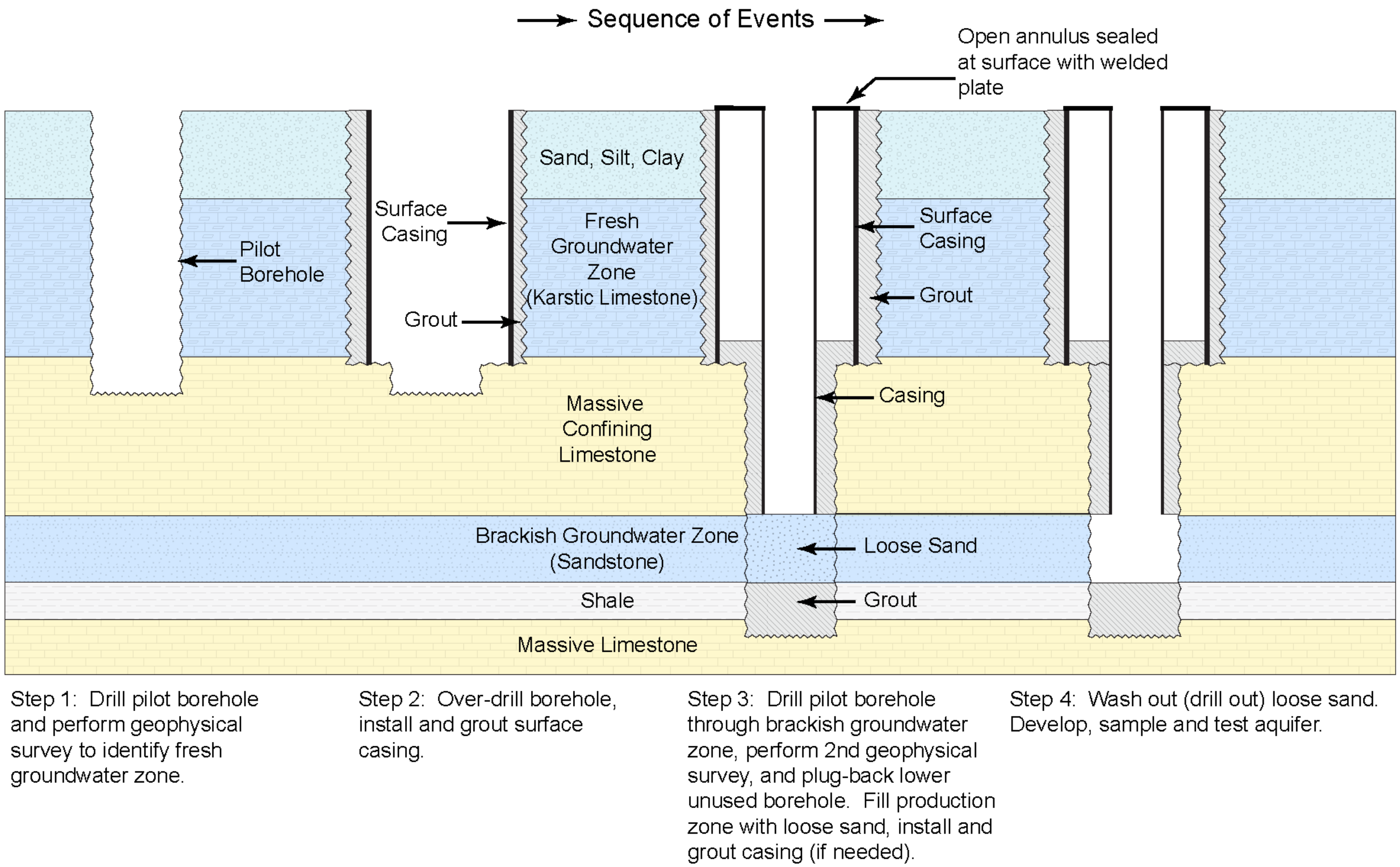


Figure 2-2. Construction sequence for single-zone test well in consolidated formations.

The advantages and disadvantages of installing single-zone test wells relative to exploratory boreholes are summarized in Table 2-2. A case study of a single-zone exploration test well installed within the Ellenburger and Hickory Aquifers for the Brown County Water Improvement District is presented in Appendix B.

Table 2-2. Advantages and disadvantages of installing single-zone test wells relative to exploratory boreholes.

Advantages	Disadvantages
• Allows installation of a "permanent" well. • Time-critical testing for aquifer properties or water quality is not a concern once well has been completed; development and testing can be performed at a later date. • Zonal testing can be performed (during the drilling process) in a similar manner as exploratory boreholes. • Higher-quality well development and aquifer testing can be performed, and better-quality groundwater samples can be collected. • Easiest and least complicated of all well types to install.	• More expensive than exploratory boreholes.

2.2.2.2 Clustered Test Wells

Depending on the nature of the brackish groundwater resource being investigated and how much information is needed in the vertical dimension, multiple single-zone test wells may be installed in one general area or location, with each well installed to intersect test intervals at specific depths. These are referred to as clustered wells. Although referred to here as clustered test wells, these are identical to, and are constructed the same as, single-zone test wells, with spacing between the test wells generally about 20 to 30 feet or more. All boreholes naturally deviate when drilled, and typically have greater horizontal deviation from vertical with increasing depth. Therefore, the required distance between clustered test wells should be evaluated based on the total anticipated drill depths and the expected potential horizontal deviation of the drilled pilot boreholes.

Clustered test wells are beneficial because multiple single-zone test wells can be installed in one location. Site access can be difficult to obtain, so if site access is granted, installation of multiple wells to evaluate multiple production zones in one location might be desired. Once a geophysical survey is performed for the deepest clustered test well (drilled first), the geophysical log can be evaluated to select production zone completion intervals or potential core collection intervals for other test wells that target shallower production zones without performing additional geophysical surveys. The installation challenges for clustered test wells are generally the same as those for individual single-zone test wells. The advantages and disadvantages of installing clustered test wells are summarized in

Table 2-3. Because clustered wells are simply multiple single-zone test wells completed at different depths in close proximity to one another, a separate case study was not included for this type of well.

Table 2-3. Advantages and disadvantages of clustered test wells.

Advantages	Disadvantages
• Same as for single-zone test wells. • If the first clustered well is drilled to the maximum depth of investigation, the geophysical log can be evaluated to determine production and completion zones for the other wells without additional geophysical surveys. Core collection intervals for the remaining wells can be determined from the drill cuttings and geophysical log from the clustered well drilled first. • Multiple wells can be installed in one local area, which is especially helpful if site access is difficult. • Well materials for all wells can be staged in one general area. • Reduces field time during subsequent data collection events.	• Same as for single-zone test wells. • Well spacing should be calculated to prevent borehole deviation that could cause intersection of the boreholes at depth.

2.2.2.3 Multiport Test Wells

Multiport test wells are wells completed with multiple screens at different depths, allowing for testing and water quality sample collection from multiple zones within a single borehole. As described in Australian Drilling Industry Training Committee (1997):

> Multiport systems are designed to permit sampling of multiple, discrete (separated) zones in a single access tube. Elements of the systems consist of a sampling-port tube with isolating packers, which are strung in the desired configuration. Such systems may be installed through a screen with filter-pack zones separated by grout, or in an open rock borehole. The packers are inflated to seal the zones.

To use a multiport system within a well completed in unconsolidated formations, a casing string with multiple screened intervals must be installed to isolate each zone, with filter pack, bentonite seals, and grout installed within the annulus as appropriate. After the casing string is installed, the multiport system can be deployed, and the multiport system packers can be inflated to isolate the production zones for testing through special sampling ports or pumping ports within each zone. Multiport systems can be installed directly into consolidated formations if the borehole wall rock surfaces are smooth enough to allow the packers to effectively isolate the zone from over and underlying fluids. Once the packers are inflated with water, they cannot be deflated for removal of the multiport system; the installation is permanent. Figure 2-3 presents a drawing of the Westbay Monitoring System by Westbay Instruments (Westbay), one of the manufacturers of multiport systems.

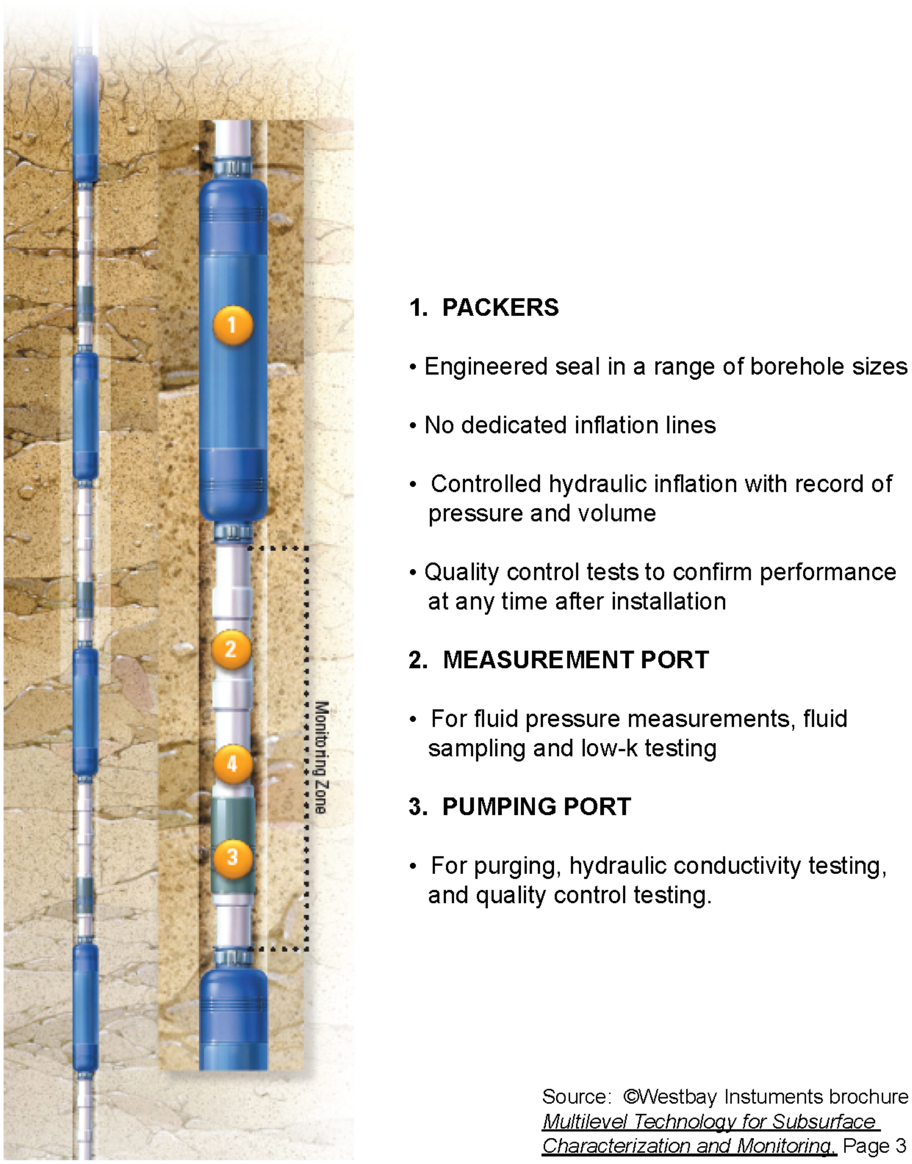


Figure 2-3. Westbay multiport monitoring system (source: Westbay, 2021).

Multiport well technology has been successfully used in hydrogeologic investigations for years. A study of a multiport well was performed by the U.S. Department of Energy (USDOE) at the Hanford site in Washington as described in Gilmore (1989). Their findings were as follow:

> The system's major advantage is its modular design, which allows versatile monitoring configurations that can be easily customized to any location and installed in a single well. Another advantage is that the samples and pressure measurements are taken outside the access tube through the sampling port. This eliminates the need to purge the access tube during sampling, and therefore the sample's fluid chemistry is not altered as a result of degassing, oxidation, biogenic activity, and precipitation. The lag time on fluid pressure measurements is also reduced relative to a conventional standpipe well. Additionally, the

> multiport system allows the integrity of coupling valves, joints, and the annular seals to be verified during installation and operation.

Gilmore (1989) also identified some challenges as follows:

> One of the major disadvantages of the (multiport) system is that the operation of the system is labor intensive and requires substantial training. The installation of the system in a backfilling operation is more difficult than conventional standpipe well construction, because the multiple screened intervals and the PVC construction required additional protection during backfilling. In addition, very little maintenance can be performed after the system is installed by backfilling, and should the system components fail, the life span of the system would be curtailed.

A case study of a multiport test well installed for the Barton Springs/Edwards Aquifer Conservation District (BSEACD) is included in Appendix C. This study indicated that for studies that involve investigations deeper than approximately 600 feet, multiport wells were more economical than installing single nested wells. The cost for the multiport system components for a 1,100-foot multiport test well, including technical support, and equipment rental, minus the cost of drilling was approximately $90,000 in 2016.

The general procedure for installing multiport test wells in consolidated and unconsolidated formation materials is as follows:

1. Drill pilot borehole, perform geophysical survey, and install surface casing to isolate fresh groundwater.
2. Extend pilot borehole through brackish groundwater zone to maximum depth of investigation.
3. Evaluate drill cuttings (lithology), perform second geophysical survey, and evaluate potential permeable zones and groundwater salinity zones favorable for brackish groundwater production (from geophysical log).
4. Plug back borehole to bottom of deepest potential production interval.
5. Install well screen and casing if needed.
6. Install the multiport system and inflate the packers.
7. Develop and perform groundwater sampling and/or slug testing in each production zone.
8. Retain multiport test well for a permanent monitor well or remove multiport system components and plug and abandon multiport test well.

The advantages and disadvantages of installing multiport test wells relative to other methods are summarized in Table 2-4.

Table 2-4. Advantages and disadvantages of installing multiport test wells.

Advantages	Disadvantages
• Requires only one well casing string to test multiple zones through a single access tube (multiport sampling system). • Cost effective if multiple test zones are needed for deeper brackish groundwater exploration studies. • Can be installed in unconsolidated formations isolated with conventional well screens and casing, or in open hole consolidated formations. • Modular design that allows custom configurations. • Minimal development of the test zones is needed after installation. • Integrity of seal between production zones can be evaluated after installation.	• Multiport sampling system is relatively expensive and may not be economical for shallower brackish groundwater investigations. • After the packers are inflated, the installation is permanent and cannot be moved; the multiport components become an integral part of the well. • Labor intensive and requires special training and equipment for proper installation, operation, testing, and sampling.

2.2.2.4 Nested Test Wells

The main benefit of nested test wells is that one nested well can be installed to monitor or test multiple production zones, which would theoretically be less expensive than installing multiple single-zone test wells (though it can be more expensive). In addition, one nested test well could potentially use less surface area than multiple single-zone test wells, which is an advantage in areas where land availability is very constrained.

Nested test wells are installed using similar drilling and installation methods described for single-zone test wells, except that multiple wells (casing and screen) are completed at different depth intervals within the same borehole. Because nested well boreholes must be large enough to accommodate multiple well casings, they are larger than those required for a single well borehole of equivalent well diameter. Nested test wells can be installed in consolidated or unconsolidated formation materials, and the installation procedure is the same for both material types.

Well development, aquifer testing, and sampling are the same as for single-zone test wells. However, nested test wells are the most difficult type of test well to install properly, and particular attention needs to be focused on obtaining effective seals between the multiple well screens within the borehole. Some key issues to consider regarding nested test wells are as follow:

- Nested test wells are more suitable for installation in consolidated formation materials than in unconsolidated material because consolidated formations provide greater formation stability. This is because the installation of well materials, depending upon the complexity, could require a relatively long period of time, and it may be difficult to avoid borehole degradation and sloughing during the installation period in an unconsolidated formation. If borehole degradation associated with well installation in unconsolidated formation materials is a concern, then an outer casing with properly placed screens, filter pack, and bentonite seals can be installed, followed by installation of the individual nested test wells.

- Care must be taken to ensure that the bentonite seals are installed adjacent to low-permeability formation materials to prevent movement of formation fluids along the borehole annulus, and proper placement of bentonite seals depends on proper centering of multiple casings within the borehole annulus.
- Specially manufactured centralizers (including custom-manufactured centralizers to accommodate the number of casings nested in the borehole) are required to ensure that the filter pack, bentonite, and grout are maintained at a uniform thickness between and outside of each screen/casing nested well.
- To improve the likelihood of a successful nested test well installation, the tremie pipe should be installed to the deepest zone needed, concurrent with the installation of the well screen and casing sets, such that the tremie pipe can be sequentially removed during installation of the filter pack and bentonite seals from the bottom of the borehole up. Installing the tremie pipe after the well screen and casing is installed may not be possible due to interference from the centralizers and multiple casing strings.
- The difficulty of installation increases with the number of nested test wells installed in one borehole, and with increasing depth of installation. Creative planning and execution may be needed while installing the nested test well screens, casing, centralizers, and tremie pipe, as all components must be suspended above the borehole and simultaneously lowered to the desired depth.

The general procedure for installing nested test wells is as follows:

1. Drill pilot borehole, perform geophysical survey, and install surface casing to isolate fresh groundwater. Use surface casing with large enough diameter to accommodate the anticipated number of nested wells needed.
2. Extend pilot borehole through brackish groundwater zone to maximum depth of investigation.
3. Evaluate drill cuttings (lithology), perform second geophysical survey, and evaluate potential permeable zones and groundwater salinity zones favorable for brackish groundwater production (from geophysical log).
4. Plug back borehole to bottom of deepest potential production interval.
5. Over-drill borehole to a large enough diameter to accommodate multiple test wells in one borehole annulus, drilled to the bottom of lowest potential production interval.
6. Construct the nested test well assembly with all components and removable tremie pipe while lowering the assembly into the borehole.

7. For each test zone, install filter pack around screens, bentonite seals, and grout through the tremie pipe, while progressively removing the tremie pipe up to each successively shallower interval.
8. Develop each nested test well to promote formation yield.
9. Perform aquifer pump tests and/or collect groundwater samples for chemical analysis from each nested test well.
10. Retain the nested test wells for future hydraulic testing and/or water sample collection for chemical analysis or plug and abandon nested test wells.

Figure 2-4 presents a well construction diagram for a nested test well penetrating three permeable brackish groundwater zones within unconsolidated geologic formations. The same construction methods are used for installation of a nested test well within consolidated and unconsolidated formation materials.

The advantages and disadvantages of installing nested test wells are summarized in Table 2-5. A case study of a nested test well installed for an aquifer storage and recovery investigation at the Deer Valley Water Treatment Plant in Phoenix, Arizona is presented in Appendix D.

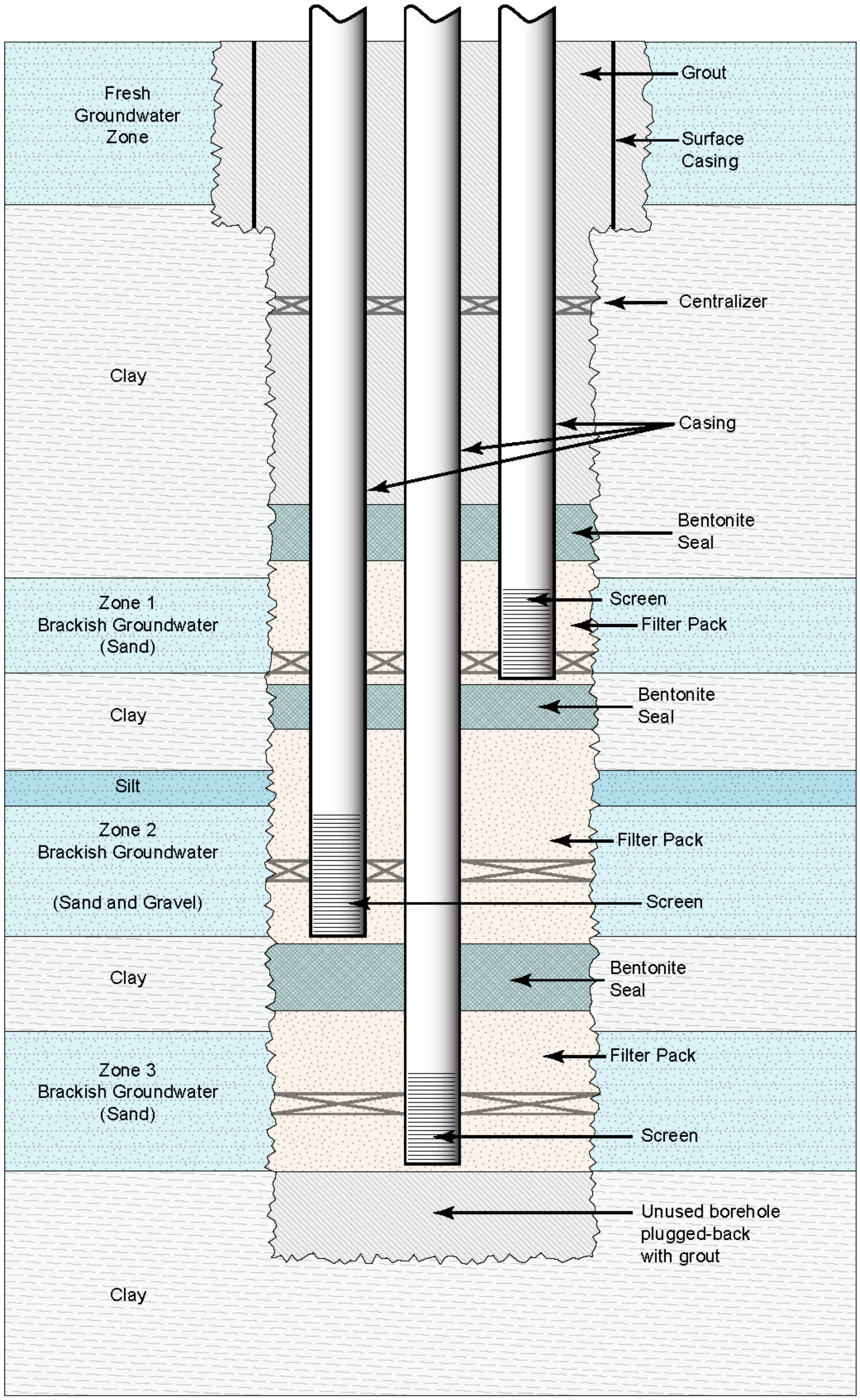


Figure 2-4. Schematic of a nested well.

Table 2-5. Advantages and disadvantages of installing nested test wells.

Advantages	Disadvantages
• Multiple wells with variable depths can be installed in one location where land availability is constrained.	• Most difficult, time-consuming, and expensive type of exploration well to install. Requires complex well design. • Installation in unconsolidated formation materials may require proper installation of outer screen, casing, filter pack, and bentonite seals before the nested wells are installed, adding to the project complexity and cost. • Proper centering of each nested well with centralizers is important to ensure that the well materials are placed properly and within the intended intervals, which requires special care during installation.

3 Drilling, Completion, and Development Methods

Many methods are available for drilling and constructing brackish test boreholes and test wells. The most appropriate method for installing any particular test borehole or test well should be determined based on local geologic conditions, budgetary limitations, and the intended purpose/design of the borehole and/or well. Of these, the local geologic conditions will have the greatest impact on selection of the most appropriate drilling method. Some drilling methods are susceptible to problems in areas with loose, porous formations due to lost circulation conditions (where drilling fluid flows into the adjacent formation rather than along the borehole annulus) and/or sloughing boreholes. Some drilling methods have depth limitations or may tend to cause extensive borehole skin damage (wall cake development) that must be addressed during well development. The most appropriate drilling method is a site-specific decision that should be made based on the experience and knowledge of local drillers and groundwater professionals.

Of the available methods summarized in Section 3.1, direct mud-rotary and direct air-rotary are the most common techniques for drilling test boreholes, and these two techniques along with flooded reverse-rotary are the most common techniques for drilling test wells.

Well completion (Section 3.2) is a term used to describe the process of converting a borehole into a well. Multiple methods can be used to achieve well completion, depending on the drilling methods used, well depth, and zones that require isolation and/or production.

Once a well is completed, it is typically developed prior to being used. Well development (Section 3.3) is the process of removing residual drilling fluids and additives from the borehole, filter pack, and surrounding aquifer that are left over from the drilling and well completion process. These materials may block the pores in the aquifer and the filter pack material, which reduces the flow of groundwater from the aquifer to the well.

3.1 Drilling Methods

For brackish groundwater exploration, the common methods for drilling test boreholes or wells include, but are not limited to, the following categories:

- Direct mud-rotary
- Direct air-rotary
- Flooded reverse-rotary
- Dual-rotary
- Other well drilling methods less commonly used, such air-rotary casing hammer, Becker hammer drill, and cable tool

Each of these methods is described in more detail in the following subsections.

3.1.1 Direct Mud-Rotary

The direct mud-rotary drilling system is one of the most commonly used systems for drilling test boreholes and wells. With this and all other rotary drilling methods, the formation is crushed and broken up by a drill bit at the bottom of the borehole, and the pulverized formation material is brought to the land surface by a circulated drilling fluid (often called drilling mud). Direct circulation drilling systems involve the flow of drilling fluid downward through the center of the drill pipe, out the drill bit, and up the annulus outside the drill pipe until it returns to the surface. As the fluid exits the drill bit at the bottom of the borehole, it entrains the drill cuttings and brings them to the surface. The drilling fluid that returns to the surface with the entrained particles is diverted to a “mud pit,” where the particles can settle to the bottom and the “clean” fluid can be recirculated down the borehole. The direct mud-rotary circulation system is shown on Figure 3-1. Figure 3-2 is a photograph of a small portable steel open-top mud pit.

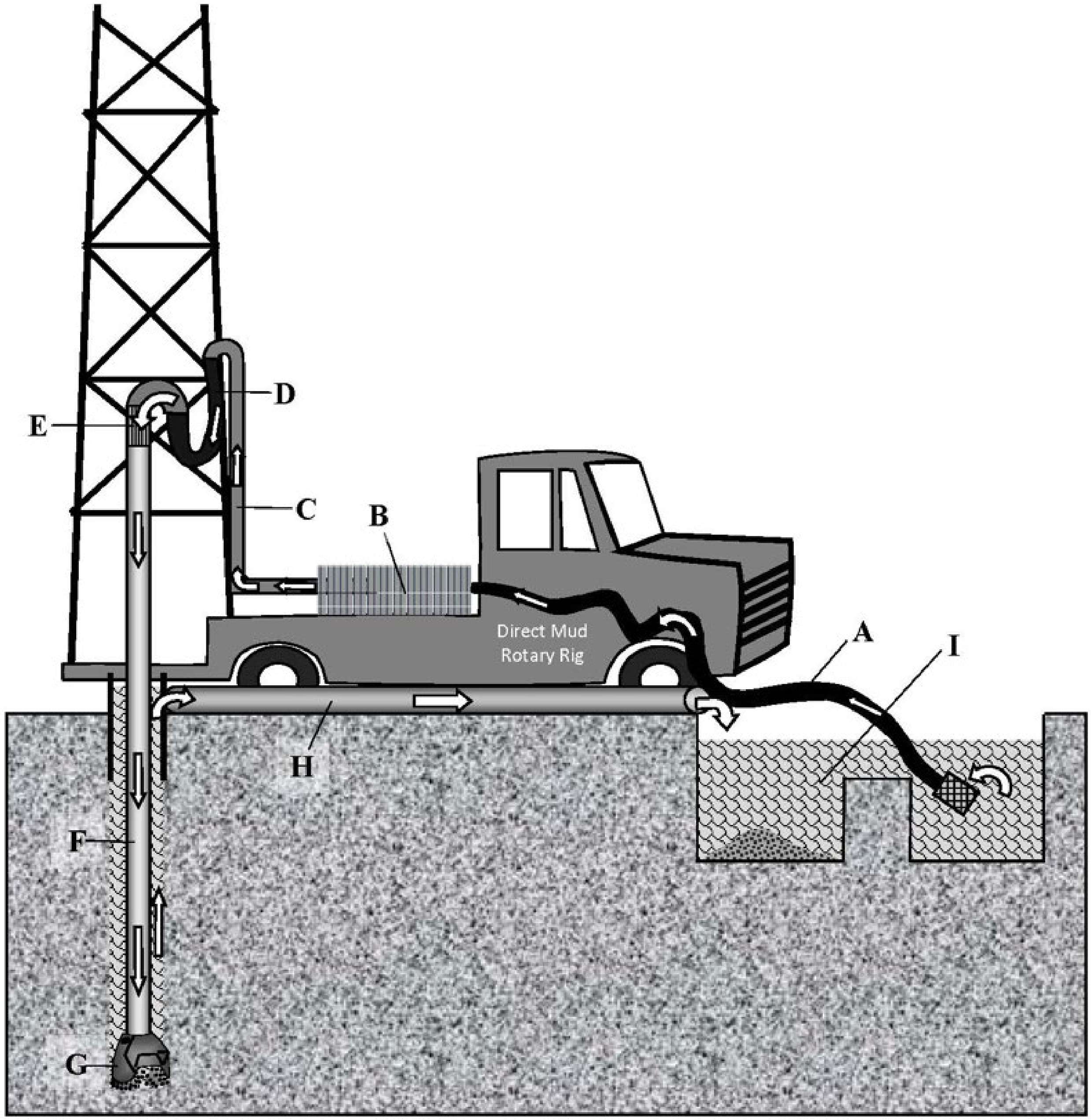


Figure 3-1. Direct mud-rotary drilling system (source: Glotfelty, 2019). The drilling fluid circulation path is shown by arrows. A: Intake line, B: Mud pump, C: Stand pipe, D: Kelly hose, E: Swivel, F: Drill pipe and collars, G: Drill bit, H: Return flow line, I: Mud pit (may be above-ground open-top steel tank).

Figure 3-2. Mud pit (source: Gonzales County Underground Water Conservation District).

The advantages of the direct mud-rotary drilling method include the ability to effectively remove cuttings from the borehole and the capability to manipulate drilling fluid properties to address problems such as unstable formations, lost circulation, and swelling clays. A disadvantage of this drilling method is that the water table cannot be identified as the borehole is being drilled because the hole is kept full of drilling fluid. For larger-diameter boreholes, the cost of drilling is also higher than some other methods due to the need for a large volume of drilling fluid with additives (Glotfelty, 2019). Mud-rotary drilling methods have been used routinely in the oil industry for accessing oil and gas production zones at depths greater than 25,000 feet below ground surface.

Drilling fluid properties, including consistency, viscosity, weight, chemical composition, and reaction with native formation fluids, is a topic beyond the scope of this document. However, the drilling program should include a driller and/or mud engineer that understands the complex nature of drilling fluid use for brackish groundwater exploration. Drilling mud data—including, but not limited to, mud weight and electrical resistivity—should be collected during the drilling process. Brackish groundwater zones will have a direct impact on the performance of drilling fluids, which may require modification of the drilling fluid chemistry with additives. A description of drilling fluid properties is available in several publications, including the *Practical Handbook of Ground-Water Monitoring* (Nielsen, 1991) and *Groundwater and Wells*, 2nd edition (Driscoll, 1986) and 3rd edition (Sterrett, 2007).

3.1.2 Direct Air-Rotary

The direct air-rotary drilling system is similar to the direct mud-rotary system, except that compressed air replaces drilling mud as the circulated fluid. Direct air-rotary drilling involves use of an air compressor to cause pressurized air to flow downward through the center of the drill pipe, out the drill bit, and up the annulus outside the drill pipe to remove the drill cuttings through a blooey line (Figure 3-3).

Air-rotary drilling can use a tri-cone drilling bit for sediments and softer rocks or a hammer bit with a downhole pneumatic hammer for hard, brittle formations (Figures 3-4 and 3-5). The downhole hammer bit operates like a jack hammer, with a pneumatic hammer just above the drill bit causing rapid pounding on the bottom of the borehole to break up the formation into cuttings for circulation out of the borehole by the flowing compressed air. The hammer bit does not have cones, but rather incorporates tungsten carbide inserts (buttons) to accommodate the action of the hammer to break up and pulverize the formation.

If abundant groundwater is flowing into the borehole while drilling with the downhole hammer method, it is possible for water to enter the borehole faster than it can be removed by circulation of compressed air. When this occurs, this situation is called “flooded out” or “water logged” by drillers, at which point the driller must remove (trip out) the drill string and switch to conventional direct rotary drilling with a tri-cone bit or mud-rotary drilling.

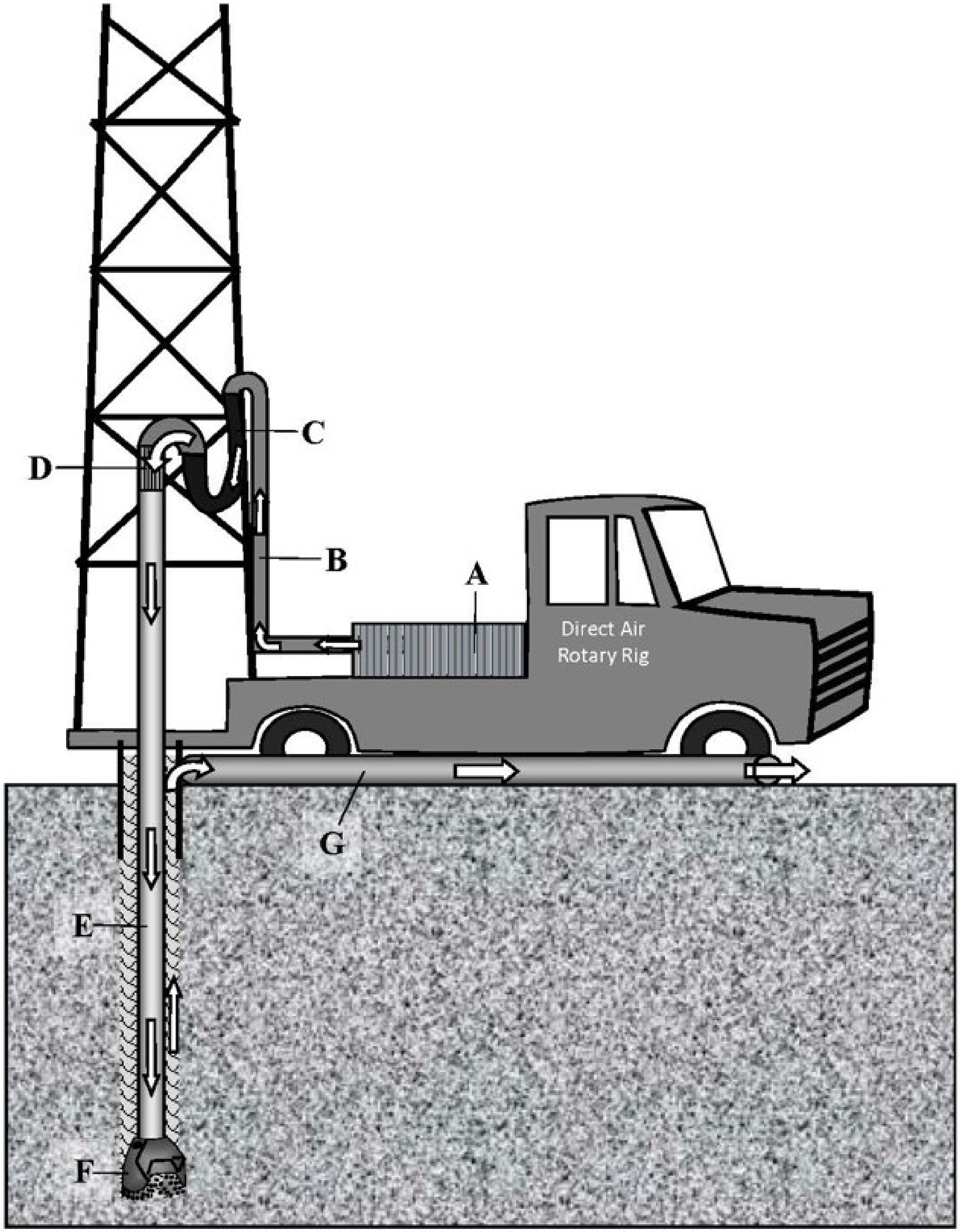


Figure 3-3. Direct air-rotary drilling system (source: Glotfelty, 2019). The drilling fluid circulation path is shown by arrows. A: Air compressor, B: Stand pipe, C: Kelly hose, D: Swivel, E: Drill pipe and collars, F: Drill bit, G: Blooey line.

Figure 3-4. Tri-cone bit.

Figure 3-5. Hammer bit.

As a compressible fluid, the air used in air-rotary drilling has a viscosity characteristic. Dry air has the lowest viscosity, which can be increased with a small amount of injected water to improve the fluid's borehole cleaning properties. This is called "mist" air-rotary drilling, which is a common practice to help clean the hole and prevent dust problems at the land surface. If a surfactant (soap) is added to the injected water, the fluid viscosity is further increased. The addition of soap and water to the compressed air circulated through the borehole is called "foam" air-rotary drilling. If the formation has very porous conditions or open fractures in the rock, the cuttings can still be removed from the borehole by injecting a mixture of water, soap, and polymer into the stream of compressed air to create a very viscous but light fluid (similar to shaving cream). This is called "stiff foam" air-rotary drilling.

Advantages of the air-rotary drilling method include its ability to effectively remove cuttings from the borehole with minimal wall cake accumulation, so well development (the removal of all residual drilling fluids form the borehole) is readily achieved. This drilling method is relatively inexpensive because a large volume of drilling fluid/mud, along with costly additives, is not needed. The water table can be identified during air-rotary drilling because the borehole is stabilized only with compressed air, so groundwater production can be noted when the water table is encountered. It should be noted that a certain amount of bit submergence is required before the groundwater can be airlifted to the land surface, so the first arrival of water discharge does not necessarily indicate the water table depth. Experienced drillers can usually provide a reasonably accurate estimate of the water table depth, or the static water level can be measured with a water level indicator (sounder) after the air compressor has been turned off. Water level measurements cannot always be conducted through the interior of the drill pipe, as some drilling conditions call for the driller to include a check valve (float) in their drill string that will prevent the water inside the drill pipe from equilibrating with the water table depth.

A disadvantage of air-rotary drilling is that because the borehole stabilization relies on the circulation of pressurized air, there is a necessary interruption of that stabilization when the driller "makes a connection" and adds another joint of drill pipe. While making a connection, the driller must turn off the air compressor, so if the formation is unconsolidated or loose, it may slough into the borehole and could result in stuck drill pipe (Glotfelty, 2019).

3.1.3 Flooded Reverse-Rotary

For drilling programs involving large-diameter boreholes, which are more common for production wells than test borings or wells, the flooded reverse-rotary drilling method is an effective means of addressing some common challenges. Larger-diameter boreholes require a substantial volume of drilling fluid to fill the annulus between the drill pipe and borehole wall. The large cross-sectional area between the drill pipe and the borehole wall makes it difficult to circulate the fluid at an adequate uphole velocity required to lift the drill cuttings to the surface. The reversed direction of fluid circulation, which is downward through the annulus and up through the center of the drill string (Figure 3-6), facilitates the upward discharge of fluids through the center of the drill pipe. This is because the cross-sectional area of the drill pipe is much smaller than that of the annular space, and adequate uphole velocities can be achieved at lower circulation flow rates. The borehole can therefore be cleared using lower-viscosity drilling fluids such as clear water with just a few additives like soda ash and polymer. This eliminates the cost of building a large volume of more expensive drilling fluid. Of course, more viscous drilling fluids can also be used with the flooded reverse drilling system when desired.

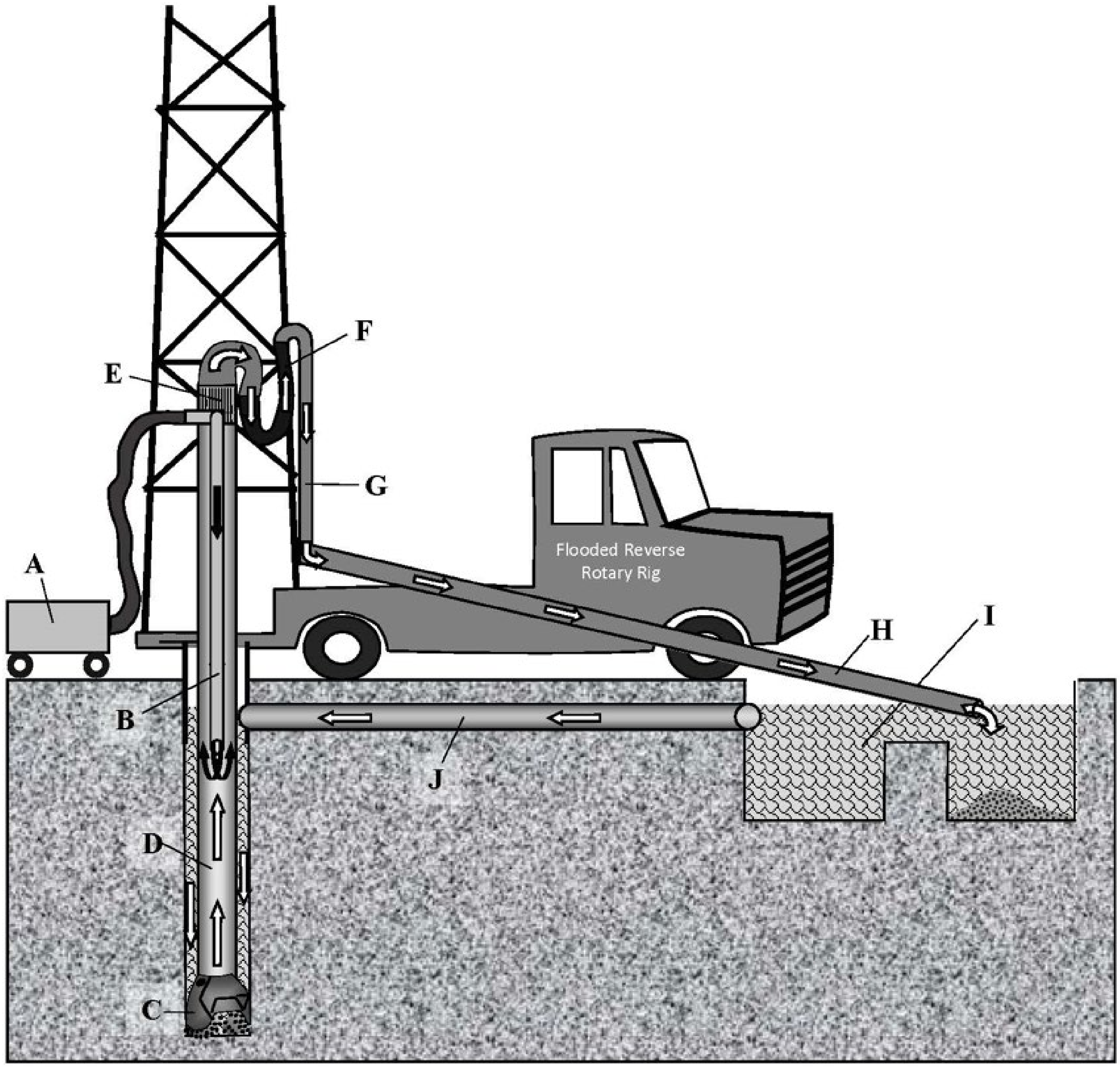


Figure 3-6. Flooded reverse-rotary drilling circulation system (source: Glotfelty, 2019). The compressed air flow path is shown by solid arrows, while the drilling fluid circulation path is shown by open arrows. A: Air compressor, B: Air line, C: Drill bit, D: Drill pipe and collars, E: Swivel, F: Kelly hose, G: Stand pipe, H: Flow line, I: Mud pit, J: Return flow line.

The advantages of the flooded reverse-rotary drilling method include the ability to effectively remove cuttings from a large-diameter borehole and the capability to manipulate drilling fluid properties when needed to address downhole problems or unstable formations. A disadvantage of this drilling method is that a water supply is needed (ranging from 50 to 300 gallons per minute [gpm] during borehole drilling), and the water table cannot be identified while the borehole is being drilled, as the hole must be kept full of fluid to near land surface (Glotfelty, 2019).

Flooded reverse-rotary drilling methods often use compressed air in conjunction with water-based drilling fluids to improve the movement of drill cuttings to the ground surface. Special dual-walled drill pipe, consisting of an inner chamber for water-based drilling fluids and an outer chamber for air (also known an integral air passage pipe), is used for this purpose. Some of the older flooded reverse-rotary drilling methods used air lines installed within the drill pipe or air lines attached to the outside of the drill pipe (Driscoll, 1986).

3.1.4 Dual-Rotary

The dual-rotary drilling method provides an effective means of installing wells in unstable formations such as loose sand, gravel, or cobbles. Borehole stabilization for the dual-rotary drilling method is achieved by advancing “DR” casing while the boring is being drilled. Thus, compressed air or drilling fluids are not required to keep the borehole open, which can be problematic in loose sands and gravels that are very porous because the formation permeability will allow drilling fluid to rapidly infiltrate into the adjacent strata and thus fail to provide a positive pressure (hydraulic head) to keep the borehole open and stabilized. Similarly, the high porosity of coarse-grained formations will prevent compressed air from establishing and maintaining an adequate positive pressure for borehole stabilization.

The dual-rotary rig has two hydraulic rotary drive heads (Figure 3-7). The upper head (connected to the interior drill string) is similar to a top-head drive on a conventional rotary drilling rig. The lower rotary head (connected to the exterior casing string) is designed to grip the DR casing that extends via welded sections into the borehole as it is advanced. A drill shoe equipped with tungsten carbide inserts is welded to the base of the DR casing to facilitate rotation of the casing as it is advanced into the borehole. Dual-rotary drilling can be conducted using direct circulation or flooded reverse circulation.

The upper and lower drive heads operate independently, such that the interior or exterior strings can be individually positioned to address various drilling conditions. For wells that are to be constructed with a pre-manufactured well screen and filter pack rather than by just perforating the DR casing, the well installation involves a “pull-back” completion that necessitates removal of the DR casing simultaneous with filter pack installation after a smaller-diameter permanent well screen and casing have been installed inside the DR casing (Glotfelty, 2019).

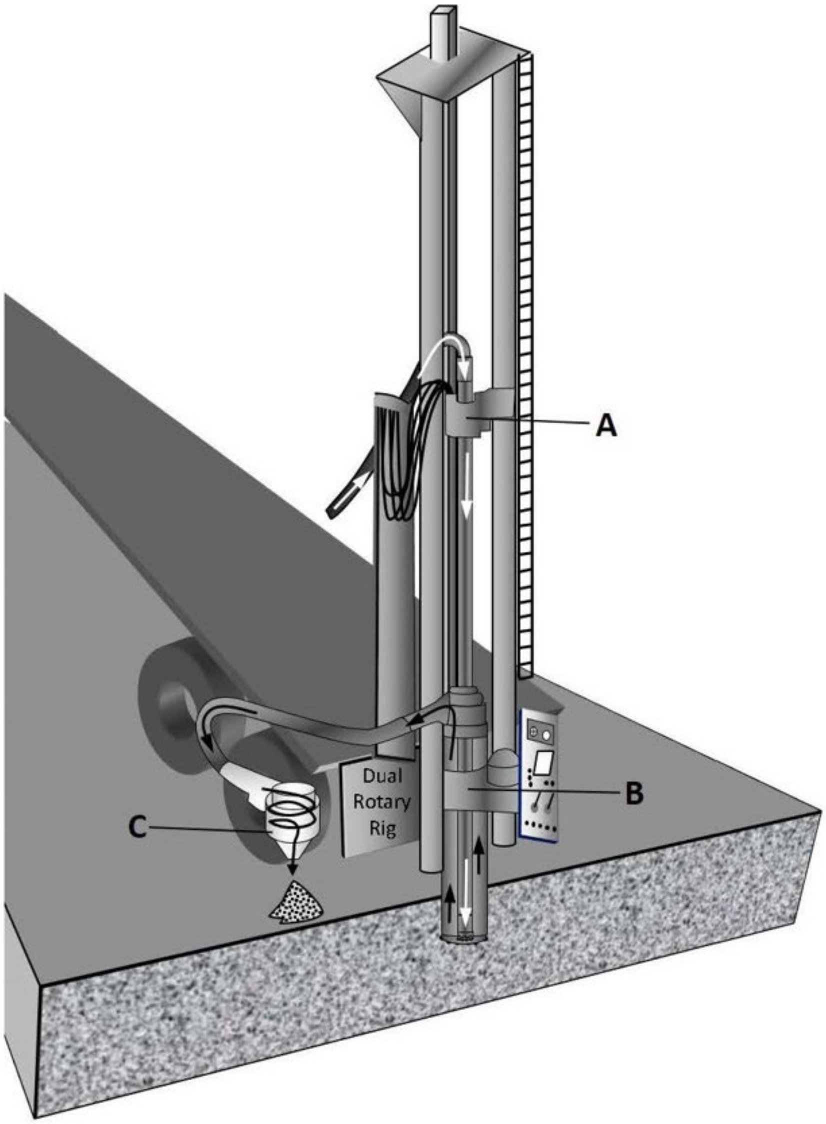


Figure 3-7. Dual-rotary circulation drilling system (source: Glotfelty, 2019). The compressed air or drilling fluid flow path is shown by arrows. The upper drive head (A) rotates the inner drill pipe, and the lower drive head (B) rotates the DR casing. Cuttings are discharged to a cyclone (C) or a mud pit.

3.1.5 Other Drilling Methods

Several other drilling methods that may be useful for brackish groundwater investigations are described in the following subsections. These methods are used less commonly than the previously described methods.

3.1.5.1 Air-Rotary Casing Hammer

The air-rotary casing hammer (ARCH) drilling method combines direct air-rotary drilling with the use of a casing hammer without the use of drilling mud. An oversized casing is driven (without rotation) into an undersized bore created using air-rotary drilling methods. A schematic of the ARCH drilling method is provided as Figure 3-8.

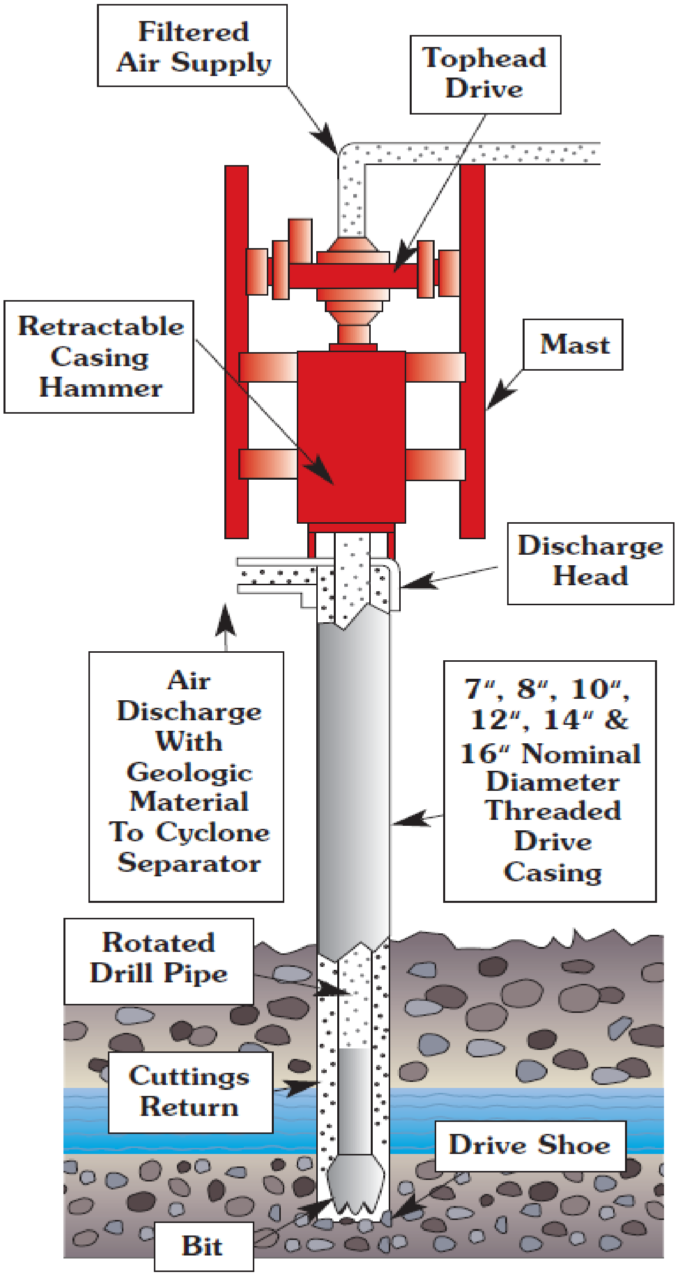


Figure 3-8. Air-rotary casing hammer drilling method (source: WDC Exploration and Wells, Undated). Compressed air travels through the rotating top drive, drill pipe, and drill bit, while the outer threaded drive casing is advanced with a casing hammer. Drill cuttings travel through the annular space between the inner rotating drill string and the outer drive casing to the ground surface, where they are separated using a cyclone. Multiple diameter drive casings can be used in a telescopic manner to achieve deeper drilling depths.

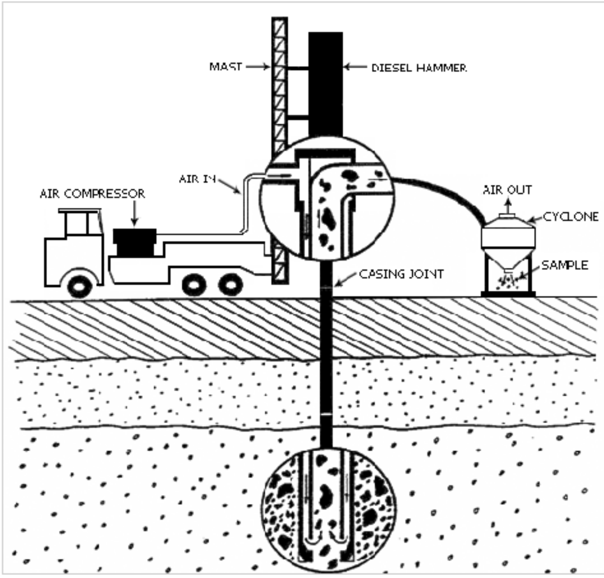
The ARCH method is good for drilling through unconsolidated formations, including conglomerates with larger cobbles, as it is a "casing-while-drilling" method. Multiple telescopic casing intervals can be installed and removed, without the need to install permanent casing strings. After the borehole has been drilled to its total depth, the inner drill pipe can be removed and well screen, casing, filter pack, bentonite seal, and grout can be installed while the outer drill casing is removed. This method ensures that formation materials will not cave in on the well materials as the well is constructed. Other advantages are that very little water is used during the drilling process, and therefore fluid waste generated during drilling is limited. The use of air allows for almost immediate cuttings recovery for examination by the on-site geologist, as the cuttings are discharged through a cyclone at the ground surface. This is also a relatively fast drilling method; drill depth limitations are approximately 1,000 feet, but drill rates of 50 feet per hour are not uncommon. Disadvantages are primarily associated with drilling very productive aquifers, where a significant influx of groundwater into the borehole will generate a lot of water.

3.1.5.2 Becker Hammer Drill

The Becker hammer drilling method is similar to the ARCH drilling method, although it uses no internal rotating drilling tools (but it can be fitted with them to drill through hard or difficult drilling conditions). The Becker hammer drilling method is suited to drilling through unconsolidated formation materials that could be encountered in some shallow brackish groundwater formations, including formations with large cobbles or boulders that could create difficult drilling conditions for other drilling methods. A schematic of the Becker hammer drill process is provided as Figure 3-9.

This method uses a double-walled drive pipe driven by a percussion hammer, while compressed air is forced down the annulus of the dual-walled (integral air passage) drive pipe to lift the drill cuttings to the surface through the center of the drive pipe. At the top of the boring, the cuttings are diverted through a discharge hose to a cyclone, which slows down the discharge velocity. The cuttings are accumulated in containers, where samples can be collected for analysis by the on-site geologist. Drilling rates of up to 50 feet per hour can be achieved in gravel, sand, and cobble formations, accompanied by continuous sample collection with optimum sample recovery. Once bedrock is reached, conventional drilling methods are used to drill the rest of the borehole, with the double-walled pipe serving as the overburden casing (surface casing). Once the borehole has reached its total depth, the double-walled drive pipe is withdrawn (description modified from the Great West Drilling web site [www.greatwestdrilling.com]).

The Becker hammer drill method is best used for drilling borings less than 500 feet deep, and various size drill strings can be used to drill a borehole from 5.5 to 9 inches in diameter. Deeper drilling depths up to 1,000 feet are possible with the use of telescopic drill strings, or conventional air/mud rotary methods for deeper drilled intervals. One benefit of the Becker hammer drilling method is that the drill cuttings are deposited at the ground surface with minimal mixing, and can be readily evaluated by the on-site geologist. The on-site geologist will also know precisely when a groundwater-bearing unit is encountered, as water will be discharged through the cyclone at the ground surface.



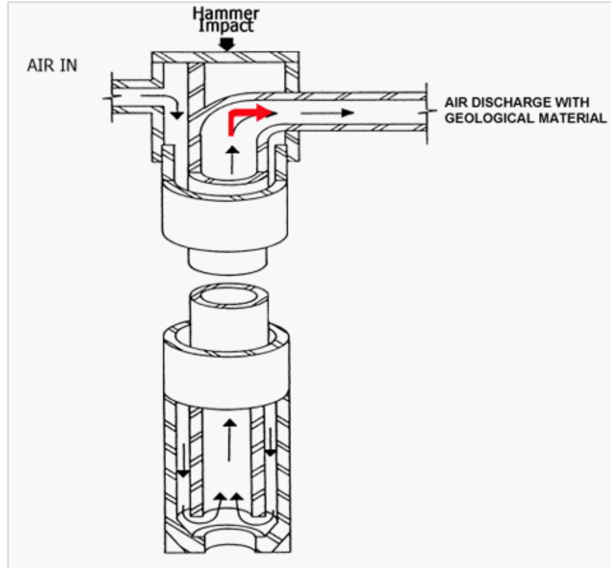


Figure 3-9. Becker hammer drilling method (source: Great West Drilling, 2021). Compressed air travels through the annulus (interstitial void) of the dual-wall drive pipe as the drive pipe is driven. No rotation of the drive pipe occurs. Drill cuttings are entrained in the compressed air and are discharged through a cyclone at the ground surface.

Another benefit similar to the ARCH method is that after drilling to the total depth of investigation, well materials such as screen, casing, filter pack, bentonite seal, and grout can be installed inside the drive pipe as the drive pipe is removed, ensuring that the borehole integrity is maintained while the well is being constructed. Because the drive pipe performs as surface casing, surface casing may not need to be installed.

A significant disadvantage of the Becker hammer drill method is that most geophysical survey methods (except the neutron log) cannot be used with the drive pipe installed.

3.1.5.3 Cable Tool

The cable tool drilling method is the oldest well drilling technique, first developed in China around 4,000 years ago. The cable tool drilling method involves advancing the borehole by breaking up the formation with a heavy drill bit suspended from a cable that is intermittently raised and dropped. The reciprocal motion of the drill bit results from the movement of the cable as it passes through a sheave at one end of the walking beam. The walking beam pivots at one end, and is moved up and down at the other end by its connection to a pitman arm attached to the rig's crankshaft. After the cable tool drill bit has broken up the formation into cuttings, they are removed by bailing. Drill depths using cable tool methods can be as deep as 5,000 feet, with diameters ranging from 3 inches to 8 inches (Driscoll, 1986). In addition to the cable, the components of the cable tool drill string include (from the bottom up) the drill bit, drill stem, drilling jars, and swivel socket (Figure 3-10). This drilling method could be effective for installation of brackish test wells in relatively shallow unconfined formations or in areas where the ground surface terrain would limit access by other, larger drilling rigs. However, the drilling process is slow compared to other more modern methods, and application of this method is very rare. Drilling rates of 10 to 20 feet per day are common (Nielsen, 1991).

Figure 3-10. Cable tool drilling rig (source: Clear Creek Associates). The walking beam (yellow) moves up and down (green arrow), which provides the motion of the drill cable. The drill string standing to the left of the rig includes the drill bit (at the base), drill string, and drilling jars (at the top of the photograph).

3.2 Well Completion

Once the borehole has been drilled or reamed to its total depth, a well is installed. Well completion is a term used to describe the process of converting a borehole into a well. Multiple methods can be used to achieve well completion, depending on the drilling methods used, well depth, and zones that require isolation and/or production. An extensive discussion on well completion materials is presented in the *Practical Handbook of Ground-Water Monitoring* (Nielsen, 1991) and *Groundwater and Wells*, 2nd edition (Driscoll, 1986) and 3rd edition (Sterrett, 2007). The following subsections provide general descriptions of common components that may go into a well completion.

3.2.1 Borehole Plug-Back

After the production zone of a test well (or the lowest production zone of a multiport or nested test well) has been determined, the deepest unused portion of the borehole is usually plugged back (filled) with a grout mixture, which is a small quantity of bentonite mixed with Portland cement, to a depth immediately below the production zone. The plug-back depth is typically determined by reviewing the geophysical log, drill cuttings, and lithologic logs prepared by the on-site geologist. The plug-back process is usually performed prior to reaming the borehole for installation of well materials.

Grout is usually preferred over bentonite for plugging back boreholes because it solidifies as it cures, forming a hard fill material at the bottom of the borehole. Pure bentonite is often used for sealing boreholes above the screen pack interval and/or as an alternative material to grout from the top of the filter pack to the ground surface. However, pure bentonite is not recommended for plugging back intervals below the production zone because hydrated bentonite is soft, and any filter pack materials installed above it could sink into the bentonite and/or the bentonite may swell into the filter pack and invade the screened interval. These situations can be avoided by grouting a short interval above the plug-back interval if bentonite is used.

3.2.2 Casing

Casing is pipe that is installed into a borehole to prevent formation material (rock, sand, gravel) from collapsing into the well bore. Multiple casings may be installed in a well, with the largest-diameter casing installed first, followed by successively smaller casings, if used. Casing can be made from a variety of materials, including PVC, fiberglass, carbon steel, high steel low alloy (HSLA), or stainless steel. Fiberglass casing is well suited for deeper wells completed in brackish (corrosive) groundwater zones because it is stronger than PVC, less prone to corrosion than carbon steel or HSLA, and less expensive than stainless steel or HSLA. A more in-depth discussion on the use of fiberglass casing, including its structural performance, is documented in the report *Fiberglass Casing Use in Texas Public Supply Wells* (R.W. Harden & Associates, 2013).

Several types of casing may be used in an exploratory brackish well, depending on the investigation goals, the depth of the well, and the nature of the geologic formations encountered while drilling (Figure 3-11). These include conductor casing, surface casing, intermediate casing, and production casing.

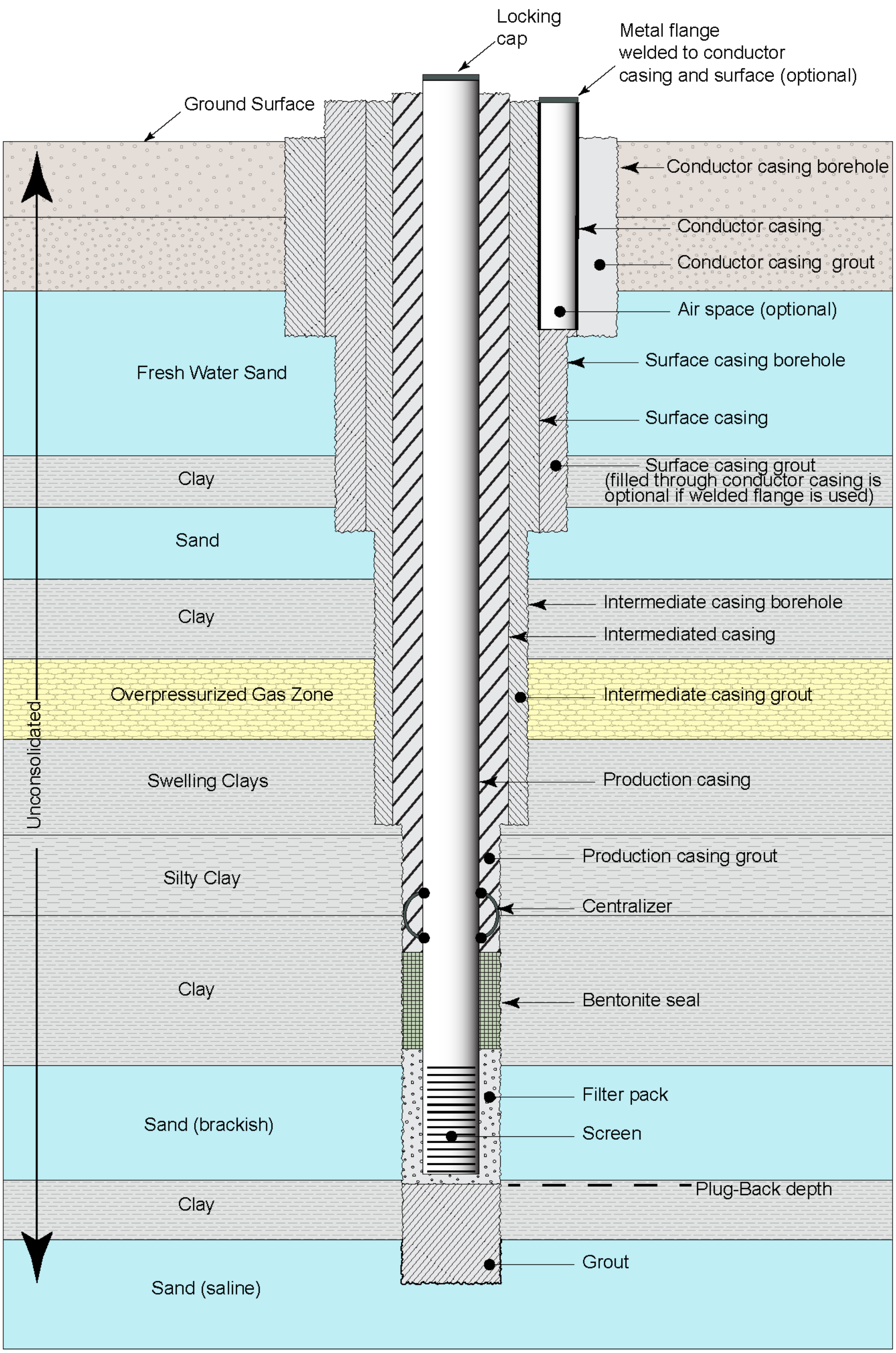


Figure 3-11. Standard well completion in unconsolidated formation materials.

Conductor casing is generally installed at shallow depths, and is relatively large in diameter (Figures 3-12 and 3-13). Conductor casing is installed to prevent caving in of unconsolidated formation materials below the drilling rig. In some locations, unconsolidated formation materials can be undermined during the drilling process and cause the drilling rig's stability to be compromised. Conductor casing is also installed in areas where undermining may not be a concern, but where a solid facility to support the drill rig and associated apparatus may be needed, or as a conduit to divert drilling fluids to a mud pit or other device used to process drill fluids and cuttings. A metal flange is often welded to the top of the conductor casing to allow drilling and production tools to be bolted to the flange.

Figure 3-12. 30-inch conductor casing.

Figure 3-13. Installing conductor casing.

Surface casing is smaller in diameter than conductor casing, and is typically installed in the borehole to protect shallow fresh groundwater zones and to isolate and stabilize shallower unconsolidated formation materials from falling downward into the borehole (Figure 3-14). Surface casing is typically cemented in place from its protective depth to ground surface, including inside the conductor casing (if installed). Sometimes the cost of cement is spared by welding or bolting a steel plate over the casings at the surface to isolate the space between the conductor casing and the surface casing.

Figure 3-14. 20-inch surface casing.

With deeper wells, an intermediate casing may be installed to isolate deeper formations that include unstable formation materials, clay or shale intervals that swell, or formations that contain pressurized, flammable, or toxic gas. This casing may also be used to isolate shallow aquifers with better water quality from deeper brackish zones. Intermediate casing is installed from a safe distance below those zones to the ground surface and is cemented in place, sometimes including inside the surface casing.

Production casing is usually the last string of casing to be installed and cemented in place above the production zone(s). Production casing can be installed either open-ended or with screen attached. As discussed in Section 3.2.3, screen is casing with manufactured openings to allow the entry of fluid into the completed well.

3.2.3 Screens

Screens are required for production zones that contain unconsolidated or unstable formation materials that would slough into the open borehole. Screens can be attached directly to and concurrent with the production casing installation, or they can be installed after open-ended production casing has been installed. For open-ended casing installations, a stinger (length of pipe and screen having a smaller outside diameter than the inside diameter of the production casing) can be installed in the production zone, with the upper end of the stinger held in place against the production casing with a flow-through packer. The stinger is attached to the drill pipe and lowered through the production casing to the desired depth, and then the drill pipe is turned slowly until the packer tightens (the packer has a rubber seal that is tightened as it is turned). Filter pack material between the stinger screen and the annular space can be added by pumping (washing) the filter pack through a one-way valve attached to the bottom of the stinger screen or a cross-over tool installed above the screen (Driscoll, 1986). After the filter pack has been installed, the drill pipe is unscrewed from the packer and the drill pipe is removed.

Screens are manufactured with a wide variety of methods, materials, and sizes that are highly dependent upon the structural integrity required, formation particle size, filter pack size, and desired hydraulic results. The simplest screens are slotted pipes, and more complex screens are manufactured with wire-wraps or louvers. Common screen materials include steel, stainless steel, and PVC. Screen slot size is a term used to describe the size of the openings that comprise the screen openings, which is measured as thousandths of an inch (0.001 inch). For example, a 50-slot screen will have openings of 0.05 inch. Screen slot sizes are selected to prevent excessive formation particles or filter pack material from entering the well. Collection of formation materials from the production zone during drilling is a good practice, as sieve analysis of the native formation particle sizes can be performed to select the optimum filter pack and screen slot size(s). Properly sized wire-wrapped or louvered screens are preferable to slotted screens and provide higher well efficiency and lower operational costs. A diagram of common well screen types is provided as Figure 3-15.

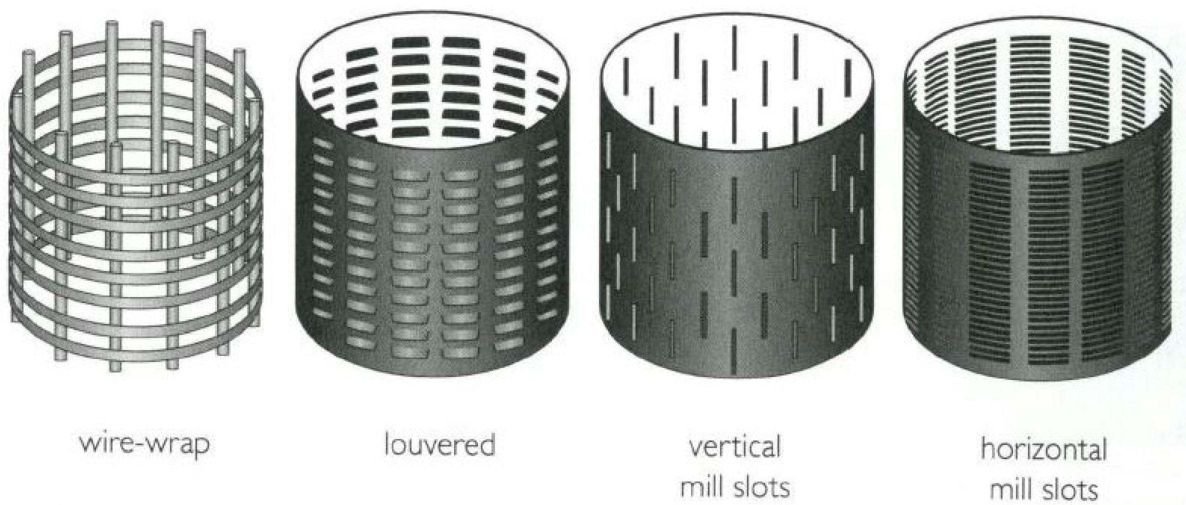


Figure 3-15. Common well screen types (source: Glotfelty, 2019).

3.2.4 Filter Pack, Bentonite Seals, and Grout

After installation of the casings and screens, additional materials required to complete the well include filter pack, bentonite seals, and grout.

The filter pack is typically a uniformly graded sand or gravel that serves as a filtering media between the well screen and aquifer formation material. The filter pack prevents aquifer formation material from flowing through the well screen during pumping, which can damage pump equipment and clog pipes and tanks in the water system. The filter pack is installed around the well screens and a pre-determined thickness above and below the well screens. The filter pack grain size is selected based on the formation particle size and screen slot size, and can range from fine sand to gravel-size grains. Filter pack should be well-rounded, well-sorted, and composed of silicious material that is hard and inert. In special applications when optimum hydraulic production is desired (e.g., municipal water supply wells), manufactured spherical glass beads may be used instead of sand or gravel.

The optimum size of filter pack selection is generally determined by the size of formation materials collected from the production zone during drilling process that are submitted for sieve analysis. The entire screen should be surrounded by the filter pack, and the filter pack should extend above the screen to compensate for filter pack settling. However, the distance that the filter pack should extend above the screen should also be a function of where the bentonite seal is placed, as discussed below.

Bentonite seals are used to seal off the annular space between the well casing and the borehole wall above the filter pack. Bentonite seals should always be installed within the annulus of the borehole and production casing that is adjacent to competent low-permeability formation materials. Installing bentonite seals adjacent to formation materials with high hydraulic conductivity will not prevent hydraulic communication, as fluids will travel around the bentonite seal through the conductive formation materials. The minimum thickness of the bentonite seal required is generally dictated by regulation (5 to 10 feet thick), but a thicker bentonite seal may be warranted if the formation materials with lower hydraulic conductivity are located higher above the screened interval.

Grout is the last well material to be installed above the bentonite seal for single-zone test wells or in intermediate zones between multiport or nested test wells. Grout is a mixture of bentonite, Portland cement, and water that is generally pumped through a tremie pipe from the top of the bentonite seal to the ground surface for wells with screen and production casing installed simultaneously.

It is also common, particularly for deep wells, for grout to be installed for conductor and intermediate casing using what is commonly called the oilfield method. In this approach, grout is pumped directly through the inside of the casing, and it rises up around the annular space outside the casing to the ground surface. This approach can also be used to grout the production casing of wells with open hole completions (Section 3.2.5), but the grout is emplaced before the production interval is drilled. Applied correctly, this approach is generally superior to the tremie method when working at significant depths; however, it is more costly.

The grout volume is usually calculated to determine the amount to pump, followed by water and an expendable wiper plug to displace the grout. Evidence of a good grouting job (tremie pipe or casing displacement method) is usually documented by uniform flow of excess grout (gray color) flowing freely at the ground surface and devoid of drilling mud, air bubbles, and/or formation water.

For wells installed in unconsolidated formation materials with screen and production casing, well materials are installed in successive order of filter pack, bentonite seal, and grout. For multiport or nested test wells, the process is repeated, but with grout (instead of bentonite) installed above the bentonite seal of the next-lowest production interval to the bottom of the next-higher production interval to prevent bentonite intrusion into filter pack/screened interval as described in Section 3.2.2.

Filter pack, bentonite seals, and grout are usually installed using a tremie pipe, which is a small-diameter conductor pipe with flush threads (no protruding pipe collars) temporarily installed between the production casing and/or screen and the borehole. The tremie pipe ensures that the well materials are installed to the intended depths without bridging, which could potentially occur if the materials were installed by dumping them into the annulus from the ground surface. Materials installed through the tremie pipe can be introduced to their respective zones using gravity fall methods (filter pack and bentonite pellets/chips), or materials can be pumped (filter pack, bentonite slurry, and grout). Grout should always be installed from the top of the bentonite seal to the ground surface by pumping it through a tremie pipe to ensure complete filling of the annulus without air pockets or voids. Filter pack materials can also be installed by pumping them through a one-way valve on the bottom of a stinger screen as described in Section 3.2.3.

3.2.5 Open Hole Completion

The void space in the earth resulting from drilling a borehole is often called "open hole." Open hole intervals drilled through consolidated formation materials competent enough to not slough or cave into the borehole do not need screen or casing to maintain the well integrity. A borehole can often be converted to an open hole well by installing surface casing to protect the open hole from materials caving in from (typically) upper unconsolidated materials near the ground surface. It is also common that casing may be installed to the production zone, but the production zone may not require well screen and may be completed as an open hole well. A generic schematic of an open hole completion is provided in Figure 3-16.

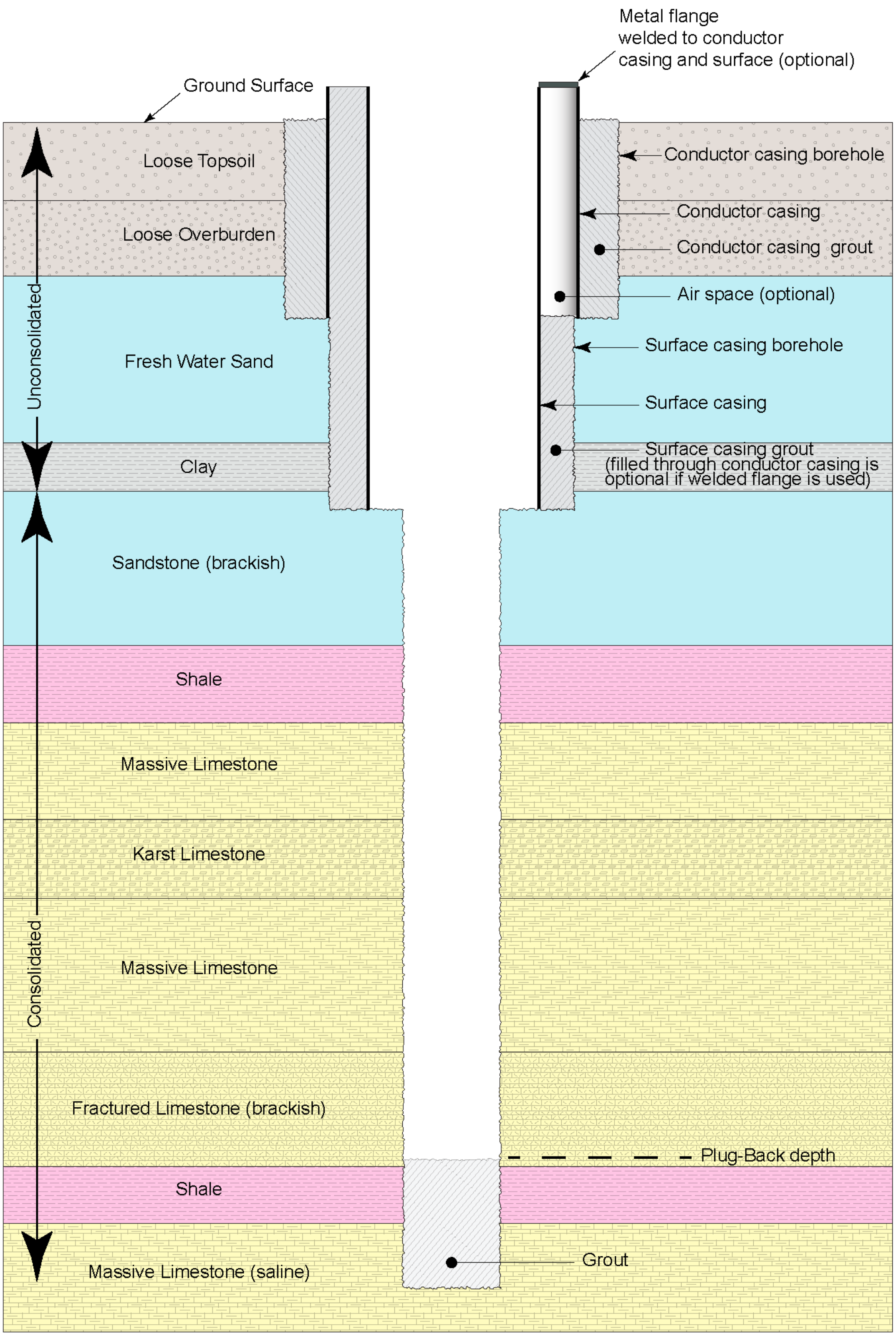


Figure 3-16. An open hole completion in consolidated formation materials.

3.3 Well Development

Development is the process of removing residual drilling fluids from the filter pack/screened interval and promoting the flow of native formation water from the production zone into the well. Adequate well development must be conducted prior to hydraulic testing or collecting groundwater samples for analysis. Development is performed until the resultant discharge water is clear and/or within specifications that indicate groundwater entering the well has stable quality. Typical indicators of this condition are consistent, consecutive measurements of groundwater temperature, electrical conductivity, pH, and turbidity. Development can be performed in test boreholes or wells, using one or a combination of the following methods:

- *Airlift:* Airlift methods use an air hose installed to a depth within or below the production zone with sufficient air pressure applied to blow/surge formation water to the ground surface.
- *Swabbing/surging:* Special brushes and rubber blocks designed to be inserted into test wells are worked up and down using the drill rig or a special well development rig. The up-and-down swabbing and surging action can be an effective method for dislodging drilling mud and formation materials from the filter pack and well screen.
- *Bailing:* A bailer is a cylinder-shaped pipe constructed with an internal loose ball on the bottom that allows water to enter as it is lowered into water, but covers (seals) a hole on the bottom of the bailer as it is removed. The bailer is lowered into a well using the drill rig or service rig sand line (a small-diameter steel cable for light-duty lifting purposes), and then retracted to extract water.
- *Pumping:* An electrical submersible pump fitted with discharge piping to the ground surface can be used to develop wells by pumping. If sized correctly, the pump can also be used to perform aquifer testing in the same well. Pumping may not be possible in some exploratory applications such as zonal testing where the drill pipe's inside diameter is too small to accommodate the pump and electrical wires, or exploratory wells with small diameters.

A combination of the above techniques may often be applied to successfully develop a well.

4 Drilling Costs

Drilling costs associated with installing exploratory boreholes and wells is highly dependent on the number of boreholes or wells installed, the depth of the brackish groundwater resources, and the character of the geologic units being drilled. Before any drilling program begins, a desktop review of existing information should be performed as described in Section 5.

Factors that affect drilling costs include, but are not limited, to the following:

- *Protection of fresh groundwater:* Fresh groundwater is a valuable resource and must be protected through installation of surface casing. For example, in Texas, the Gulf Coast Aquifer provides fresh water from geologic formations up to approximately 2,000 feet deep, so costs for deeper brackish groundwater exploration in areas underlain by the Gulf Coast Aquifer would need to consider costs for drilling and installing extensive surface casing.
- *Depth of investigation:* The depth of drilling required to define a brackish groundwater resource will dictate the size of the drilling rig and the support equipment needed. Deeper drilling generally requires larger and additional drilling equipment. Exploratory boreholes and wells less than 1,000 feet can generally be installed using mobile, rubber-tire drilling rigs. Deeper drilling programs may require the use of "land rigs" that are transported to the site and set up in pieces.
- *Character of geologic units being drilled:* Drilling through bedrock formations such as limestone, sandstone, or granite may be significantly more time-consuming and costly than drilling through semi-consolidated sediments such as the Carrizo-Wilcox Aquifer or unconsolidated sediments such as the Ogallala or Gulf Coast aquifers because drilling through consolidated materials generally requires more time. However, drilling through unconsolidated formations can be more expensive than drilling through consolidated formations because additional casing may be required to isolate unconsolidated formation.
- *Drilling through pressurized or oil/gas containing formations:* Oil and/or natural gas occurs naturally in subsurface formations throughout Texas. Drilling through zones of potential over-pressure and/or exposure to hydrogen sulfide-containing gas presents a serious health and safety hazard. Blow-out prevention devices and methane/hydrogen sulfide detection devices, used by trained experts may be needed, which would increase the drilling costs. Intermediate casing may also be required to isolate such intervals. In some instances, drillers familiar with this type of drilling and having the necessary equipment to address pressurized or oil/gas containing formations may be required for brackish groundwater exploration. During economically favorable periods of oil and gas exploration/development, oil and gas drilling rigs may be difficult to procure, and during economically depressed periods, drilling rigs may be abundant. These factors may also greatly impact the cost of drilling.

- *Type of boreholes or wells needed:* The type of exploratory borehole or well needed will greatly influence the project cost. Exploratory boreholes are the least expensive method to collect data on a brackish groundwater resource. Single-zone test wells, multiport test wells, and nested test wells are increasingly more expensive to install.
- *Number of zonal test intervals needed:* For zonal testing, additional time is needed for groundwater development, sampling, and hydrologic testing. Some test boreholes may only require zonal testing in one or two intervals, and others may require zonal testing in several intervals, which will increase the drilling costs.
- *Waste disposal:* Brackish groundwater exploration will likely generate drilling mud and production water that may require special disposal consideration, including waste characterization testing, transportation costs to the disposal facility, and disposal costs per gallon. Depending on the location of the brackish resource being investigated and the type of disposal required for production water generated during drilling and testing, the cost may increase significantly due to the cost of waste disposal.

Pricing for four hypothetical drilling scenarios in Texas was requested from nine different drilling contractors. Responses were received from four of these contractors for at least one scenario. Based on these responses, major exploration borehole and test well costs, including high and low drilling costs for each hypothetical scenario, are presented in Tables 4-1a through 4-1d. The tables include costs for all materials (drilling mud, casing, screen, filter pack, grout, etc.) but do not include costs for geophysical surveys, use of blow-out preventers, gas monitoring, or professional project oversight.

Table 4-1a. Estimate of major costs for exploratory test borehole.

Item	Unit	Quantity	Low Unit Rate	High Unit Rate	Events	Low Cost	High Cost
1. Mobilization and site setup	lump sum	1	$5,000	$40,000	1	$5,000	$40,000
2. Drill borehole to maximum depth of investigation, ream and prepare borehole for geophysical logging.	foot	1,500	$30	$184	1	$45,000	$276,000
3. Standby for geophysical survey	hour	4	$300	$450	1	$1,200	$1,800
4. Plug and abandon borehole	foot	1,500	$9	$20	1	$13,500	$30,000
5. Lodging and per diem for drill crew (assume 4 drill crew members x 30 days)	day	40	$180	$300	1	$7,200	$12,000
6. Other miscellaneous items like well reports, fluid replenishment, small items	lump sum	1	$200	$7,000	1	$200	$7,000
7. Proper and legal disposal of drill fluids and brackish development water	gallon	2,000	$0	$1	1	$600	$2,000
Total Low Cost						**$72,700**	
Total High Cost							**$368,800**

Hypothetical scenario: 400-mile round-trip mobilization to drill one 8-inch-diameter exploratory borehole to 1,500 feet through unconsolidated formation materials (gravel, sand, silt, clay). Assume 30 days needed to complete the work.

Table 4-1b. Estimate of major costs for exploratory test borehole with zonal testing.

Item	Unit	Quantity	Low Unit Rate	High Unit Rate	Events	Low Cost	High Cost
1. Mobilization and site setup	lump sum	1	$6,000	$50,000	1	$6,000	$50,000
2. Drill 8-inch-diameter pilot borehole to 1,500 feet	foot	1,500	$30	$184	1	$45,000	$276,000
3. Standby for geophysical survey	hour	5	$300	$450	1	$1,500	$2,250
4. Widen (ream) borehole to 14 inches	foot	1,500	$30	$198	1	$45,000	$297,000
5. Install 10-inch-diameter surface casing	foot	1,500	$40	$65	1	$60,000	$97,500
6. Drill 8-inch-diameter borehole from 1,500 to 2,000 feet and prepare borehole for geophysical logging.	foot	500	$30	$184	1	$15,000	$92,000
7. Standby for geophysical survey (1,500 to 2,000 feet)	hour	4	$300	$450	1	$1,200	$1,800
8. Plug-back borehole to bottom of deepest potential production interval using a tremie pipe. Assume plug-back depth of 1,400 feet.	foot	100	$12	$75	1	$1,200	$7,500
9. Attach screen or slotted casing (eductor pipe) on end of drill pipe and lower eductor pipe to the desired test interval. Test from bottom interval and pull up for each successively shallower interval.	hour	2	$300	$1,200	5	$3,000	$12,000
10. Using a tremie pipe, install filter pack around eductor pipe and bentonite seal above and below the eductor pipe interval (assume 20-foot educator pipe, 30-foot filter pack, and two 5-foot bentonite seals), or	foot	40	$0	$75	5	$0	$15,000
11. Set up and deploy inflatable packers above and below the eductor pipe (*cost not included in total*).	hour	1	$300	$600	5	$1,500	$3,000
12. Develop well to promote formation yield. Purge the production interval of any residual construction water using air lift method and/or swab tool. Collect water sample for chemical analysis.	hour	8	$300	$2,400	5	$12,000	$96,000
13. Subcontract Chemical Analysis - dissolved silica, iron, calcium, magnesium, sodium, potassium, bicarbonate, sulfate, chloride, nitrate (as nitrogen), total dissolved solids, hardness (as $CaCO_3$), pH, and specific conductance.	lump sum	1	$1,200	$2,150	5	$6,000	$10,750
14. Perform a slug test by installing a pressure transducer below the static water level and adding several gallons of water as quickly as possible. Upload/save transducer data.	lump sum	1	$1,500	$3,200	5	$7,500	$16,000

Table 4-1b. Estimate of major costs for exploratory test borehole with zonal testing.

Item	Unit	Quantity	Low Unit Rate	High Unit Rate	Events	Low Cost	High Cost
15. Drill out the filter pack and bentonite materials and plug and abandon the borehole.	foot	1,500	$15	$45	1	$22,500	$67,500
16. Proper and legal disposal of drill fluids and brackish development water	gallon	4,000	$1	$1	1	$3,600	$4,000
17. Lodging and per diem for drill crew (assume 6 drill crew members x 15 days)	day	40	$180	$300	1	$7,200	$12,000
Total Low Cost						**$236,900**	
Total High Cost							**$1,064,800**

Hypothetical scenario: 600-mile round-trip mobilization to drill one 8-inch-diameter test borehole to 2,000 feet with zonal testing through unconsolidated formation materials. Assume drilling 8-inch pilot borehole to 1,500 feet, performing geophysical survey, then reaming borehole to 14 inches for installation of 10-inch-diameter steel surface casing. Drill 8-inch-diameter borehole to 2,000 feet, clean borehole, and prepare for geophysical logging. Assume 5 zonal testing intervals.

Table 4-1c. Estimate of major costs for single-zone test well in unconsolidated formation materials.

Item	Unit	Quantity	Low Unit Rate	High Unit Rate	Events	Low Cost	High Cost
1. Mobilization and site setup.	lump sum	1	$2,000	$24,000	1	$2,000	$24,000
2. Drill 7⅞-inch-diameter pilot borehole to 400 feet.	foot	400	$30	$184	1	$12,000	$73,600
3. Standby for geophysical survey (upper 400 feet of borehole).	hour	4	$300	$550	1	$1,200	$2,200
4. Widen (ream) borehole to 12 inches.	foot	400	$20	$198	1	$8,000	$79,200
5. Install 8-inch-diameter surface casing.	foot	400	$40	$65	1	$16,000	$26,000
6. Drill 7⅞-inch-diameter borehole from 400 to 600 feet and prepare borehole for geophysical logging.	foot	200	$30	$184	1	$6,000	$36,800
7. Standby for geophysical survey (400 to 600 feet).	hour	4	$300	$450	1	$1,200	$1,800
8. Plug-back borehole to bottom of production interval using a tremie pipe. Assume plug-back depth of 550 feet.	foot	50	$12	$16	1	$600	$775
9. Clean out borehole to prepare it for installation of screen and casing.	foot	550	$1	$165	1	$550	$90,750
10. Using a tremie pipe, install filter pack in annulus around screen from plug-back depth to bottom of first competent clay zone (assume 490-foot depth; 60 feet of sand) and bentonite seal from 480 to 490 feet (10 feet).	foot	70	$30	$350	1	$2,100	$24,500
11. Install grout within annulus to ground surface using a tremie pipe (490 feet to surface).	foot	490	$20	$40	1	$9,800	$19,600
12. Develop well to promote formation yield and collect water sample for chemical analysis.	hour	10	$300	$975	1	$3,000	$9,750
13. Subcontract Chemical Analysis - dissolved silica, iron, calcium, magnesium, sodium, potassium, bicarbonate, sulfate, chloride, nitrate (as nitrogen), total dissolved solids, hardness (as $CaCO_3$), pH, and specific conductance.	lump sum	1	$1,200	$2,500	1	$1,200	$2,500
14. Perform 24-hour aquifer pump test; includes transducer/computer rental, installation/removal of pump, and submittal of raw pump test data.	lump sum	1	$5,000	$16,000	1	$5,000	$16,000
15. Plug and abandon the test well.	foot	550	$12	$25	1	$6,600	$13,750
16. Proper and legal disposal of drill fluids and brackish development water	gallon	4,000	$1	$1	1	$3,600	$4,000

Table 4-1c. Estimate of major costs for single-zone test well in unconsolidated formation materials.

Item	Unit	Quantity	Low Unit Rate	High Unit Rate	Events	Low Cost	High Cost
17. Lodging and per diem for drill crew (assume 6 drill crew members x 7 days)	day	40	$180	$300	1	$7,200	$12,000
18. Other miscellaneous items like well reports, fluid replenishment, small items	lump sum	1	$200	$7,000	1	$200	$7,000
Total Low Cost						**$76,450**	
Total High Cost							**$444,225**

Hypothetical scenario: 200-mile round-trip mobilization to install one 4-inch-diameter single-zone test well to 550 feet through unconsolidated formation materials. Assume drilling 7⅞-inch pilot borehole to 400 feet, followed by geophysical survey, then reaming borehole to 12 inches for installation of 8-inch-diameter PVC surface casing. Drill 7⅞-inch-diameter borehole to 600 feet, clean borehole and perform second geophysical survey. Plug-back borehole to 550 feet and install 40 feet 4-inch-diameter PVC slotted screen to plug-back depth and 560 feet of 4-inch PVC casing to surface. Develop well using air lift method, collect groundwater sample, and perform aquifer test. Plug and abandon well. Clean up site and dispose of drilling fluids.

Table 4-1d. Estimate of major costs for single-zone test well in consolidated formation materials.

Item	Unit	Quantity	Low Unit Rate	High Unit Rate	Events	Low Cost	High Cost
1. Mobilization and site setup.	lump sum	1	$3,000	$32,000	1	$3,000	$32,000
2. Drill 7⅞-inch-diameter pilot borehole to 600 feet.	foot	600	$30	$160	1	$18,000	$96,000
3. Standby for geophysical survey (upper 600 feet of borehole).	hour	5	$300	$550	1	$1,500	$2,750
4. Widen (ream) borehole to 12 inches.	foot	600	$20	$184	1	$12,000	$110,400
5. Install 8-inch-diameter surface casing.	foot	600	$40	$56	1	$24,000	$33,600
6. Drill 7⅞-inch-diameter borehole from 600 to 900 feet and prepare borehole for geophysical logging.	foot	300	$30	$198	1	$9,000	$59,400
7. Standby for geophysical survey (600 to 900 feet).	hour	4	$300	$450	1	$1,200	$1,800
8. Plug-back borehole to bottom of production interval using a tremie pipe. Assume plug-back depth of 850 feet.	foot	50	$12	$16	1	$600	$775
9. Clean out borehole to prepare it for installation of screen and casing.	foot	250	$1	$165	5	$250	$41,250
10. Install and grout casing.	foot	700	$16	$40		$11,200	$28,000
11. Develop well to promote formation yield and collect water sample for chemical analysis.	hour	10	$300	$550	5	$3,000	$5,500
12. Subcontract Chemical Analysis - dissolved silica, iron, calcium, magnesium, sodium, potassium, bicarbonate, sulfate, chloride, nitrate (as nitrogen), total dissolved solids, hardness (as $CaCO_3$), pH, and specific conductance.	lump sum	1	$1,200	$2,150	5	$1,200	$2,150
13. Perform 24-hour aquifer pump test; includes transducer/computer rental, installation/removal of pump, and submittal of raw pump test data.	lump sum	1	$5,000	$15,000	5	$5,000	$15,000
14. Plug and abandon the test well.	foot	850	$12	$15	5	$10,200	$12,750
15. Proper and legal disposal of drill fluids and brackish development water.	gallon	8,000	$1	$1	1	$7,200	$8,000
16. Lodging and per diem for drill crew (assume 6 drill crew members x 8 days).	day	40	$180	$300	1	$7,200	$12,000
17. Other miscellaneous items like well reports, fluid replenishment, small items.	lump sum	1	$200	$7,000	1	$200	$7,000

Table 4-1d. Estimate of major costs for single-zone test well in consolidated formation materials.

Item	Unit	Quantity	Low Unit Rate	High Unit Rate	Events	Low Cost	High Cost
Total Low Cost						**$103,550**	
Total High Cost							**$440,375**

Hypothetical scenario: 400-mile round-trip mobilization to install one 4-inch-diameter single port test well to 850 feet through consolidated formation materials. Assume drilling 7⅞-inch pilot borehole to 600 feet, followed by geophysical survey, then reaming borehole to 12 inches for installation of 8-inch-diameter steel surface casing. Drill 7⅞-inch-diameter borehole to 900 feet, clean borehole, and perform second geophysical survey. Plug-back borehole to 850 feet. Install open-ended steel casing from 700 feet to ground surface. Develop well using air lift method, collect groundwater sample, and perform aquifer test. Plug and abandon well.

5 Pre-Drilling Data Collection

A significant amount of information and data can be developed prior to the commencement of drilling operations. Much of this information is collected and evaluated when conducting the initial phases of a study on a potential brackish groundwater source. There are a variety of resources that can be used to help understand conditions that may be encountered when drilling an exploratory brackish well, much of which is covered in the 2008 *TWDB Brackish Groundwater Exploration Guidance Manual* (LBG-Guyton, 2008). This section provides a brief summary of the data that may be collected before a drilling program commences. Much of the available data can be obtained from several state databases as described below. Data obtained from these databases is usually very reliable, but it should be evaluated for accuracy and suitability before it is relied upon.

For decades, the TWDB has produced or contracted for numerous reports on groundwater resources around the state (www.twdb.texas.gov/publications/reports/index.asp). Reports, maps, imagery, and other types of information are also available from the Bureau of Economic Geology (BEG) Store, (store.beg.utexas.edu/), U.S. Geological Survey (USGS) publications website, (pubs.er.usgs.gov/), and a variety of other public sources. These resources should be reviewed to identify basic characteristics of the brackish groundwater resources being considered for development. Available reports may provide a general idea of the geologic units that will be encountered during drilling, and provide a framework for the development of a conceptual model of the geologic/hydrogeologic environment of the target aquifer and what might be expected in terms of well production capacity, water quality, and the location of the brackish groundwater.

A review of existing reports will often provide only a broad overview of groundwater resources across large areas. Some reports may provide information on a particular county, while others may focus on larger regions of multiple counties or cover an entire aquifer. This broad information will help narrow to specific area(s) to consider for an exploratory well. Once a site for an exploratory well has been selected, detailed data in and around that site are needed to help understand what conditions may be encountered during the drilling and testing of an exploratory brackish groundwater well. Several resources are available that may provide this type of data.

The TWDB Water Data Interactive Groundwater Data Viewer (www3.twdb.texas.gov/apps/WaterDataInteractive/GroundWaterDataViewer) provides an interactive map that can be used to determine if there are well data available in the area of interest from a variety of sources. The site includes water well information from the TWDB Groundwater Database, the submitted drillers reports from the Texas Department of Licensing and Regulation (TDLR), and well information from the TWDB Brackish Resources Aquifer Characterization System (BRACS) Database, as shown in Figure 5-1.

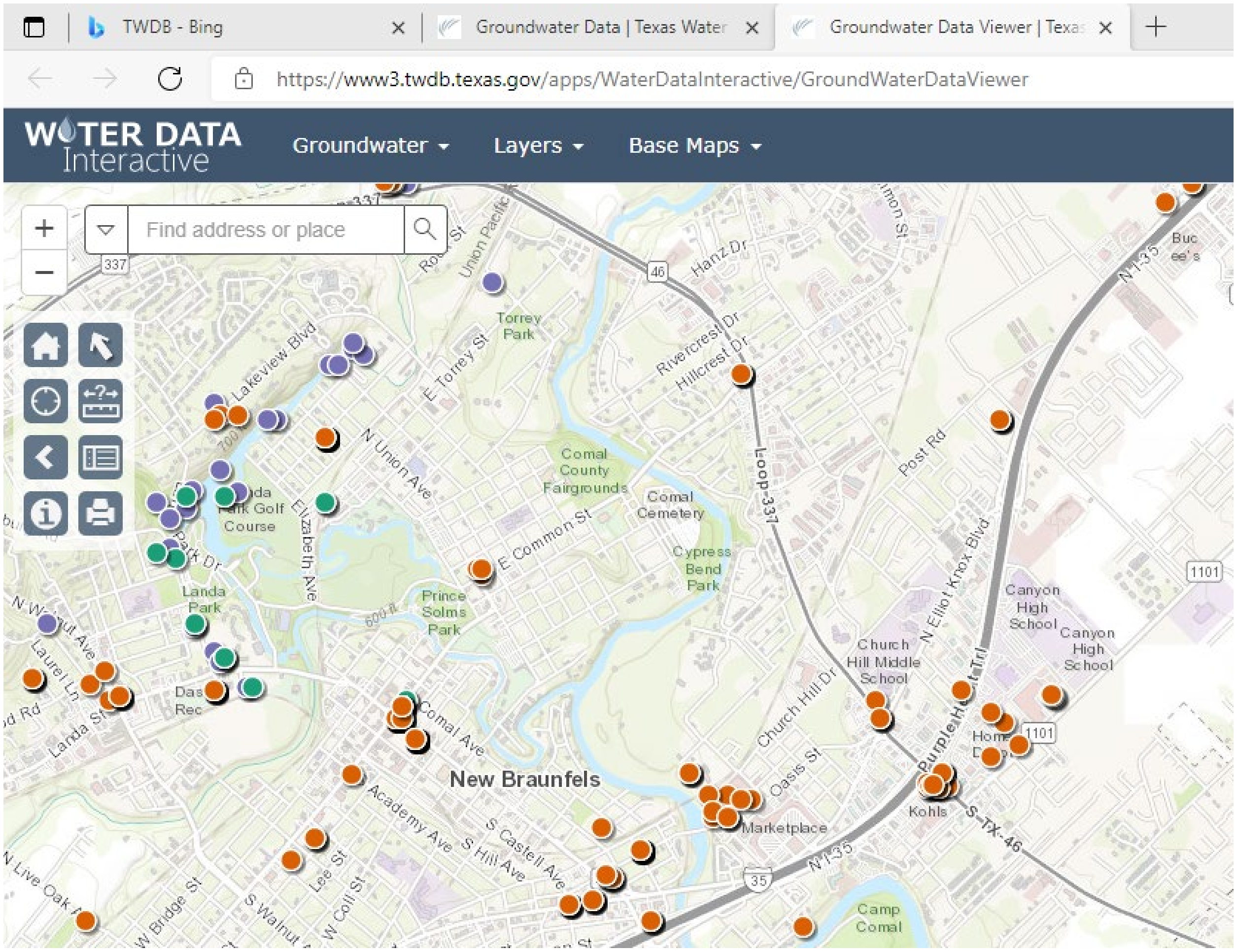


Figure 5-1. **Screenshot from the TWDB Water Data interactive website. This map shows the availability of TWDB database wells (purple dots), TDLR well reports (orange dots), and BRACS database wells (green dots).**

The TWDB Groundwater Database (www.twdb.texas.gov/groundwater/data/gwdbrpt.asp) contains data on selected wells, springs, and oil and gas test wells, and may include detailed information on well completion, testing, water quality, and water levels. These data have been compiled by the TWDB over many decades. Data available from the database may include scans of well records, water level data, water quality data, and well construction details. An example data sheet and scanned data file for a database well are shown in Figures 5-2 and 5-3, respectively.

Texas Water Development Board (TWDB)
Groundwater Database (GWDB)
Well Information Report for State Well Number
58-54-518

GWDB Reports and Downloads | **Well Basic Details** | Scanned Documents

State Well Number	5854518
County	Bastrop
River Basin	Colorado
Groundwater Management Area	12
Regional Water Planning Area	K - Lower Colorado
Groundwater Conservation District	Lost Pines GCD
Latitude (decimal degrees)	30.196667
Latitude (degrees minutes seconds)	30° 11' 48" N
Longitude (decimal degrees)	-97.305834
Longitude (degrees minutes seconds)	097° 18' 21" W
Coordinate Source	Global Positioning System - GPS
Aquifer Code	124SMBR - Simsboro Sand Member of Rockdale Formation
Aquifer	Carrizo-Wilcox
Aquifer Pick Method	
Land Surface Elevation (feet above sea level)	463
Land Surface Elevation Method	Interpolated From Topo Map
Well Depth (feet below land surface)	660
Well Depth Source	Driller's Log
Drilling Start Date	
Drilling End Date	7/31/1997
Drilling Method	Mud (Hydraulic) Rotary
Borehole Completion	Gravel Pack w/Screen

Well Type	Withdrawal of Water
Well Use	Public Supply
Water Level Observation	Miscellaneous Measurements
Water Quality Available	Yes
Pump	Submersible
Pump Depth (feet below land surface)	
Power Type	Electric Motor
Annular Seal Method	
Surface Completion	
Owner	Aqua WSC Replacement (CS#2)
Driller	Russell Drlg Co Inc
Other Data Available	Drillers Log
Well Report Tracking Number	
Plugging Report Tracking Number	
U.S. Geological Survey Site Number	
Texas Commission on Environmental Quality Source Id	G0110013S
Groundwater Conservation District Well Number	
Owner Well Number	REPLACEMENT CS-2
Other Well Number	
Previous State Well Number	
Reporting Agency	Texas Water Development Board
Created Date	7/24/2002
Last Update Date	8/29/2008

Remarks	Replacement well for Camp Swift #2.

Casing

Diameter (in.)	Casing Type	Casing Material	Schedule	Gauge	Top Depth (ft.)	Bottom Depth (ft.)
12	Blank	Steel			0	490
18	Blank	Steel			2	489
12	Screen	Stainless Steel			490	650
12	Blank	Steel			650	660

Well Tests - No Data

Tuesday, August 3, 2021 *State Well Number 58-54-518* *Page 1 of 14*

Figure 5-2a. Example page 1 of TWDB database well information report.

Texas Water Development Board (TWDB)
Groundwater Database (GWDB)
Well Information Report for State Well Number
58-54-518

Lithology

Top Depth (ft.)	Bottom Depth (ft.)	Description
0	22	CLAY
22	104	SANDY CLAYS
104	161	SAND
161	192	SHALE
192	245	SAND
245	271	SHALE
271	364	SAND
364	445	SHALE
445	480	SANDY
480	487	SHALE & ROCK
487	660	SAND W/ SOME SHALE STRKS

Annular Seal Range - No Data

Borehole - No Data

Plugged Back - No Data

Filter Pack - No Data

Packers - No Data

Tuesday, August 3, 2021 *State Well Number 58-54-518* *Page 2 of 14*

Figure 5-2b. Example page 2 of TWDB database well information report.

Texas Water Development Board (TWDB)
Groundwater Database (GWDB)
Well Information Report for State Well Number
58-54-518

Water Quality Analysis

Sample Date: 5/21/1998 **Sample Time:** 1100 **Sample Number:** 1 **Collection Entity:** Texas Water Development Board

Sampled Aquifer: Simsboro Sand Member of Rockdale Formation

Analyzed Lab: LCRA - Lower Colorado River Authority **Reliability:** Sampled using TWDB protocols

Collection Remarks: No Data

Parameter Code	Parameter Description	Flag	Value*	Units	Plus/Minus
39086	ALKALINITY FIELD DISSOLVED AS CACO3		180	mg/L	
00415	ALKALINITY, PHENOLPHTHALEIN (MG/L)		0	mg/L	
00410	ALKALINITY, TOTAL (MG/L AS CACO3)		167	mg/L	
01106	ALUMINUM, DISSOLVED (UG/L AS AL)	<	4	ug/L	
01095	ANTIMONY, DISSOLVED (UG/L AS SB)	<	1	ug/L	
01000	ARSENIC, DISSOLVED (UG/L AS AS)	<	2	ug/L	
01005	BARIUM, DISSOLVED (UG/L AS BA)		116	ug/L	
01010	BERYLLIUM, DISSOLVED (UG/L AS BE)	<	1	ug/L	
00440	BICARBONATE ION, CALCULATED (MG/L AS HCO3)		203.8	mg/L	
01020	BORON, DISSOLVED (UG/L AS B)		83	ug/L	
71870	BROMIDE, DISSOLVED, (MG/L AS BR)		0.16	mg/L	
01025	CADMIUM, DISSOLVED (UG/L AS CD)	<	1	ug/L	
00915	CALCIUM, DISSOLVED (MG/L AS CA)		74.6	mg/L	
00445	CARBONATE ION, CALCULATED (MG/L AS CO3)		0	mg/L	
00941	CHLORIDE, DISSOLVED (MG/L AS CL)		50.7	mg/L	
01030	CHROMIUM, DISSOLVED (UG/L AS CR)		3.1	ug/L	
01035	COBALT, DISSOLVED (UG/L AS CO)	<	1	ug/L	
01040	COPPER, DISSOLVED (UG/L AS CU)	<	2	ug/L	
00950	FLUORIDE, DISSOLVED (MG/L AS F)		0.16	mg/L	
00900	HARDNESS, TOTAL, CALCULATED (MG/L AS CACO3)		221	mg/L	
01046	IRON, DISSOLVED (UG/L AS FE)		1710	ug/L	
01049	LEAD, DISSOLVED (UG/L AS PB)	<	1	ug/L	
01130	LITHIUM, DISSOLVED (UG/L AS LI)		31.1	ug/L	
00925	MAGNESIUM, DISSOLVED (MG/L AS MG)		8.57	mg/L	
01056	MANGANESE, DISSOLVED (UG/L AS MN)		234	ug/L	
01060	MOLYBDENUM, DISSOLVED (UG/L AS MO)	<	1	ug/L	
01065	NICKEL, DISSOLVED (UG/L AS NI)		2.9	ug/L	
71851	NITRATE NITROGEN, DISSOLVED, CALCULATED (MG/L AS NO3)	<	0.18	mg/L	
00631	NITRITE PLUS NITRATE, DISSOLVED (MG/L AS N)	<	0.04	mg/L	
00608	NITROGEN, AMMONIA, DISSOLVED (MG/L AS N)		0.12	mg/L	
00623	NITROGEN, KJELDAHL, DISSOLVED (MG/L AS N)	<	0.07	mg/L	
00090	OXIDATION REDUCTION POTENTIAL (ORP), MILLIVOLTS		-100.7	MV	
00400	PH (STANDARD UNITS), FIELD		6.83	SU	
00666	PHOSPHORUS, DISSOLVED (MG/L AS P)	<	0.1	mg/L	
00935	POTASSIUM, DISSOLVED (MG/L AS K)		2.88	mg/L	

Tuesday, August 3, 2021 *State Well Number 58-54-518* *Page 4 of 14*

Figure 5-2c. Example page 4 of TWDB database well information report.

Texas Water Development Board
Well Schedule

new well

State Well No. 58 54 518 Previous Well No. County BASTROP 021

River Basin COLORADO 14 Zone 3 Lat. 30 11 48 Long. 097 18 20 Accuracy of Coord. 1

Owner's Well No. CS #2 REPLACEMENT Location ____ 1/4, ____ 1/4, Section ____, Block ____, Survey ____

Owner AQUA WSC Driller RUSSELL DRLG CO INC

Address P.O. DRAWER P BASTROP TX 78602 Tenant/Oper. ____

Date Drilled 07 31 1997 Depth 660 Source of Depth Datum D Altitude 463 Source of Alt. Datum M

Aquifer SIMSBORO 124SMBR Well Type W User 31500

Aquifer ID 10

Well Construction Const. Method MUD ROTARY H Casing Material STEEL S

Completion Under Ream/Gravel packed G Screen Material SS R

Lift Data Pump Mfr. ____ Type SUMB S Setting 340'

Motor Mfr. ____ Power ELEC E Horsepower

Yield Flow ____ GPM Pump ____ GPM Meas.,Rept.,Est. ____ Date ____

Performance Test Date ____ Length of Test 36 hr Production 1142 GPM

Static Level ____ ft. Pumping Level ____ ft. Drawdown 125 ft. Sp.Cap. 9 GPM/ft.

Water Use Primary PUBLIC P Secondary ____ Tertiary ____

Quality (Remarks) ____

Other Data Available Water Level M Water Quality Y Logs D Other Data

Water Levels

Date	Meas.
05 21 1998	-169.80
05 31 1997	-137.

Casing or Blank Pipe (C)
Well Screen or Slotted Zone (S)
Open Hole (O)
Cemented from 0 to 487

	Type	Diam. (in.)	Setting (feet) From	To
1	C	18	2	489
2	C	12		490
3	S	12	490	650
4	C	12	650	660
5				
6				
7				
8				
9				
10				
11				
12				
13				
14				
15				
16				

(20 max)

Recorded By John ASENSIO Date Record Collected or Updated 05 21 1998 Reporting Agency 01

Remarks 1 REPLACES WELL C-S #2.

Aquifer 124 SMBR
Well No. 58-54-518

97-0402-07-97

Figure 5-3. Example page 1 of TWDB scanned data file.

The TDLR Submitted Drillers Report (SDR) Database (www.twdb.texas.gov/groundwater/data/drillersdb.asp) is populated with data from the Texas Well Report Submission and Retrieval System (TWRSRS). This system was started in 2001 and began collecting well reports in 2003. Since that time, all wells drilled in Texas have drillers' reports entered into this system. This database contains information on the material encountered during drilling and well construction details, and may contain an initial water level, well production rates and associated drawdown, and other data associated with the drilling and installation of the well. An example submitted driller's report is shown in Figures 5-4a and 5-4b.

Another database available from the TWDB is the BRACS database. With funding approved in 2009 by the 81st Texas Legislature, the BRACS Program was created to thoroughly characterize the brackish groundwater resources within the state. The BRACS database was designed to store well and geology data on the brackish groundwater resources across the state. A significant effort has been expended by the TWDB to develop the BRACS Program (including the BRACS database), and it is updated regularly with new information, including other databases, studies/documents, geophysical well logs, water quality data, aquifer test data, geographic information system (GIS) data, and useful links. The BRACS database can be downloaded from www.twdb.texas.gov/innovativewater/bracs/database.asp.

Other non-TWDB resources include the Railroad Commission of Texas (RRC), which maintains an interactive database called the Surface Casing Estimator for determining the depth to fresh water (coastal.beg.utexas.edu/surfacecasing/#!/). This interactive database provides depth estimates for surface casing installations related to oil and gas production to protect usable groundwater, including the base of fresh water, base of usable quality water (defined as total dissolved solids less than 3,000 mg/L), and base of underground source of drinking water (Figure 5-5). Data from this database may provide additional detail in areas for which data may not be available from the TWDB database, and it is an additional resource that may be tapped during the pre-drilling data collection phase.

STATE OF TEXAS WELL REPORT for Tracking #529352

Owner:	**Gonzales County UWCD**	Owner Well #:	**MWCZ-10**
Address:	**522 Saint Matthew Street Gonzales, TX 78629**	Grid #:	**67-13-2**
Well Location:	**11995 FM 713 Rosanky, TX 78953**	Latitude:	**29° 50' 47.8" N**
		Longitude:	**097° 26' 26.4" W**
Well County:	**Caldwell**	Elevation:	**No Data**

Type of Work: **New Well** Proposed Use: **Monitor**

Drilling Start Date: **11/5/2019** Drilling End Date: **11/15/2019**

Borehole:

Diameter (in.)	*Top Depth (ft.)*	*Bottom Depth (ft.)*
8.25	**0**	**210**
7.88	**210**	**298**

Drilling Method: **Mud (Hydraulic) Rotary**

Borehole Completion: **Filter Packed; Screened; Straight Wall**

Filter Pack Intervals:

Top Depth (ft.)	*Bottom Depth (ft.)*	*Filter Material*	*Size*
87	**210**	**Sand**	**12/20**

Annular Seal Data:

Top Depth (ft.)	*Bottom Depth (ft.)*	*Description (number of sacks & material)*
0	**85**	**Cement 15 Bags/Sacks**
85	**87**	**Bentonite 2 Bags/Sacks**

Seal Method: **Tremie**

Sealed By: **Driller**

Distance to Property Line (ft.): **No Data**

Distance to Septic Field or other concentrated contamination (ft.): **No Data**

Distance to Septic Tank (ft.): **No Data**

Method of Verification: **No Data**

Surface Completion: **Surface Slab Installed** **Surface Completion by Driller**

Water Level: **66 ft.** below land surface on **2019-11-20** Measurement Method: **Electric Line**

Packers: **No Data**

Type of Pump: **No Data**

Well Tests: **Pump** **Yield: 7 GPM with 7.75 ft. drawdown after 24 hours**

Plug Information:

12/9/2019 6:43:07 AM *Well Report Tracking Number 529352* *Page 1 of 3*
Submitted on: 12/9/2019

Figure 5-4a. Example TDLR submitted drillers report (page 1).

Description (number of sacks & material)	Top Depth (ft.)	Bottom Depth (ft.)
Cement	**210**	**298**

Water Quality:

Strata Depth (ft.)	Water Type
87 - 210	**Carrizo**

Chemical Analysis Made: **Yes**

Did the driller knowingly penetrate any strata which contained injurious constituents?: **No**

Certification Data: The driller certified that the driller drilled this well (or the well was drilled under the driller's direct supervision) and that each and all of the statements herein are true and correct. The driller understood that failure to complete the required items will result in the report(s) being returned for completion and resubmittal.

Company Information: **Geoprojects International, Inc.**

8834 Circle Dr
Austin, TX 78736

Driller Name: **Evan K. Schaefer** License Number: **58772**

Comments: **No Data**

Lithology:
DESCRIPTION & COLOR OF FORMATION MATERIAL

Top (ft.)	Bottom (ft.)	Description
0	**60**	**Well graded gray to reddish-brown Sand**
60	**155**	**Gray and tan Clay**
155	**165**	**Fine to medium graded Sand**
165	**195**	**Gray Clay**
195	**200**	**Sand with Clay lenses**
200	**298**	**Gray Clay with cemented sand lenses at 240-243 and 285-287**

Casing:
BLANK PIPE & WELL SCREEN DATA

Dia (in.)	Type	Material	Sch./Gage	Top (ft.)	Bottom (ft.)
4.95	**Blank**	**New Plastic (PVC)**	**SDR17**	**0**	**130**
4.95	**Screen**	**New Plastic (PVC)**	**SDR17 0.020**	**130**	**210**

IMPORTANT NOTICE FOR PERSONS HAVING WELLS DRILLED CONCERNING CONFIDENTIALITY

TEX. OCC. CODE Title 12, Chapter 1901.251, authorizes the owner (owner or the person for whom the well was drilled) to keep information in Well Reports confidential. The Department shall hold the contents of the well log confidential and not a matter of public record if it receives, by certified mail, a written request to do so from the owner.

Please include the report's Tracking Number on your written request.

Texas Department of Licensing and Regulation
P.O. Box 12157
Austin, TX 78711
(512) 334-5540

12/9/2019 6:43:07 AM *Well Report Tracking Number 529352* *Page 2 of 3*
Submitted on: 12/9/2019

Figure 5-4b. Example TDLR submitted drillers report (page 2).

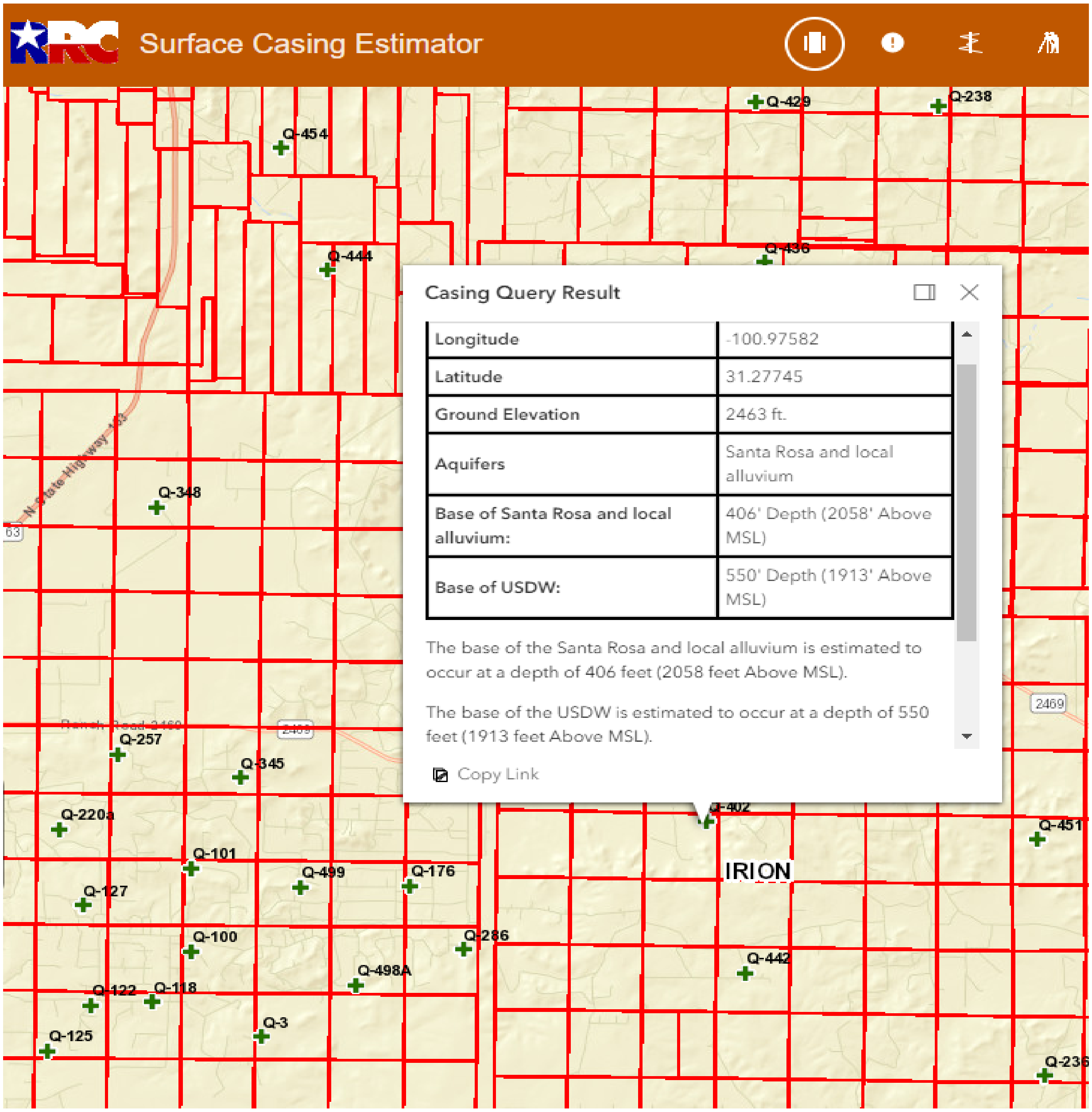


Figure 5-5. **RRC surface casing estimator website.**

Another RRC data source consists of existing geophysical logs (sometimes referred to as Q-logs). The RRC began archiving images of geophysical well logs received in 2004, and these images can be searched on the RRC's website at rrcsearch3.neubus.com/esd3-rrc/index.php?_module_=esd&_action_=keysearch&profile=15 (Figure 5-6). Paper copies of an estimated 1.5 million logs are also available at the BEG's Geophysical Log Facility (GLF) (www.beg.utexas.edu/about/facilities/geophysical-log-facility), which has been the caretaker of the RRC's geophysical logs since 1985. This facility was established in 1983, and all operators of oil and gas wells are required to provide at least one copy of a well log for every well that is new, deepened, or plugged.

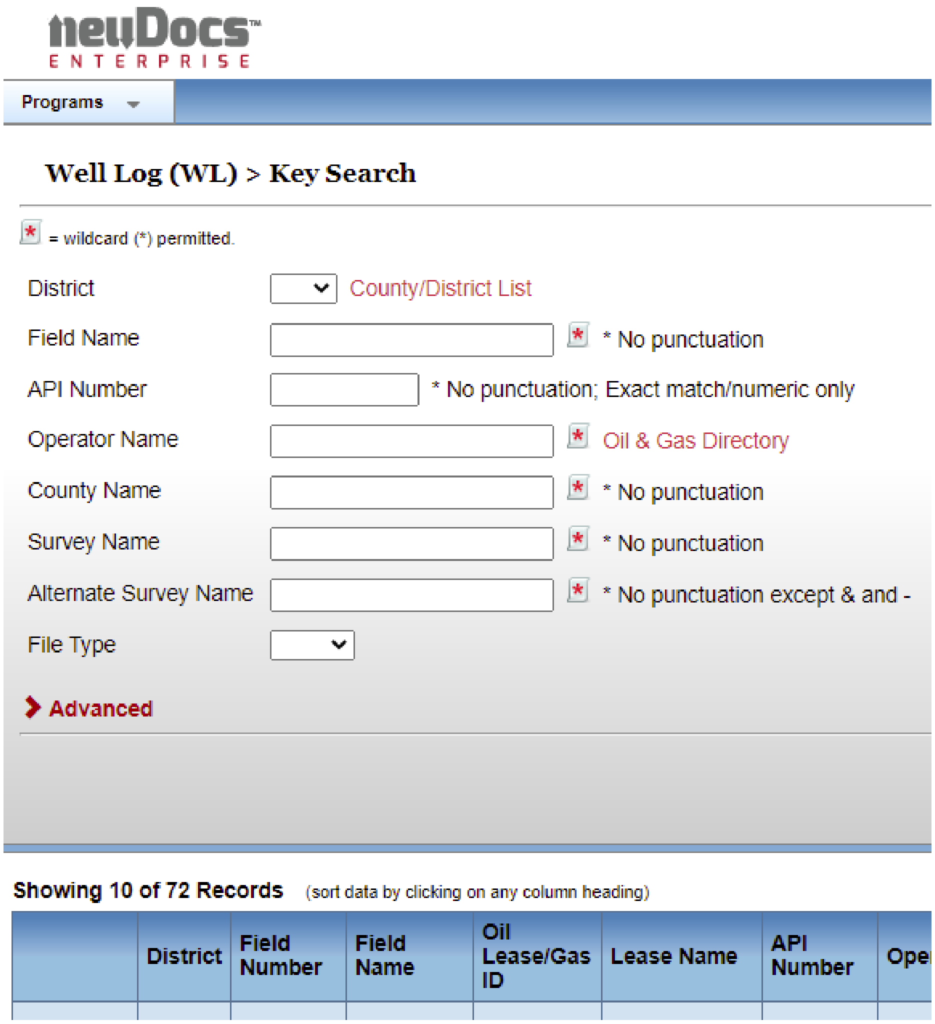


Figure 5-6. **RRC well log search website.**

The USGS maintains a database of publications and well logs. An interactive website can be used to view and download geophysical logs using a simple query at https://webapps.usgs.gov/geologlocator/#!/ (Figure 5-7).

Collection of data from the public sources described in this section in and around an identified site for brackish groundwater exploration may provide some detail regarding the conditions that may be encountered during drilling operations. The level of detail will vary based on the exploratory well location and the type and amount of existing data available near the selected site. Once available public data have been collected and assessed, an exploratory well or wells will be needed to develop site-specific data on the brackish groundwater source being considered, and the planning for these exploratory well(s) will be supported by the pre-drilling data collection efforts.

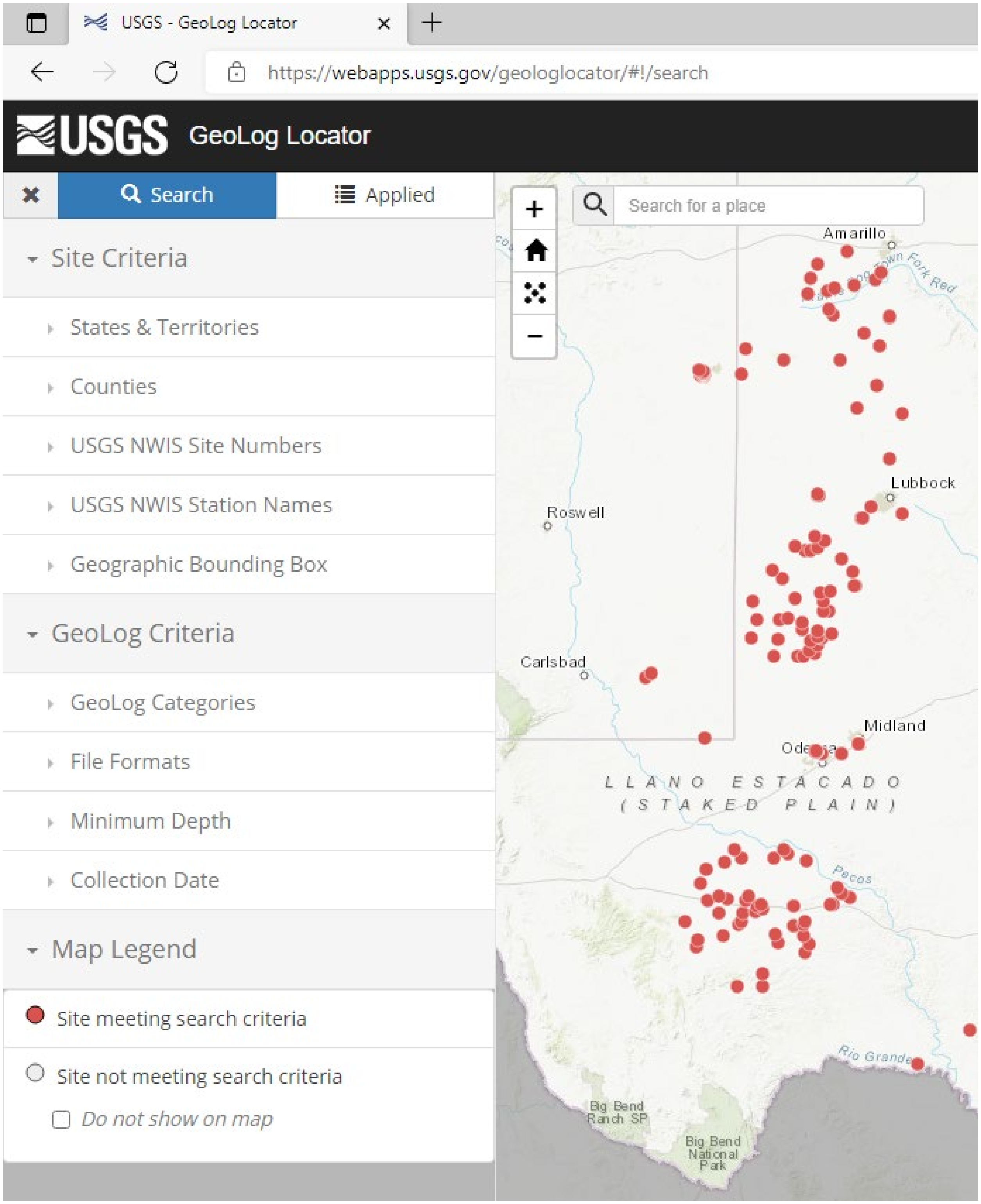


Figure 5-7. **USGS GeoLog Locator website.**

6 Data Collected During Drilling

Valuable information can and should be collected during the exploration borehole or pilot borehole drilling process. The pre-drilling data collection process described in Section 5 should provide general information about the depths and types of formations to be penetrated. The same data will likely be used to select the most appropriate drilling equipment for the project. Selection of drilling companies should be based on their equipment and experience drilling in the general area of the study. Local drilling companies (and individual drillers) with specific experience can provide information not recorded in published studies.

Before drilling begins, it is a good idea for the on-site geologist to meet with the driller to discuss the results of pre-drilling data collection. The driller may share their experience or knowledge of drilling in the area. At a minimum, the on-site geologist should ask the driller to inform the on-site geologist of noticeable changes in drilling that might provide clues about the formations being penetrated. It is not unusual for a driller to pause drilling, walk over to the geologist, and say something like “hard drilling at 355 feet” or “the drill rate increased, I think we hit a sand streak between 410 and 415 feet.” Most drillers keep a small notebook in their pocket to record details during drilling, and they use the notes to prepare State Well Reports after drilling is completed. It is good practice for the on-site geologist to maintain a pipe tally (log of the drill string components such as drill bit, drill bit sub, drill collar, drill pipe, etc.) including their lengths, and the height of the drill rig table, so that the depth of the drill bit is always known during the drilling process. Specific information that can be obtained during drilling is described in the following subsections.

Information collected during drilling can be logged on a field data form that has places for all of the pertinent information to be noted in an organized manner. Field data forms can be customized to include the required information for the borehole or well prior to commencing field operations. Field data forms should be organized and stored for future reference and are a standard part of the report submittal to the client upon completion of the well. An example field form is provided in Figure 6-1.

Drill Cuttings Log Page 2 of 4

Well ID:

Coordinates: Bit Size: 7 7/8 Land Elev.: 570'

Date	Time Start	Time End	Drilling Time	Depth Interval		Description
2/28/19	1628	1644	16	150	160	SP – Sand, fn to med grained
	1644	1702	18	160	170	SP – a/a pink (5YR 7/4) mostly qtz.
2/28/19	1702	1710	8	170	180	170 to 175' a/a. Trip out drill pipe. 174 to 176' white (5YR 8/1) silty clay
2/29/19	1132	1140	8			
	1140	1155	15	180	190	SP – Sand, pinkish grey (7.5 YR 3/1) crs to v. crs. 98% qtz. sub rounded to well rounded. 2% chert
	1155	1211	16	190	200	SP – a/a
	1211	1235	24	200	210	CL – Silty clay, dk gray (7.5 YR 3/0) / pink (7.5 YR 8/4) mottling w/ fn pyrite xyls / lignite; plastic
	1235	1257	22	210	220	CL – a/a gray (7.5 YR 5/1) w/ minor fn tan sand. plastic.
	1257	1323	26	220	230	CL – a/a. Hard drilling at 227-229'; possible fn SS. gray silty clay above and below SS interval.
	1323 ream hole	@1342 1400	37	230	240	CL – a/a pinkish gray (7.5 YR 6/2)
	1400	1424	24	240	250	CH – Fat clay, pinkish gray (7.5 YR 6/2)
	1424	1447	23	250	260	CH – a/a
	1447	1510	23	260	270	CH – a/a
3/1/19	278'	@1530	20	270	280	CH – a/a, gray (7.5 YR 6/1). Driller reported hard drilling 274-285'
3/4/19	280'	@1224	4			
	1228	1251	23	280	290	CH – a/a gray clay
	1251	1315	24	290	300	CL – a/a 290 to 295 underlain by lt. gray (7.5 YR 7/1) sandy clay. Hard drilling 297.5 to 298.5 per driller.

Figure 6-1. Example field data form. Note drill rate decrease when drilling from sand unit to clay unit around 200 feet and notes derived from driller's comments.

6.1 Drilling Rates

The rate at which the drill string advances should be recorded by the on-site geologist. Drill rates can provide information about the formations penetrated, and can help the on-site geologist prepare a more accurate lithologic log. For example, slow drill rates and the presence of clay drill cuttings would indicate drilling through a clay formation. Within the same drilled interval, the drill rate might speed up for a short period of time, and the on-site geologist might evaluate the drill cuttings again and discover a small amount of silt or sand that might not have been noticed if drill rates were not monitored. The on-site geologist can update their lithologic log to include the presence of a silt or sand layer. Another example might be slow drilling with abundant drill rig chatter, which could indicate entry into a gravel zone; this could be confirmed by collection of drill cuttings. The on-site geologist should be aware of the rig activities in progress, and should record only drill rates based on penetration while drilling. The driller will often pause the drilling process to adjust the drilling fluid mixture, or work the drill string up and down to ream the hole. The time needed to perform those tasks should not be included in the drill rate calculations. One good practice for the on-site geologist is to maintain a log of time and drill depths based on the time each new drill pipe begins rotation (if rotary drill methods are used) and when drilling stops to make up a new connection. An example of drill rates recorded on a field form is presented on Figure 6-1, where the drill rate slowed while drilling through a sand unit into a clay unit at a depth of approximately 200 feet.

For some drilling operations, a strip chart recorder (Geolograph™ or similar manufacturer) is used to record the drilling rate of penetration in minutes per foot (Figure 6-2). A cable is attached from the Geolograph to a pulley on top of the drill rig derrick, and a mechanical device measures the downward movement of the Kelley, which is recorded on the Geolograph. The driller must disengage the Geolograph each time a new pipe connection is made or for other non-drilling operations discussed above so that the Geolograph will only record drilling rate of penetration data. Often the driller will hand-annotate the strip chart with notes to document non-drilling activities such as mixing drilling mud, tripping-out to change the drill bit, or special drilling conditions.

Figure 6-2. Geolograph.

6.2 Fluid Loss/Gain Intervals

When using mud-rotary drilling methods, drilling mud is prepared and contained within a mud pit, which may be a metal tank or earthen pit. The purpose of drilling mud is to lubricate and cool the drill bit, to provide a fluid to transport drill cuttings to the ground surface for extraction from the borehole, and to form a “mud cake” to stabilize the sidewalls of the borehole. Some gradual loss of mud is expected to occur during drilling. However, while drilling through formations with relatively high hydraulic conductivities, drilling fluids may be consumed at a higher rate. In some intervals of high formation conductivities, such as in gravel zones or voids/caverns in limestone, swift or total drilling fluid loss can occur; this condition is called loss of circulation or lost circulation. Conversely, fluid gain during drilling might indicate a formation that is pressurized (natural gas) or under artesian conditions (groundwater). Fluid loss and gain information can provide information useful for interpreting the types of hydraulic properties and/or dangers of formations penetrated, and should be recorded by the on-site geologist while drilling occurs.

6.3 Lithologic Description of Drill Cuttings

The on-site geologist usually prepares a lithologic log of drill cuttings collected during the drilling process. Extra drill cuttings are often saved for future examination and analysis in labeled plastic open-mouth bottles or canvas sample bags (Figure 6-3). A member of the drilling crew will typically collect drill cuttings during each 5- to 10-foot interval of drill string advancement and lay the samples in rows (Figure 6-4). The on-site geologist will use several field tools to help describe the drill cuttings, which may include a magnifying glass or microscope, grain size comparison chart, Munsell® color book or Munsell® CAPSURE Color Matching Tool (optional), a 10 percent solution of hydrochloric acid (to determine calcium carbonite content and/or limestone/dolomite rock types) by the degree of chemical reaction, Alizarine Red S (to help discern limestone from dolomite rock), a knife or sharp object to help segregate grains and/or estimate rock hardness, pencil or pen designed to write in the rain, field notebook, pre-printed lithologic/well construction forms, camera or cell phone with a camera function, paper towels, a plastic bag for trash, a sieve sized to retain fine sands, and a bucket of water to wash mud from the drill cuttings. A water-proof backpack, plastic document container, or briefcase is also advised to protect paperwork during inclement weather.

After drilling has finished, the geologic formation changes—called formation breaks—from the lithologic log should be compared to the geophysical log to refine and update the lithologic log entries.

Figure 6-3. Bagged drill cuttings (source: DBS&A).

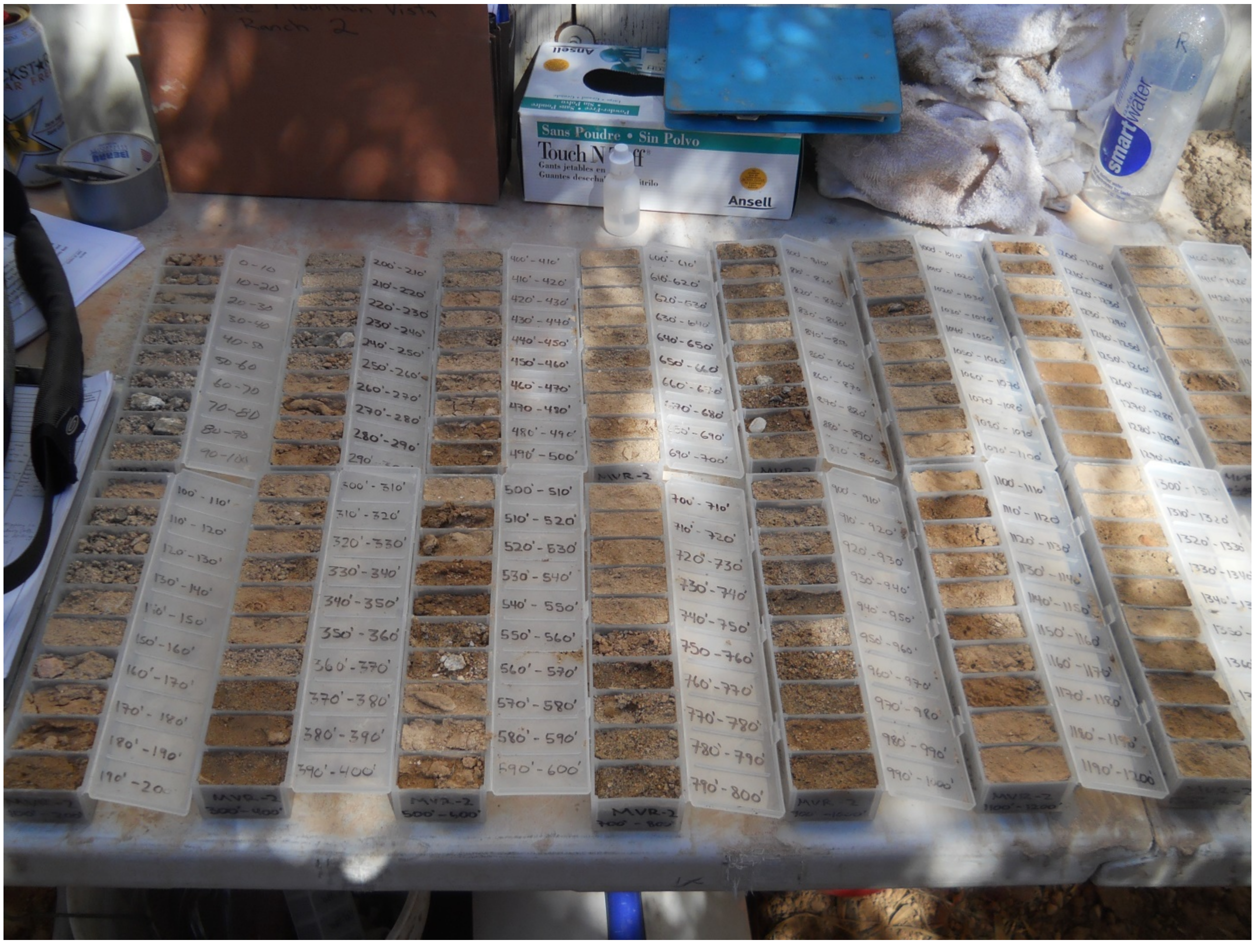


Figure 6-4. Drill cutting trays laid out for examination by the on-site geologist (source: DBS&A).

6.4 Zonal Testing

Zonal testing (also known as depth-specific sampling) can be performed after drilling the borehole. The drill bit is removed, and a temporary section of slotted pipe or short screen known as an “eductor pipe” is attached to the end of the drill pipe and lowered to the desired test interval. After filter pack and bentonite seals (or inflatable packers) are installed above and below the eductor pipe, the formation can be developed to remove residual drilling fluids from the formation, and a groundwater sample can be collected. A falling head test (also known as a slug test) can also be performed after the aquifer has stabilized. After the formation has been tested and sampled, the eductor pipe can be pulled up to a higher elevation to another test interval, and the process can be repeated. Zonal testing can be performed in either consolidated or unconsolidated formation materials. Illustrations showing the general steps for performing zone testing within hypothetical boreholes in consolidated and unconsolidated formations are presented in Figures 6-5 and 6-6, respectively.

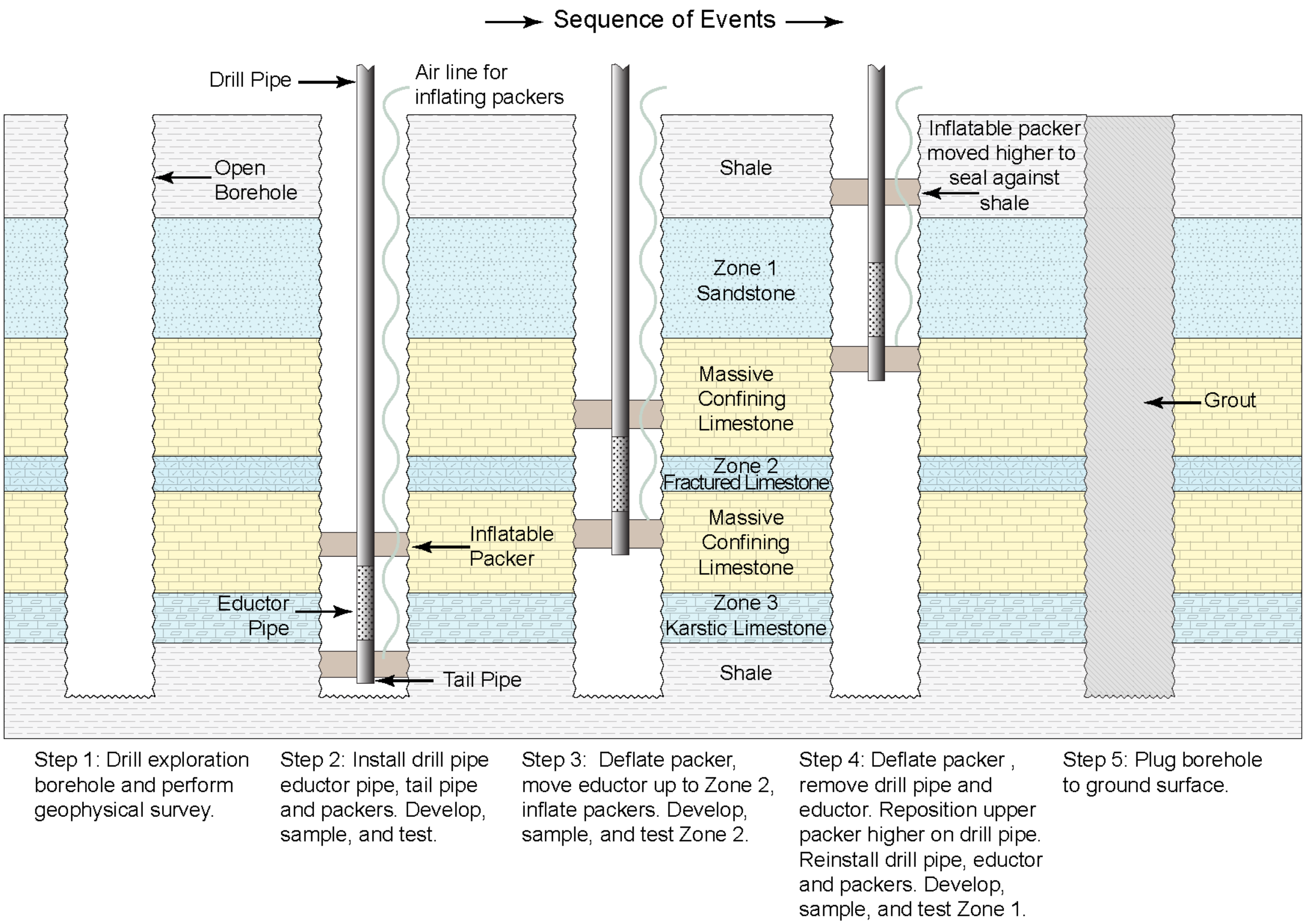


Figure 6-5. Steps for performing zonal testing in consolidated formations.

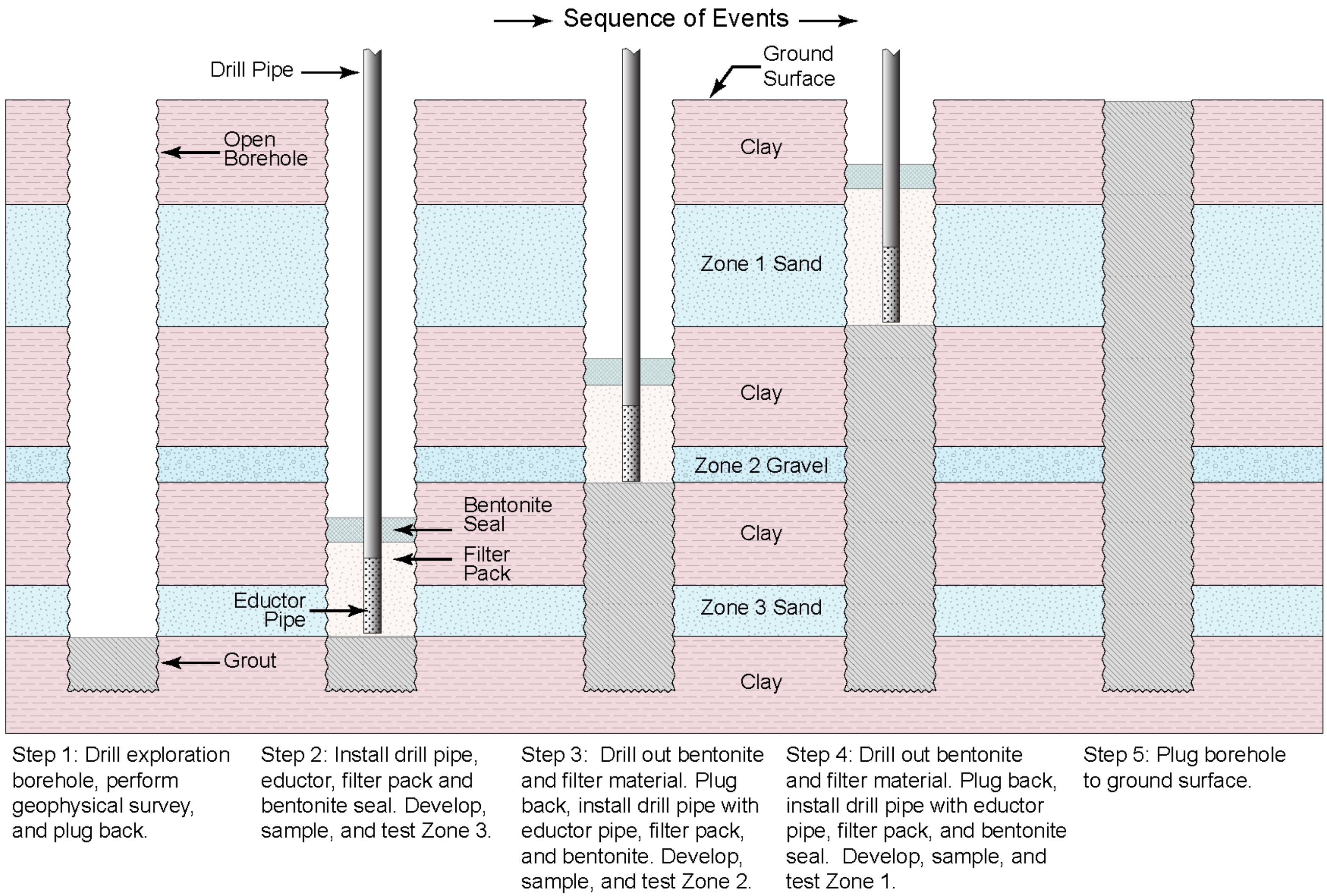


Figure 6-6. Steps for performing zonal testing in unconsolidated formations.

6.5 Borehole Geophysical Surveys

Geophysical surveys are typically performed immediately after drilling the exploratory test borehole or pilot borehole and before installation of well materials. Multiple geophysical surveys may be performed in one borehole depending on the complexity of the well construction. For instance, a separate geophysical survey might be performed to select the optimum depth of surface casing installation to protect fresh groundwater, and a second or third geophysical survey might be performed to identify the optimum depth of intermediate or production casing and screen, including plug-back depth selection. Borehole geophysical surveys can be used to adjust or correct the formation breaks (contacts) recorded on the lithologic log, as some formation changes cannot be identified during drilling and drill cutting lag-time or other factors might not allow complete characterization of the subsurface lithologic breaks by the on-site geologist. Some geophysical methods can be used to evaluate formation or annulus data from within a cased well. Other geophysical methods can be used to estimate formation porosity, flow rates, and other properties. A more detailed discussion on geophysical methods and their individual properties and uses is provided in Section 7.

7 Geophysical Logging

The term “geophysical survey” describes the process of obtaining physical properties of the subsurface formation from a variety of geophysical tools lowered down through the borehole. The resulting strip chart plot of the geophysical data is termed a “geophysical log.” The term “logging” is a generic term used by drillers and geologists to describe the geophysical survey process, including preparation of a geophysical log, and has been adopted as such in this document. Numerous geophysical methods and related specialized downhole geophysical tools (equipment) have been developed over the past 90 years to gather specialized geophysical data. The terms “geophysical methods” and “geophysical tools” are used interchangeably within this document to describe the methods and associated tools used to perform geophysical logging.

The first geophysical surveys were prepared in the 1920s by Conrad Schlumberger, where resistivity measurements were obtained by lowering a resistivity electrode into a borehole while manually recording the readings compared to depth on graph paper, creating the first geophysical log. Over time, geophysical logging techniques have continued to advance, and use of geophysical logging is currently standard practice during groundwater exploration activities. The value of geophysical surveys in evaluating physical properties of the rock matrix and the fluids they contain has been recognized for decades. Geophysical logging services have been developed for fresh and brackish groundwater exploration, and the logging services have become readily available, more reliable, and less expensive. Some established oil and gas geophysical interpretation methods are often applied to fresh and brackish aquifers, and interpretations are being made based on the same reliable, empirical data and standards that have been used in oil and gas exploration for many years.

The only direct evidence of the geology and stratigraphy that occurs in a borehole is from drill cuttings or core. However, drill cuttings are typically collected on 5- to 10-foot intervals, and even with an aggressive coring program, only a portion of the core is generally recoverable for analysis. Drill cuttings are not a 'true' composite sample of the sampling interval, but more accurately represent a disturbed sample of the drilled cuttings, which may be intermingled with shallower formation material that has sloughed off the borehole wall above the sample depth. Lithologic descriptions of drill cuttings can vary based on the experience of the driller or geologist performing the lithologic logging.

Geophysical logs provide a continuous digital record of the borehole, which can be used in conjunction with lithologic descriptions of drill cuttings or cores to characterize the subsurface geology. Some geophysical surveys provide valuable data regarding the water quality present in the formation, which is very useful in exploration for brackish groundwater resources. Geophysical logging will typically augment the site-specific data that can be obtained from drill cuttings and/or core alone. Geophysical logging does not provide a replacement for sampling and description of cuttings or core; a geophysical log analyst cannot evaluate a suite of logs properly without knowing the general types of rocks penetrated, which is information gained from the physical examination of cuttings or core. Geophysical logs do not have a unique response to specific geologic materials; for example, high gamma radiation from shale is indistinguishable from that produced by granite. Without good empirical knowledge of the general geologic materials penetrated, there is a potential for misinterpretation if only geophysical logs are used.

The use of geophysical logging techniques can be extremely beneficial in the exploration of brackish groundwater resources, and should be considered a necessary element of any exploratory drilling program. Geophysical logs can be used to help evaluate the nature of the producing zones and the quality of the groundwater contained within them. In many brackish aquifers, exploratory boreholes or wells may be the first source of subsurface data for a particular area, and geophysical logging can provide valuable data to augment characterization of the aquifer and provide guidance as to how production wells should be completed.

7.1 How Geophysical Logging Works

Once a borehole has been drilled to its total depth, a geophysical logging tool is lowered to the bottom of the borehole. The tool is then raised at a constant rate while it actively or passively records data from the adjacent formation. For groundwater geophysical surveys, data acquisition is typically continuous from the bottom of the borehole to the land surface, depending on the tool being used. This process provides an uninterrupted analog or digital record of the borehole that can be used to distinguish geologic and/or hydrologic formation changes.

Older oil and gas geophysical surveys were often performed from the bottom of the borehole to the ground surface, and these logs can provide valuable information for groundwater investigations. Later, it was a common practice in the oil and gas industry to perform the geophysical surveys from the bottom of the borehole up to the zones of interest, and often the shallower portions of the well are bypassed. However, the upper zones of an oil and gas well are commonly of interest for fresh and brackish groundwater investigations. More oil and gas drilling operators are again performing geophysical surveys to the ground surface to better understand and quantify shallow groundwater resources.

The reference point for the geophysical survey is typically the top of the drill rig Kelly bushing, top of the well casing, or the ground surface. The reference point elevation is usually recorded on the geophysical log header page. The actual depth of the geophysical log measurements should be adjusted to the elevation of the ground surface by subtracting the height of the Kelley bushing or casing reference point from the ground surface.

7.2 Purpose of Geophysical Logging

The primary purpose of geophysical logging is to provide a better understanding of the subsurface geology and hydrogeologic conditions. The chemical and physical characteristics of geologic formations and aquifers can be inferred from geophysical logging. Geophysical logging can be instrumental in refining the geologic and hydrogeologic setting of an area, and can be used to prepare subsurface cross sections or maps. When geophysical logs are normalized and calibrated (from cuttings or cores, or from other hydrologic field tests) with measured data such as salinity, hydraulic conductivity, porosity, and well yield data, they can be used comparatively to map the aquifer's physical and chemical parameters.

Geophysical logs are also instrumental in ensuring proper well construction. They can be useful in determining well screen placement and, in the case of wells with multiple hydrostratigraphic zones of interest, can be used to select packer or annular seal placement depths. Borehole geophysical methods can also be used in conjunction with surface geophysical surveys, such as resistivity, electromagnetic, and seismic, to provide valuable measurements by which the surface surveys can be calibrated.

7.3 Geophysical Logging Process

Once the borehole has been completed to its total depth, the geophysical logging vehicle is mobilized to the site. Modern geophysical systems are highly mobile and compact digital units that are often deployed in vehicles capable of off-road travel (Figure 7-1). The geophysical systems generally consist of a winch (Figure 7-2), a digital computer processor, a laptop computer with the logging program (Figure 7-3), and the geophysical tools (Figure 7-4). The geophysical logging tools are suspended on a cable and introduced into the borehole to collect data during the geophysical survey. The cable consists of an outer core of wire rope to support the weight of the tool(s) and an inner core of insulated wires to transmit or receive electrical current and/or data to and from the tool.

Figure 7-1. Geophysical logging field operations.

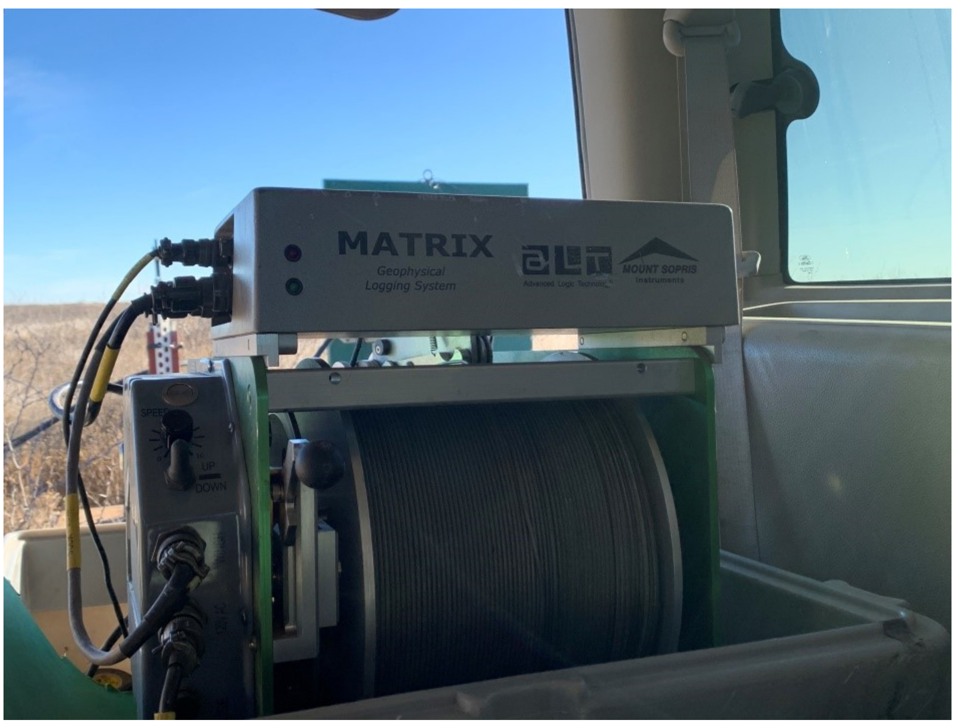


Figure 7-2. Wireline and winch.

Figure 7-3. Geophysical logging data acquisition system.

Figure 7-4. Geophysical logging tools.

Geophysical logging companies will typically have a standard "suite" of logging tools that can be run for most projects. Additional geophysical tools that may be needed for a particular investigation may be rented for use on an as-needed basis. At the conclusion of the geophysical survey, a geophysical log is typically saved to a portable computer or other storage device for later viewing or printing.

7.4 The Use of Geophysical Logs in Brackish Groundwater Exploration

Geophysical logs can be very useful for determining the water quality present in the formations around a borehole. Total dissolved solids concentrations can be derived from the spontaneous potential, single-point resistivity, normal resistivity, and induction (conductivity) logging tools. Resistivity and conductivity measurements are directly related to the dissolved ions in the undisturbed formation water with some contribution from the formation lithology. Calculations of total dissolved solids can be made in post processing using the geophysical log responses, making them the most valuable tools for determining the presence of brackish groundwater aquifers—second only to physically collecting a sample of formation water for chemical analysis.

Logs need to be interpreted on the basis of an assemblage of data, including (1) an adequate suite of logs in the logging program, (2) inspection of drill cutting samples, cores, or drilling time chart, and (3) checks against previous data sources, such as logs from other boreholes or wells within the same stratigraphic unit. Empirical knowledge of the local geology and hydrology of the subject aquifer can save steps in the evaluation of the log suite and potentially eliminate the need for some logs. If multiple geophysical logs are plotted at the same vertical depth scale, they can be viewed collectively by the geologist or engineer to match similar properties of other geophysical logs, in a process called "correlating" (Figure 7-5).

The permeability, thickness, and areal extent of a brackish groundwater aquifer are factors that define the potential usefulness of the resource for production. Aquifer thicknesses can be determined directly from several standard geophysical logs, and porosity calculations can be derived from others. Correlating geophysical curves from multiple geophysical logs can help estimate the continuity and areal extent of a potential brackish groundwater resource where logs from multiple test borings or wells are available (Section 5).

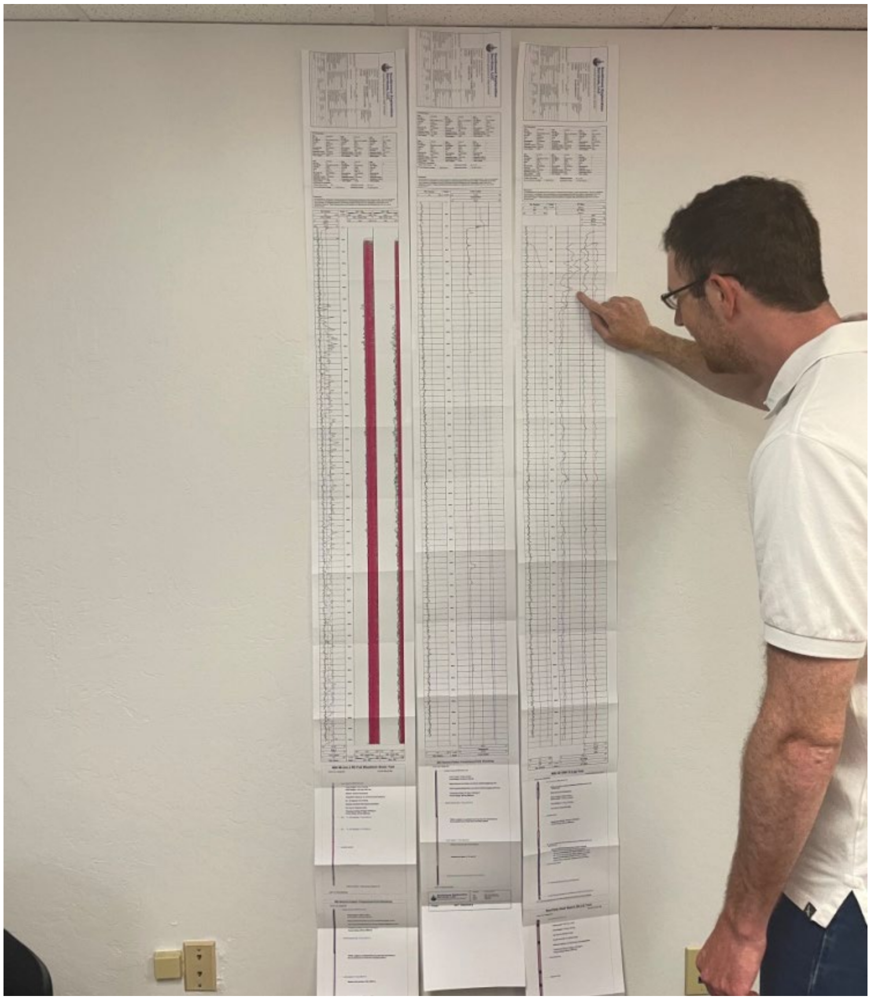


Figure 7-5. Correlating geophysical logs from three wells.

7.5 Geophysical Log Headers

Every geophysical log has a header that contains basic information about the geophysical survey, including specific information about the borehole or well and the conditions under which the geophysical survey was performed. This information is important for properly interpreting the log. Information included in the header generally includes, but is not limited to, the following:

1. Borehole or well information, including the owner, well identification number, and location.
2. Notes specifying the reference elevation where logging was measured, such as ground surface, Kelly bushing, or top of casing.
3. Information on the fluid in the hole, including resistivity, salinity, density, and temperature. The fluid information is needed for performing total dissolved solids concentration calculations.

4. Other miscellaneous information, such as the bottom hole temperature, tool operator and witnesses.

Figure 7-6 shows a typical log header.

Other important information that should be recorded includes the drilled total depth, logger's total depth, permanent datum, mud weight/resistivity, and bottom hole temperature.

The electrical resistivity of the drilling fluid is also included on the log header because electrical geophysical logs measure the difference between the drilling fluid resistivity and the resistivity of the formation. A determination of the true resistivity of groundwater is helpful to determine the total dissolved solids of the groundwater in the aquifer being characterized for brackish water investigations. Properties of the drilling fluid can be obtained in the field and recorded on the geophysical log header using a multi-meter to determine the values of salinity, pH, and conductivity (inverse of resistivity). Mud filtrate and mudcake resistivity estimates can also be made based on the weight of the drilling mud, which can be measured with a mud scale. The bottom hole temperature is often used to manually calculate the total dissolved solids concentrations from resistivity logs.

Collier Consulting, Inc.
590 E. Southloop
Stephenville, TX
(254) 968-8741

ELECTRIC LOG WITH GAMMA RAY

Well: TH #1
Well Owner:
Drilling Contractor:
County: ERATH
State: TX

Well: TH #1
Well Owner: REDACTED
Drilling Contractor: REDACTED
County: ERATH
State: TX

LOCATION
Latitude:32.19053
Longitude: -98.11290

Other Services:
NONE

Permanent Datum: GROUND LEVEL
GL to MSL: 928'
Drilling Measured From: GROUND LEVEL

Elevations:
KB: 4 FT ABOVE GL
GL to MSL: 928'

Run No.	1			
Date	2/20/2019			
Depth	591.20 ft			
Btm. Log Interval	591.20 ft			
Top Log Interval	0.00 ft			
Driller Depth	600 ft			
Bit Size	6.75 in			
Casing Btm. Driller	NONE			
Casing Btm. Logger	NONE			
Fluid Type	MUD			
Dens./Visc.	8.8/36			
ph/ Fluid Loss	xxxxx			
Source of Sample	PIT			
Rm @ Meas. Temp	3.7 OHM/81.1 F			
Rmf @ Meas. Temp.	2.8 OHM/ 81.1 F			
Rmc @ Meas. Temp.	xxxxx			
Source: Rmf/Rmc	CALC.			
Rm @ BHT	xxxxx			
Time Circ. Stopped	1 HR			
Logger on Btm.	14:30			
Tool No.	8144A			
Equipment Loc.	Truck 01			
Recording Engineer:	STEVE STONE			
Witnessed by:	MATT VAN HATTEM			

Figure 7-6. Typical geophysical log header (used with permission from Collier Consulting, Inc.).

The driller's total depth and the logger's total depth may differ by a few feet, as some material may have sloughed into the borehole between the time it takes the driller to trip out of the borehole and when the logging is conducted. In cases where the fill material is located within a critical completion zone of the planned well, the driller may be required to reinstall the drill string and clean out the borehole for another logging attempt. The permanent datum for correlation between the geologic formations and the corresponding log response is always ground level. It is not critical at the time of logging to have a surveyed ground surface elevation; however, if the driller is measuring the drilled depth from the drilling floor of the rig, a correction will be made to apply the geophysical logging depths to a land surface datum. Surveyed ground surface elevation is more important when creating maps that are based on relative distances from mean sea level, such as groundwater elevation contour maps or structural contour maps (e.g., the top or base of an aquifer or aquitard unit).

7.6 Geophysical Tool Types

Much of the content for Sections 7.6 and 7.7.2 was derived/modified from *Borehole Geophysical Techniques for Determining the Water Quality and Reservoir Parameters of Fresh and Saline Water Aquifers in Texas* (Collier, 1993). The purpose of this section is to provide readily understandable information regarding the geophysical logging tools likely to be applied to evaluate groundwater and aquifer conditions, particularly for brackish groundwater exploration. Ultimately, the decision on which tools are best suited is dependent on getting the most useful information possible within the budget for the program. There are a wide variety of geophysical survey tools, many of which provide similar information and parameter estimates (Table 7-1).

Different geophysical survey companies sometimes apply different trade names to similar logging tools. For example, the terms gamma-gamma log and density log are used for the same tool. Some geophysical tools, such as normal resistivity and induction (conductivity) tools, provide essentially the same information but use different principles of physics to derive the results. Note that many more geophysical tools are available than described in this section, but the tools most commonly used that are applicable for brackish groundwater investigations are discussed. These tools are described in the following subsections.

Table 7-1. Borehole geophysical methods for brackish groundwater investigations.

Log type	Specific Log	Borehole Conditions	Information
Electric	• Single Point Resistivity • Normal Resistivity • Lateral Resistivity • Microlog Resistivity • Induction (Conductivity) • Spontaneous Potential (SP)	• Open hole with fluid (resistivity) • Open and PVC cased holes with or without fluid (induction) • Conductive fluid (SP)	Lithology, location of PVC screens
Nuclear	• Natural and Spectral Gamma-Ray • Gamma-gamma (density) • Neutron (porosity)	• Open and cased holes with or without fluid (gamma ray) • Open holes with fluid (density, porosity)	Lithology, density, porosity
Electromagnetic	• Nuclear Magnetic Resonance (NMR)	Open and PVC cased holes with or without fluid	Lithology, salinity, porosity
Acoustic	Sonic	Open hole with fluid	Lithology (porosity)
Physical	Caliper	Open holes with or without fluid	Borehole diameter
Optical	Borehole camera	Open and cased holes with clear water or no fluid	Casing or borehole condition, caving, slope and aspect of fractures and layers
Flow	• Impeller flowmeter • Heat pulse flowmeter • Dye tracer flow profile	Open and cased holes with fluid	Water movement in the borehole / well
Temperature	• Temperature	Open and cased holes with fluids	Correction factors for other logs, flow indicator

7.6.1 Electric Logs

The term “electric log” refers to several logs that measure the flow of electricity. Several types of electric logs are typically run simultaneously, in one combination or another. The electric log suite may consist of a single point resistance tool, several normal resistivity tools (with various electrode spacings), lateral (guard) resistivity tools, induction (conductivity) tools, or spontaneous potential (SP) tools.

Resistivity is the electrical resistance of a given volume of material to the flow of an electrical current. Resistivity is inversely proportional to conductivity, which is a measure of a material’s ability to conduct electricity. The usefulness of resistivity geophysical methods is the ability to measure the resistivity of formation fluids (usually water, influenced by the total dissolved solids concentration of the water in the formation), but also the resistivity of the formation materials, although this is usually less influential on the total resistivity measurements. Water with no total dissolved solids (i.e., distilled water) does not conduct electricity, but water with total dissolved solids is conductive. All natural waters contain some amount of total dissolved solids, and brackish water is significantly more conductive than “fresh” water.

Calculations and visual interpretations used to estimate the true resistivity of the formation water (R_w) are highly dependent upon the resistivity of the drilling fluid (mud) within the borehole (R_m). Because brackish groundwater investigations may include drilling through fresh water intervals where the drilling mud has a lower resistivity than groundwater ($R_m < R_w$), and then transition to brackish groundwater, where the drilling mud has a resistivity higher than the formation water ($R_m > R_w$), interpretations can be difficult. Even more difficult are situations where the drilling mud resistivity is approximately equal to the formation resistivity.

Resistivity geophysical tools can be divided into two types, including electrode and induction. Geophysical companies commonly refer to electrode resistivity tools as "resistivity tools."

7.6.1.1 Resistivity Tools

The following subsections describe resistance and resistivity tools.

Single Point Resistance Tools

The single point resistance tool uses either one (conventional setup) or two (differential setup) downhole electrodes that measure resistance rather than resistivity. The single point resistance log provides a qualitative measurement of the formation's electrical resistance changes at the borehole wall. In general, resistance increases with grain size and decreases with increasing borehole diameter, fracture density, and reduced total dissolved solids concentration of formation water. The major benefit of using single point resistance tools is that they provide good resolution of thin geologic layers. The weaknesses of single point resistance tools are that they have limited penetration depths (distance into the formation adjacent to the borehole wall), and produce resistance data that cannot easily be quantified for calculations, especially where transitions between fresh and brackish groundwater conditions occur. Single point resistance tools should not be used as primary geophysical tools; rather, they should be run to complement the data of other geophysical tools. Single point resistance tools record data in ohms, without reference to volume, as in normal resistivity tools described in the following subsections.

Normal Resistivity

Normal resistivity tools use multiple emitting and receiving electrodes to obtain multiple resistivity readings at various depths of investigation within the formation. Multiple depths of investigation are desirable to evaluate/calculate the resistivity of the formation water from the drilling mud influenced borehole. Geophysical survey companies offer logging tools with various electrode spacing configurations, but the industry standard includes electrode spacings of 8, 16, 32, and 64 inches, commonly referred to as 8-inch normal, 16-inch normal, 32-inch normal, and 64-inch normal, respectively. The most commonly used resistivity spacings are 16-inch normal and 64-inch normal. Some geophysical companies describe the 16-inch normal as the "short normal" resistivity log, and the 64-inch normal as the "long normal" resistivity log.

Figure 7-7 presents a diagram of a normal resistivity tool with conventional electrode spacing, where electric current is introduced through the emitting E-electrode and the resulting voltages are measured at different receiving electrodes (R-8 through R-64) present on the logging tool.

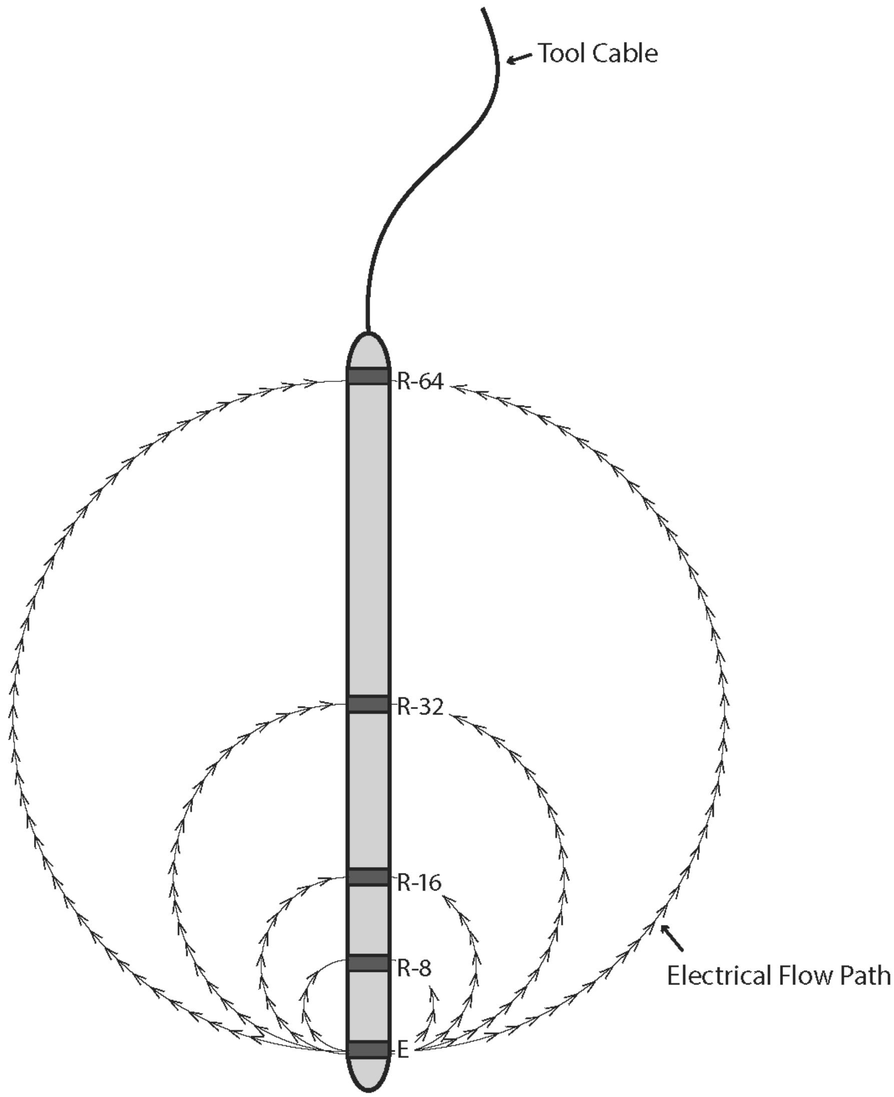


Figure 7-7. Normal resistivity tool schematic.

The spacing between the E-electrode and the receiving electrodes determines how deep into the formation the resistivity is measured. Longer spacing provides deeper penetration of the current into the formation with less influence from the borehole fluid, while shorter spacing provides less penetration into the formation but provides higher resolution for picking thin beds within a formation. The longest spacing, the R-64 electrode, commonly makes a measurement that penetrates several feet into the formation, and this measurement is considered to be a good indicator of the true formation (aquifer) resistivity. The obvious advantage of the four-electrode tool is that it investigates a greater range of depth and has a greater resolution. The four depths of investigation are also commonly used to infer zones of permeability. The more permeable a formation is, the further drilling fluids will invade into the formation.

In more permeable sand or gravel zones, the long-normal and short-normal logs will exhibit a visible separation, as the resistivity of the borehole wall (wall cake) differs from the resistivity of the undisturbed formation. The long-normal and short-normal logs will exhibit less visible separation in less permeable clay zones. However, short- and long-normal resistivity logs can be similar in extremely permeable zones where drilling fluid invasion into the formation has been extensive.

Resistivity measurements cannot be collected in cased wells, and the tool must be submerged in drilling fluids to allow electricity to flow through fluid in the borehole and into the formation. Resistivity logs commonly report the resistivity units of measure in ohm-square meters per meter, abbreviated to ohm-meter or ohm-m. Abundant research has been performed on resistivity tools relative to formation thicknesses, electrode spacing, borehole conditions, and other factors that affect log responses; these topics are outside the scope of this document. Figure 7-8 shows an example of 16-inch and 64-inch normal resistivity curves measuring resistivity from 0 to 150 ohm-m, respectively.

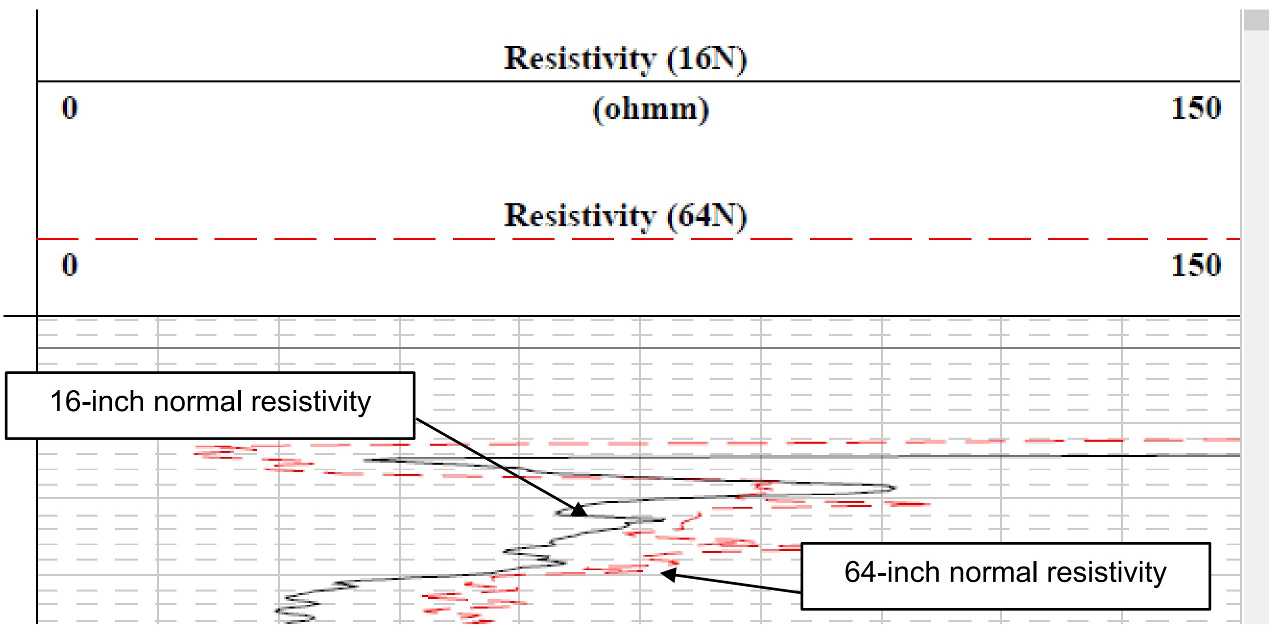


Figure 7-8. Log scale and curves for 16-inch and 64-inch electrode spacing normal resistivity tools.

Lateral Resistivity

Lateral resistivity tools were primarily used by the oil industry and provided the maximum depth of investigation for measurement of true formation resistivity, but are seldom used today for water resource investigations. A brief description is provided here because, if available, the lateral resistivity logs can provide deep penetration resistivity data. Lateral resistivity tools were resistivity tools with electrode spacing ranging from 5 to 24 feet, but the predominant spacing was 18 feet, 8 inches. Lateral resistivity logs require careful interpretation and correction relative to formation thicknesses. Figure 7-9 shows a lateral resistivity curve measuring resistivity from 0.2 to 200 ohm-m, with electrode spacing of 18 feet, 8 inches. The red line shows the lateral log, with the deepest penetration compared to the normal resistivity curves. Note on Figure 7-9 that the separation between the lateral resistivity log and other normal resistivity logs may indicate substantial formation permeability, as previously described.

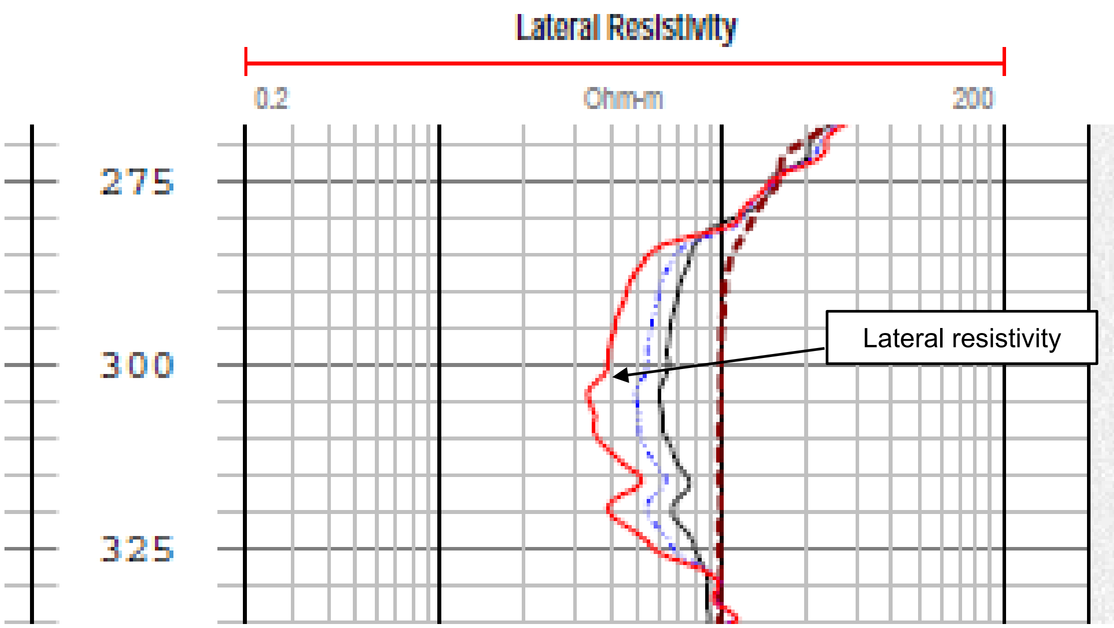


Figure 7-9. Example log for lateral resistivity tool.

Microlog Resistivity

The Microlog Schlumberger trade name, also known also known as the Minilog (Atlas Wireline), Contact log, Permalog, Micro-contact log, and Micro-survey log (others), is a resistivity tool that uses shielded pads that press against the borehole wall and measures the borehole resistivity as the geophysical tool is retrieved. The Microlog also measures the borehole size in a similar manner as the caliper log described later in this section. The Microlog essentially measures the degree of mudcake deposition on the borehole wall, and provides some indication of the formation permeability, with abundant caveats and conditions best left for seasoned geophysical analysts. However, if interpreted correctly, it can provide resistivity data of the borehole invaded zone, which could be useful for calculating the formation total dissolved solids using older oilfield geophysical logs.

Induction (Conductivity)

Induction tools use coils to induce a high frequency alternating electromagnetic field into the formation. The alternating magnetic field induces looped eddy currents in the surrounding formation, which are picked up by a receiving coil on the induction tool. The received current voltage is proportional to the formation conductivity, which is inversely proportional to the formation resistivity. In a similar manner as the resistivity tools, conductivity tools use transmitter coils and receiver coils spaced at various distances along the tool, and typically are used to prepare “shallow,” “medium,” and “deep” induction logs.

Induction geophysical logs commonly report the conductivity units of measure in millimhos per meter (mmhos/m) as shown in Figure 7-10. Some geophysical companies use the term “induction tool” and report the results in units of resistivity, after converting the conductivity units to resistivity units.

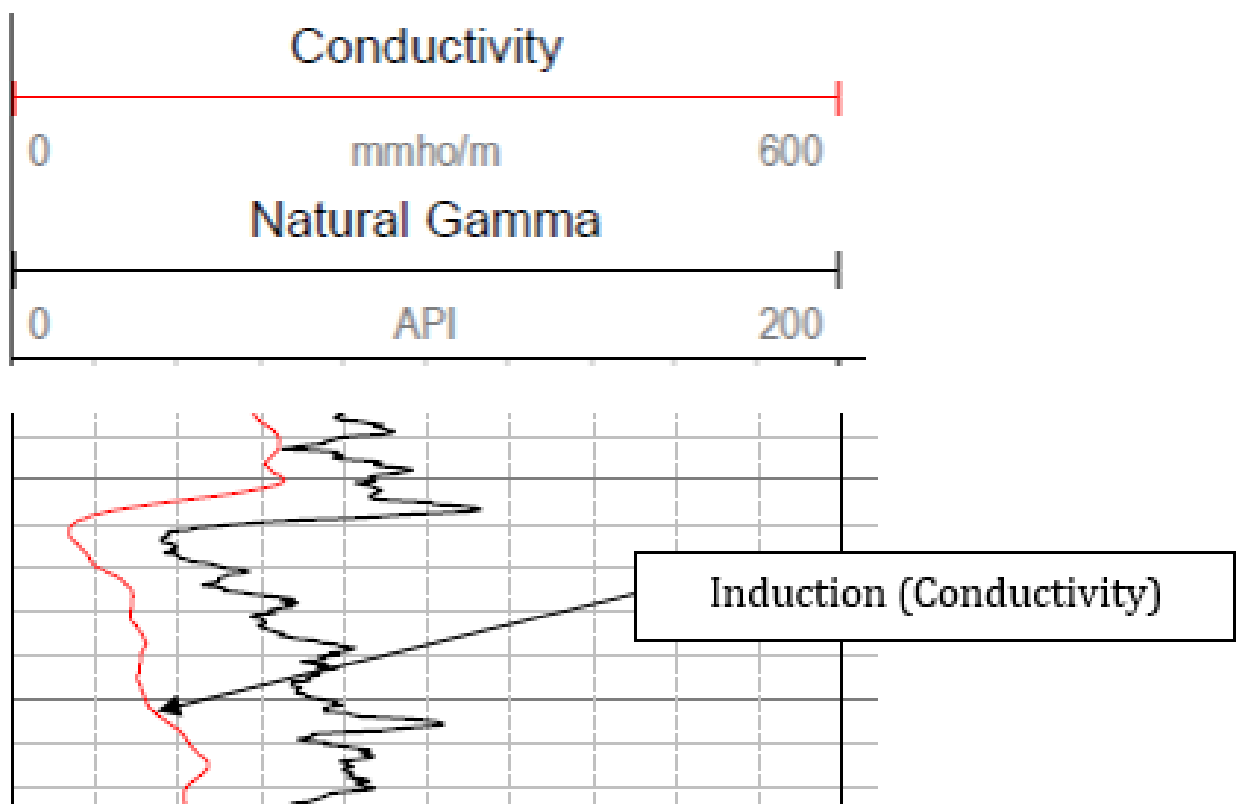


Figure 7-10. Conductivity (red line) log.

The advantage the induction tools have over the resistivity tools is that the induction tools can collect conductivity readings in water-, air-, and mud-filled boreholes. Unlike the resistivity tools, drilling fluids do not need to be present in the borehole for this geophysical log

Major factors that affect induction-log response include the concentration of total dissolved solids in the groundwater and the composition of formation materials. Induction tools can measure changes in water quality with depth and in different discrete zones.

7.6.1.2 Spontaneous Potential

The spontaneous potential log, commonly referred to as a self-potential log or an SP log, is one of the oldest borehole geophysical techniques; it was developed for oil field use in the early 1930s. This log remains one of the most commonly used geophysical logs. This log works by passively measuring naturally occurring small voltages (electric potential) resulting from electrical currents in the borehole by an electrode lowered in the borehole relative to a stable electrode grounded at the surface. Because this tool is passive, and only measures the natural potential difference between the electrode in the tool and a reference electrode, the depth of penetration provided by this tool is quite small; it only obtains data on the aquifer immediately adjacent to the edges of the borehole.

The SP log requires that a conductive fluid be present in the borehole, and therefore cannot be used in an air-filled borehole or one filled with a non-conductive fluid such as an oil-based mud. The SP curve is typically shown on the left track of the log along with the gamma curve, if logged concurrently. Both the gamma and SP curves are often used for geologic correlation. They are both useful for the determination of the formation lithology, can be used to determine the clay/sand volume percent, and can be used to derive a sand/shale boundary line. The SP log can also be used to determine the formation water resistivity from which water quality and total dissolved solids can be calculated for brackish water determination. The SP log is used mainly for lithologic correlations or for differentiating non-permeable strata in a clay-sand sequence; it is a good tool for picking up shale beds, particularly where they are thin.

Figure 7-11 shows a typical SP log in a brackish groundwater environment. The SP curve scale is 0 to 200 millivolts (mV), with a relatively high formation potential of 130 mV just above the 645-foot depth (deflection right) to a relatively low formation potential of 60 mV below 650 feet (deflection left). Low potential likely represents a clean sand. Also note the conductivity curve deflection right within the same interval (660 to 685 feet) indicating increased total dissolved solids.

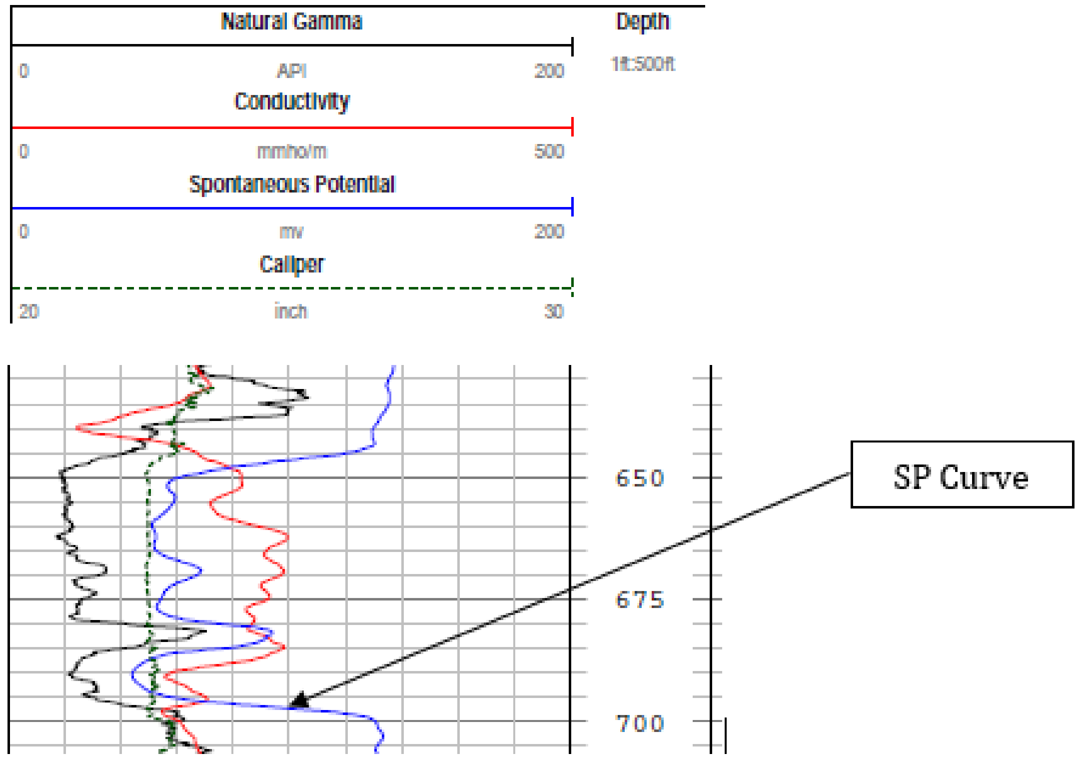


Figure 7-11. Typical SP curve (blue line).

7.6.2 Nuclear Logs

The following subsections describe different types of nuclear logs.

7.6.2.1 Natural Gamma Ray and Spectral Gamma Ray

The most widely used tool in geophysical well logging is the natural gamma ray log, also generically named "gamma," "natural gamma," and "gamma ray." First developed around 1930, these logging tools record the level of naturally occurring gamma radiation emissions from formation materials around a borehole.

The gamma ray log measures the naturally occurring gamma emissions from the decay of unstable elements in the formation surrounding the borehole; these elements are primarily potassium-40, thorium, uranium, and their daughter products. One of the most significant and abundant radioactive elements is potassium-40. As potassium-40 decays, it emits electromagnetic radiation, which the gamma ray probe detects and records. The greater the gamma ray detection (counting) rate, the higher the amount of potassium-40 in the formation. All potassium-bearing minerals, such as feldspar, biotite, and several clay minerals, contain potassium-40. Consequently, an increase in clay content in the strata typically results in a high response of the gamma ray probe; inversely, a decrease in clay content results in a low response. In many areas, arkosic (feldspar-rich, poorly weathered) sand formations will also have high gamma ray emissions. Therefore, the gamma ray log should be interpreted in conjunction with the other logs.

Spectral gamma ray tools can speciate the types of gamma radiation, and are of less interest in brackish groundwater investigations except where aquifers containing uranium might be a concern for development purposes. In zones of a borehole where relatively high natural gamma radiation might be detected, the spectral gamma ray logging tool can be deployed to further investigate naturally occurring radioactive sources that would generally be avoided in groundwater resource development.

Natural gamma ray and spectral gamma ray tools can be run in both open hole and cased hole situations, and do not require that drilling fluids be present. However, it should be noted that different types of casing have different effects on gamma ray activity; steel casing reduces the gamma ray activity by about 30 percent, while PVC has minimal impact on gamma ray activity (Collier, 1993). Cement and grout will also shift the gamma ray curve, and variations in the thickness of these materials will also introduce additional variability into the gamma ray curve.

Gamma ray tools use a scintillation counter to record American Petroleum Institute (API) gamma ray units, or simply “API units,” based on a standard consisting of 6 parts per million (ppm) uranium, 12 ppm thorium, and 2 percent potassium (Dewan, 1983). Some gamma ray tools record gamma radiation in counts per second (cps). Clay materials, such as shale, bentonite, and even some concrete, have a relatively high gamma radiation level, with a measurement of 75 to 125 API units. Sands have much lower radiation levels, with typical values of 15 to 30 API units. Mixtures of sand and clay can have any radiation level between the clay and sand levels, depending on the proportions and types of components in the mixture. Carbonates have low API levels, about 5 to 15 API units. Figure 7-12 shows an example of a natural gamma ray curve plotted adjacent to a spontaneous potential curve in fresh water sand and clay formations.

Natural gamma logs are primarily used for lithologic evaluation of the subsurface formation and aquifers. These logs are widely used for correlation between neighboring wells and for correlation with other logs run within the same borehole. Natural gamma ray curves can be used to derive a sand/shale cutoff line, which can then be used to make net sand thickness maps that can be useful in interpreting areas of higher water yields, and can also be an indicator of potential pathways for preferential water movement. Post-processing of natural gamma data can provide valuable information regarding the qualitative interpretation of other aquifer quality parameters such as effective porosity, permeability and well yield.

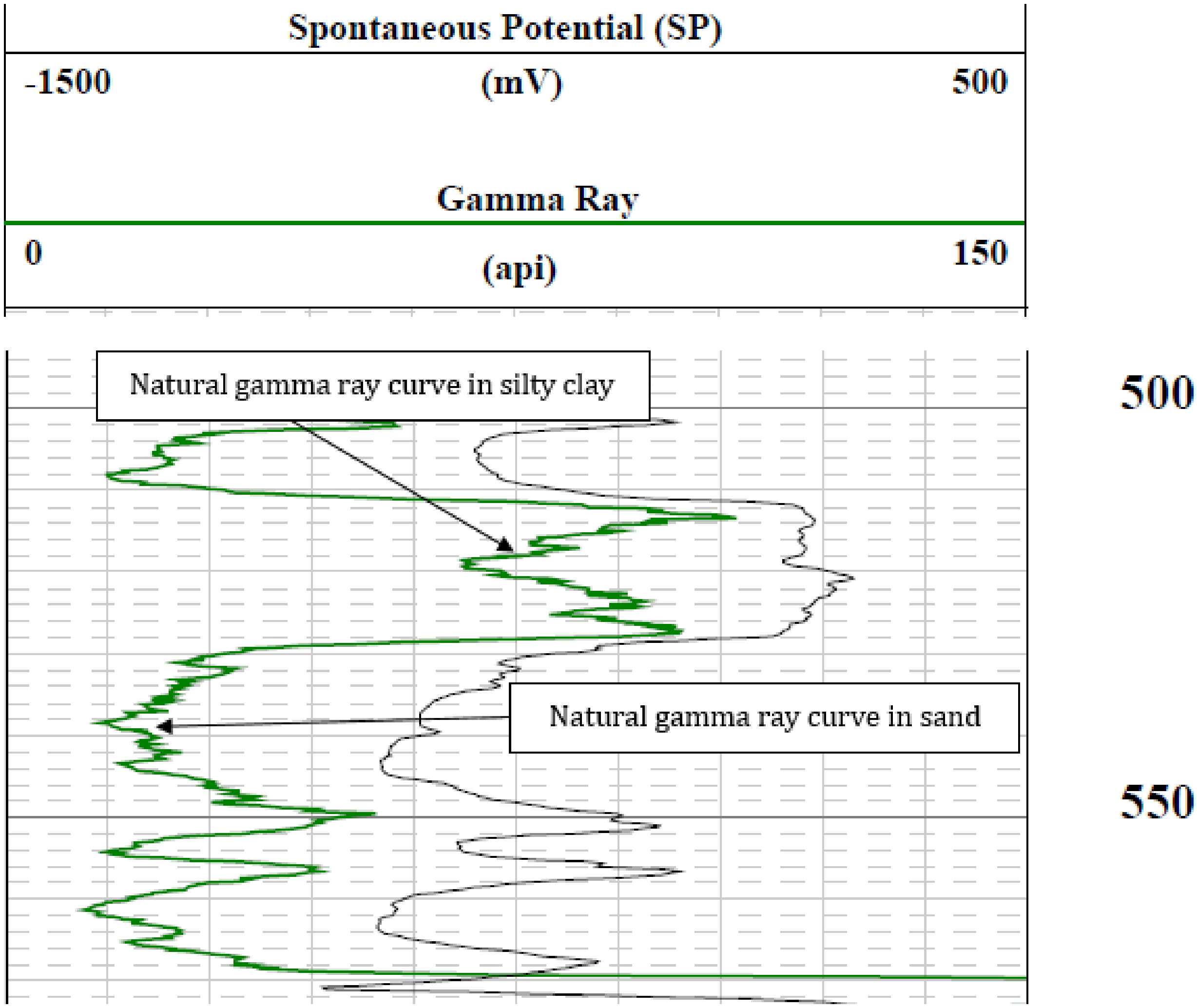


Figure 7-12. Example natural gamma log curves.

7.6.2.2 Gamma-Gamma (Density)

Gamma-gamma logs, also known as density logs, use a radioactive source that emits gamma radiation (gamma rays) into the formation materials. The gamma rays collide with electrons in the formation, which emit energy and cause electron scattering known as Compton scattering. The scattered gamma rays are received by a detector on the survey tool, which can be quantified and related to the bulk density of the formation. Because density geophysical tools use a radioactive source, special licensing, handling, and transportation regulations apply to their use. In low bulk density formations, more scattered gamma rays are received by the detector (detected), and in high bulk density formations, fewer gamma rays are detected.

Density logs have approximately 5 inches of investigation depth, and measurements are typically presented in grams per cubic centimeter (g/cm^3) (Collier, 1993). Limestone is generally used as the median density material for log plots, with a density of approximately

2.45 g/cm³ as shown in Figure 7-13, along with other typical geologic formation bulk densities.

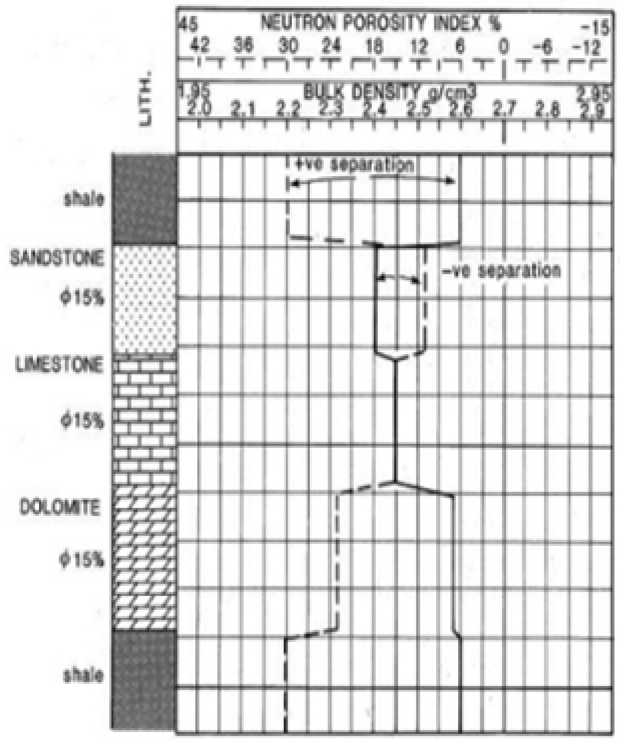


Figure 7-13. Bulk density of various formation materials (source: Rider, 1996).

Because the depth of penetration is shallow, many of the density logs have the capability to automatically correct the density readings to account for the drilling mud cake on the borehole wall. Tools that make those corrections are termed “compensated density tools.”

Porosity is a very useful parameter used in the characterization of an aquifer. It generally cannot be quantified without cores, and is often estimated based on professional judgement. If properly calibrated, density geophysical surveys can be used in conjunction with neutron logs to estimate the porosity of formation materials. Neutron logs measure the amount of hydrogen in the formation (in the form of water), so the relationship of formation density from the density survey and water content from the neutron survey can be used to estimate the formation porosity.

Porosities derived from geophysical logging are extremely useful in determining total dissolved solids estimates using the Rwa minimum method, hydraulic conductivity values for seepage velocity, resource volume estimates, well yields, and for groundwater modeling purposes.

7.6.2.3 Neutron Logs

Neutron geophysical surveys use a radioactive source to emit neutron particles. Hydrogen atoms (associated with water) are approximately the same size as neutrons, and generally cause energy loss to the neutron particles at a higher rate than other elements in surrounding formation materials. Detectors on the neutron survey tool measure the neutron count rate, which is proportional to the amount of hydrogen (water) in the formation; neutron count rate decreases as hydrogen concentrations increase (Collier, 1993). As with density surveys, neutron geophysical tools use a radioactive source; therefore, special licensing, handling, and transportation regulations apply to their use.

The neutron formation depth of investigation is relatively shallow (generally less than 10 inches) and is dependent on the strength of the radioactive source, source-to-detector spacing, and hydrogen (water) content in the borehole and formation (Collier, 1993). Compensated neutron tools are commonly used to overcome the effects of mudcake thickness.

Neutron geophysical surveys are often used in conjunction with density geophysical surveys to estimate formation porosity, and are thus often called porosity logs. Therefore, the neutron log header often indicates porosity as a percentage, but it can also be referenced in counts per second. The neutron log is also good for picking formation boundaries. Figure 7-14 presents a typical neutron curve in relation to the gamma log, showing its usefulness for correlating geologic formations and identifying saturated zones.

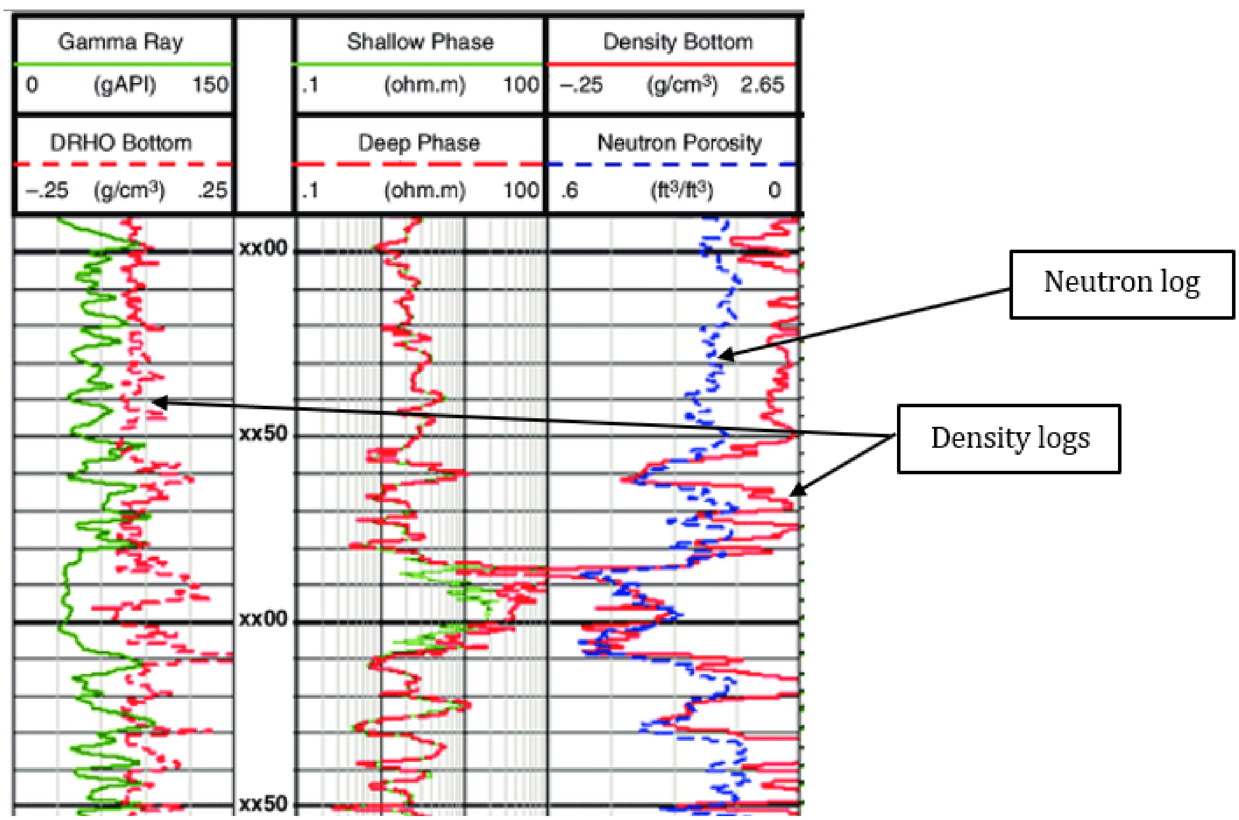


Figure 7-14. Example of density (gamma-gamma) and neutron logs.

7.6.3 Electromagnetic Logs

Nuclear magnetic resonance (NMR) tools emit a strong magnetic field, which essentially manipulates the hydrogen protons within groundwater molecules. Magnetic pulses emitted by the NMR tool cause the rotating protons in hydrogen molecules to tilt on their axis, which allows for the measurement of transverse and longitudinal relaxation times and distributions. Processing of that information allows the NMR log to directly measure the hydrogen atom quantity, which indicates the porosity (water content) of the saturated formation material. The decay time of the NMR signal indicates pore size geometry; therefore, with the combination of formation porosity and pore geometry, the logging data can be mathematically processed to provide a continuous log of formation permeability.

NMR log data can be used to map aquifer hydrogeology for groundwater investigations. They can be used to assess water distribution within an aquifer, such as the ability to measure the vertical and lateral variation in total porosity and differentiate the fraction that is occupied by free (mobile) water versus the remaining fraction occupied by bound (immobile) water. Figure 7-15 presents a typical nuclear magnetic resonance log showing clay-bound, capillary-bound, and mobile fluid volumes. The NMR tool can investigate aquifer flow potential by calculating hydraulic conductivity, specific yield, and specific retention of the rock in situ. Aquifer permeability can also be derived from analysis of NMR responses.

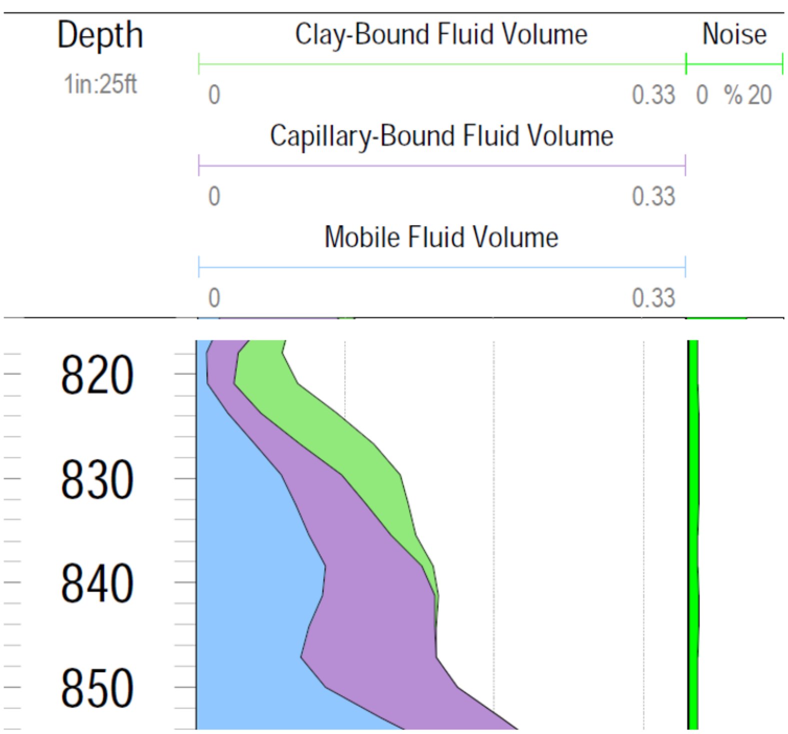


Figure 7-15. Example of nuclear magnetic resonance log. Green color shows fluid bound by clay, purple color shows fluid bound within the capillary portion of the formation, and blue color shows mobile fluids (source: High Plains Underground Water Conservation District, Dockum Test Well; USGS NWIS Site Number 341816101570901, Station Name KY-11-41-5xx).

One unique advantage that NMR provides is a measure of pore size distribution independent of lithology, without requiring a radioactive source. In the water industry, NMR logging is focused on delineating “producing” from “non-producing” zones, and further quantifying formation total versus effective porosity and hydraulic conductivity. This information can then be used to determine proper well screen locations and optimal well yield for wells. These advanced magnetic resonance tools provide direct-depth log outputs of effective porosity, total porosity, pore size distribution, water saturation, and estimated permeability for determination of aquifer quality. These outputs comprise a detailed hydrogeologic evaluation of the near-wellbore region, and are independent of conventional formation evaluation measurements, such as resistivity logs.

7.6.4 Acoustic Logs

Sonic logs (also called acoustic logs) measure the average velocity of a sound wave passing through the formation. The velocity of the sound wave changes as it passes through water and through different formation materials. The sonic log is useful for estimating relative formation density, evaluating fracture patterns in bedrock aquifers, and estimating the location of the regional static water level and perched water tables. This log is also useful for characterizing the integrity and quality of cement grout annular seals outside the casings of existing wells.

The time required (measured in microseconds per foot [μs/ft]) for a sonic wave to travel out into the formation and return back to the logging tool is termed delta t (Δt). An increase in Δt equates to decreased travel speed, which is indicative of less brittle, or more ductile, formation material. In contrast, more brittle and rigid material will propagate the sonic wave more rapidly, resulting in a smaller Δt value.

In unconsolidated alluvial sediment, lower Δt values (increased travel speeds) indicate a somewhat rigid or compacted condition that may correlate with coarse-grained or cemented sediments. The Δt values in crystalline rock formations are of a much lower magnitude (increased travel speed) than in unconsolidated sediments. The porous or fractured intervals within a crystalline rock aquifer are generally reflected as higher Δt values (decreased travel speeds) on the sonic log, where the lack of rigid crystalline rock retards the speed of the sound wave. Figure 7-16 presents an acoustic log showing the acoustic waveform response relative to clay overlain by sand.

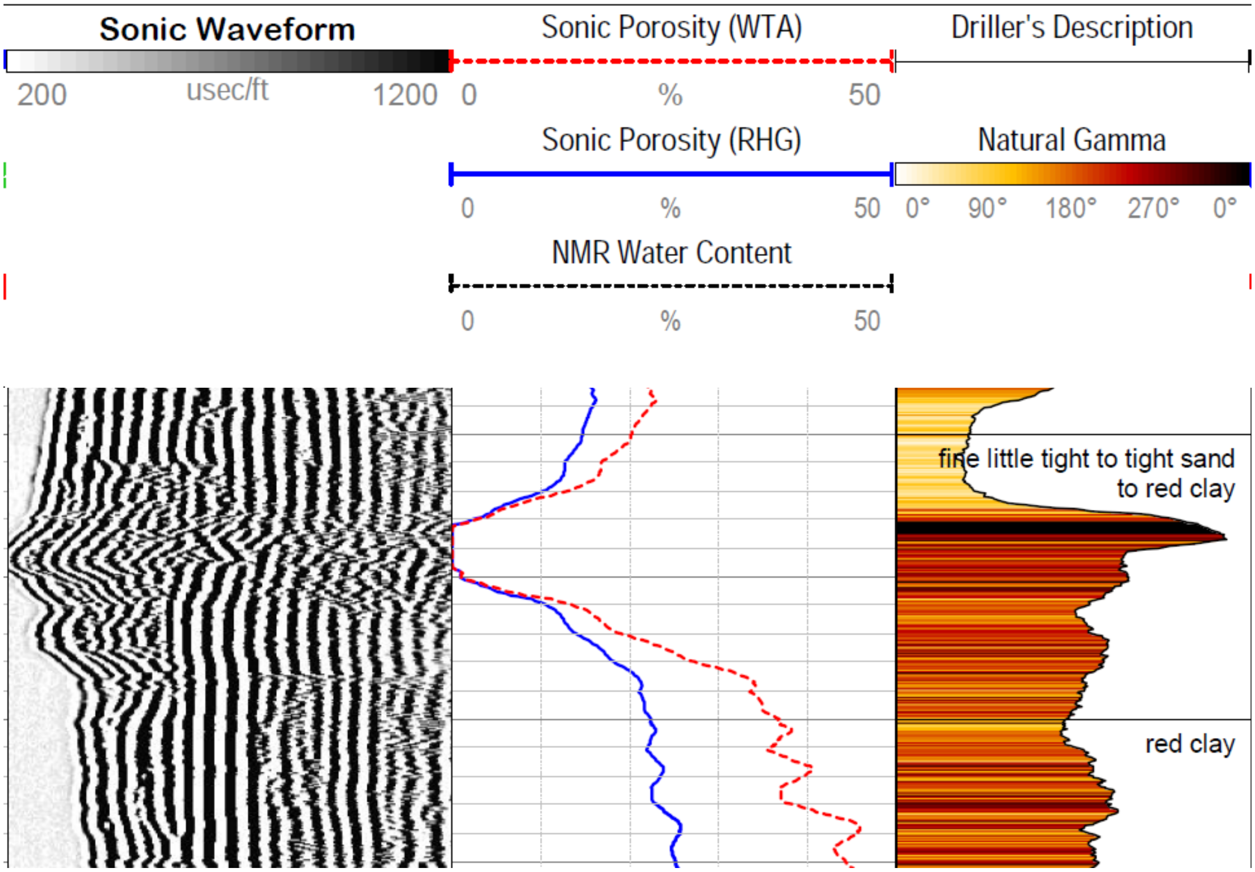


Figure 7-16. Example of an acoustic log. Sonic (acoustic) waveform plot shows deflection to the left where acoustic travel speed is reduced entering a clay zone (source: High Plains Underground Water Conservation District, Dockum Test Well).

7.6.5 Physical Logs

The caliper log provides a physical (mechanical) measurement of the borehole diameter. Changes in the borehole diameter commonly occur from formation washouts (enlarged hole diameter), buildup of the drilling mud-wall cake across permeable strata (decreased hole diameter), or swelling of natural clays in the formation (decreased hole diameter). The caliper log is used in conjunction with other logs to differentiate borehole diameter effects from actual lithologic changes. Because several of the other geophysical logs (e.g., gamma-gamma logs and sonic logs) are sensitive to borehole diameter, the caliper log is typically one of the first logs run, so that borehole diameter variations can be considered during interpretation of the other logs. Figure 7-17 presents an example of a caliper log showing a washout below a cased interval.

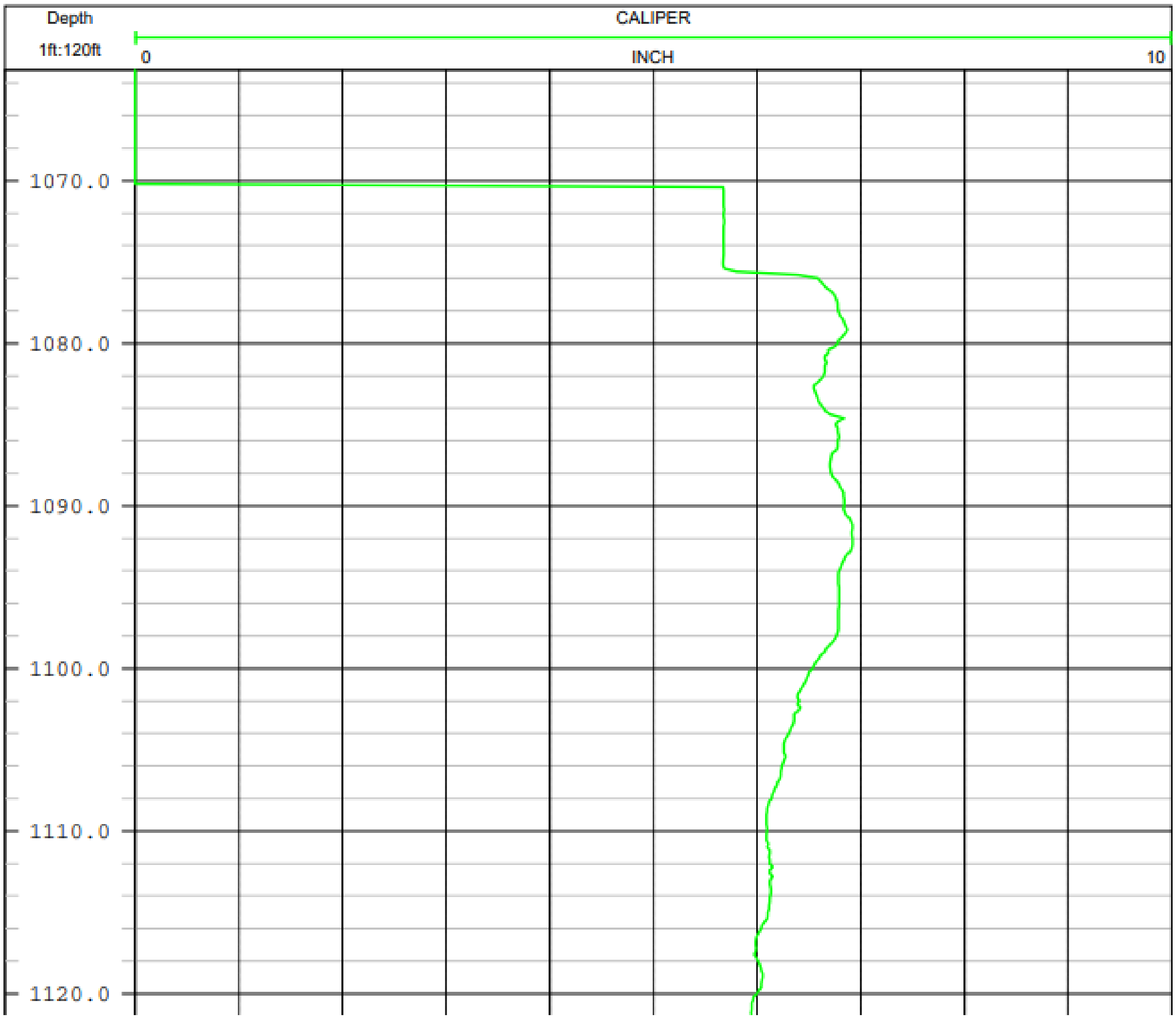


Figure 7-17. Example of a caliper log. Bottom of intermediate casing set at approximately 1,075 feet below ground surface as indicated by straight vertical line, and formation washout immediately below the casing (source: USGS GeoLog Locator; USGS NWIS Site Number: 291612099302001, USGS NWIS Station Name: YP-69-44-902 East Uvalde 2, Uvalde County, Texas).

7.6.6 Optical Logs

Borehole cameras for water resource development applications function in both open hole and cased hole situations. In both open and cased holes, the hole must be dry or contain clear fluid for best viewing.

In open boreholes, cameras can provide additional value in locating water influxes or to aid in lithologic interpretation. Features such as fractures, washouts, formation contacts, bedding plains, formation color, and grain size can be viewed. Cameras can include features such as rotating mirrors for angle viewing, directional capabilities, and small diameters for 2-inch monitor wells.

In cased holes, cameras provide data on the casing conditions of the well. Casing deterioration, screen zones, perforations, scaling, and “junk in the hole” can be seen. When these problems are spotted early, they can often be corrected and the well can be repaired. Cameras can also be used to provide data on old existing wells that may have missing or incomplete well records, and items such as depth of casing and screen intervals can be determined. Figure 7-18 presents an example of an optical log showing solution cavities within a karstic limestone interval.

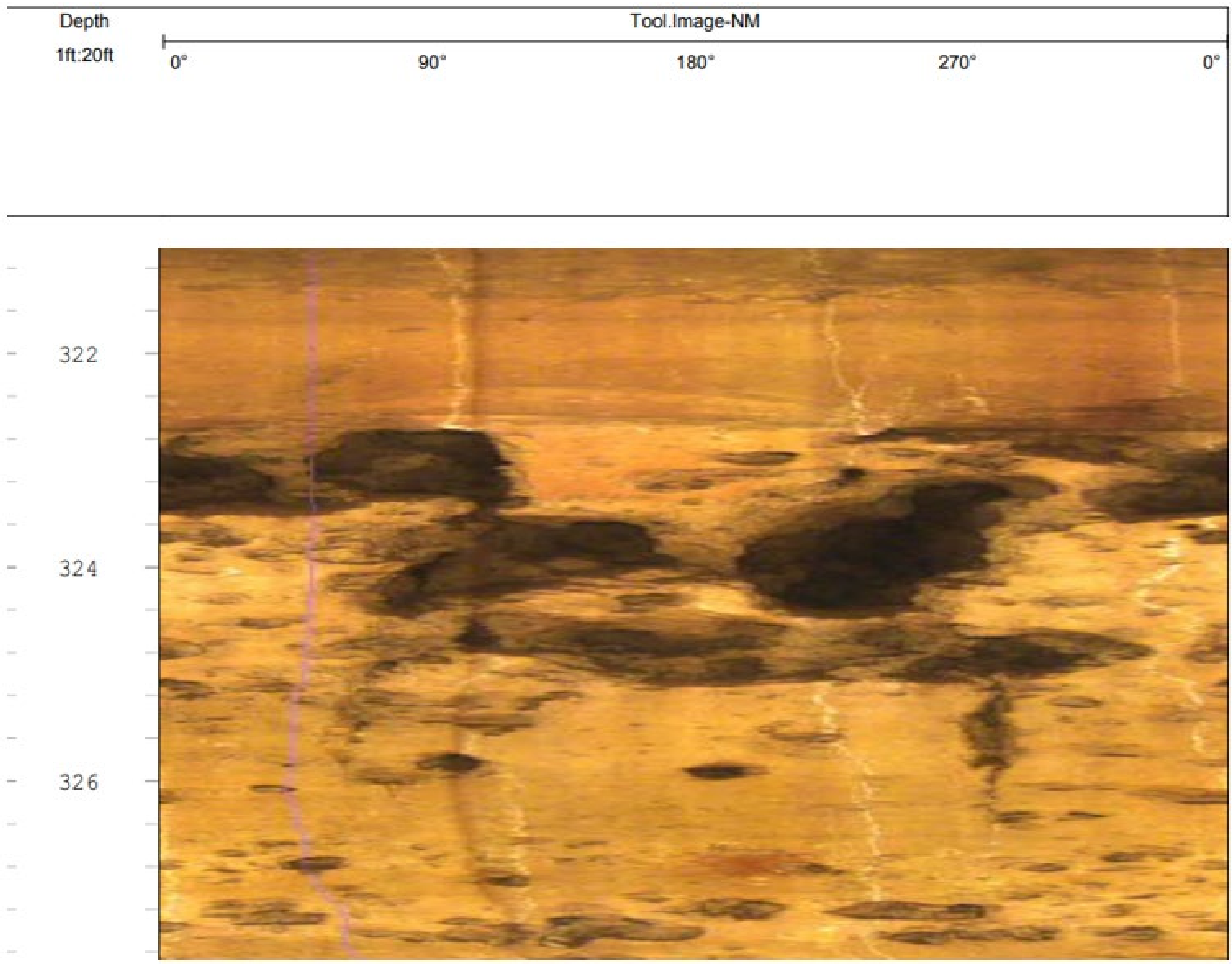


Figure 7-18. Example optical log showing sidewall image of a karstic limestone with solution cavities (source: USGS GeoLog Locator, USGS NWIS Site Number 294529098360401, USGS NWIS Station Name: CampStandley-CSI-LGR, Comal County, Texas).

7.6.7 Flow Meters

Whether they use a spinner, impeller, or heat pulse, flow meters are designed to measure the rate and the direction of groundwater flow in the borehole. Heat-pulse flow meters operate by heating a small sheet of water between two sensitive thermistors (heat sensors). A measurement of flow direction and rate is recorded when a peak temperature is recorded in one of the thermistors. Heat-pulse flow meters require a good seal between the borehole or well casing. Flowmeter data are useful in conducting hydrostratigraphic investigations and in aquifer characterization. Examples of applications include the following:

- Developing pumping flow profiles in screened or perforated cased holes
- Identification of hydrostratigraphic units
- Determining quantitative interval-specific flow rates
- Confirming predicted transmissive zones in an open hole

Figure 7-19 presents an example of a flow meter log.

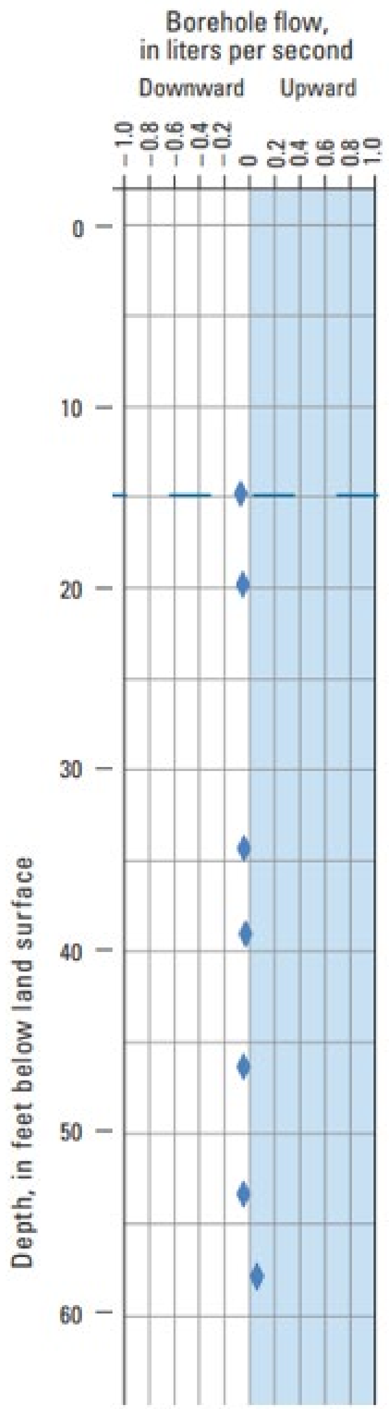


Figure 7-19. Example of flow meter log. Blue diamonds represent the flow in liters per second, with downward flow from the static water level (blue dashed horizontal line) to approximately 55 feet below ground surface and upward flow at approximately 58 feet below ground surface (source: Clarke and others, 2011).

7.6.8 Temperature Logs

Temperatures in subsurface formations generally increase with depth under normal conditions at an approximate geothermal gradient of 1 degree Fahrenheit (°F) per 100 feet. Most counties in Texas have temperature gradients of 1.0 to 2.5°F per 100 feet (Collier, 1993). Evaluation of temperature logs can provide information about the movement of groundwater within aquifers if anomalies are identified. Figure 7-20 presents a temperature log used to identify a temperature anomaly likely associated with fluid movement through a porous zone.

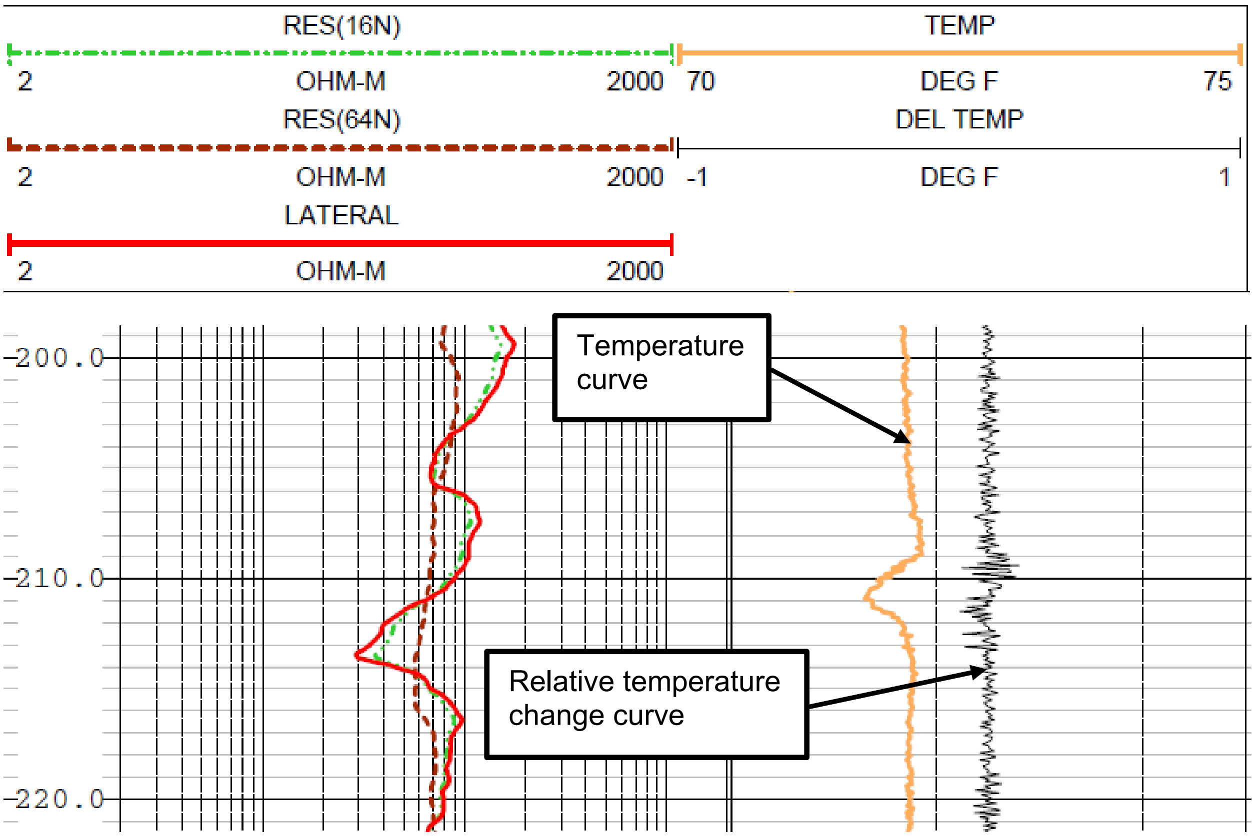


Figure 7-20. Example of a temperature log. Temperature curve shown in orange and relative temperature change curve shown in black. Note temperature reduction (cooling) below approximately 210 feet associated with permeable zone indicated by normal resistivity curves (source: USGS GeoLog Locator; USGS NWIS Site Number: 301504097501401, USGS NWIS Station Name: YD-58-42-711, Travis County, Texas).

Temperature probes are typically included in most logging tools, as many of the logging tools require calibration or correction relative to temperature. For example, total dissolved solids calculations from resistivity data require corrections based on temperature gradients.

7.7 Geophysical Log Interpretation

Despite the existence of many reference guides for geophysical log interpretation that may provide methods to estimate values for parameters such as porosity and permeability, geophysical log analysis is affected by many variables that are not always entirely understood. Correct interpretation of geophysical logs is based on a thorough understanding of the principles of each logging technique. For this reason, interpretation of geophysical logs in the petroleum industry is largely performed by professional log analysts who specialize in this type of evaluation. However, few of these specialists are working in the water resources, environmental, and engineering fields, so interpretation of logs for these applications is often carried out by those conducting the investigation, usually the consulting geologist or hydrogeologist. The sections above provide some detail on how different geophysical tools are used in brackish aquifer evaluation work, and what the data produced by these tools mean. It is important to understand that the data from multiple geophysical logs must be evaluated together to properly interpret formation characteristics and water quality in a borehole. Individual tools provide a unique set of data, but the information an individual tool can provide is limited compared to interpretations that can be made with combined data from multiple tools.

For stakeholders involved in brackish groundwater investigations that are not expert log analysts, general information about subsurface geologic formations, porosity, and relative groundwater salinity can be obtained through simple non-quantitative review of geophysical logs. The novice can also use simple quantitative calculations from measurements taken directly from logs to calculate approximate total dissolved solids concentrations. This subsection discusses log responses and visual interpretations, as well as some simple calculations that can be used to estimate total dissolved solids concentrations.

7.7.1 Visual Interpretations from Geophysical Logs

Figures 7-21 through 7-27 provide examples of common log curves for various geophysical methods in fresh and brackish groundwater zones. Example interpretations for each of these figures are provided.

Figure 7-21 is a combination of several logs from an exploration borehole drilled within a carbonate sequence. The natural gamma log response increase to the right is a result of increased radioactivity of the clay minerals within the Eagle Ford Shale formation. The natural gamma response in the overlying Austin Chalk and underlying Buda Limestone formations is less pronounced, as the chalk and limestone formations contain less radioactive clay minerals. Figure 7-21 also shows the neutron and neutron porosity log response within the formations. The log interval from 205 to 265 feet shows an increased neutron response compared to the lower portion of the Austin Chalk below 265 feet. Within the same 205 to 265 feet interval, the neutron porosity log indicates less porosity than the interval below 265 feet. The calcareous Del Rio Clay below 460 feet is identified by an increase in radioactivity by the gamma log, decreased water content by the neutron log, and increased porosity by the neutron porosity log (off-scale deflection of the neutron porosity curve).

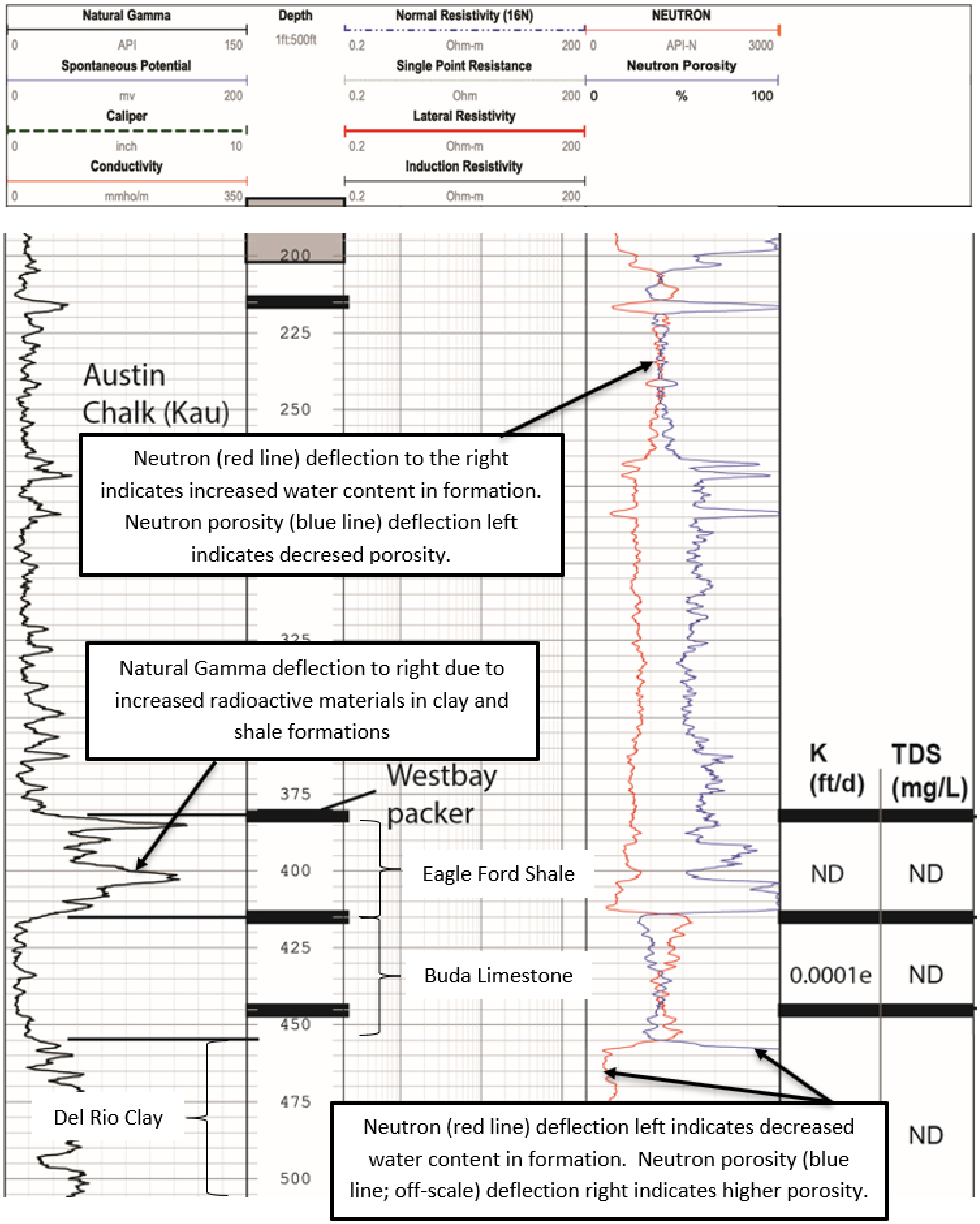


Figure 7-21. Log of borehole drilled in consolidated and unconsolidated materials within a fresh groundwater zone, showing natural gamma ray and neutron characteristics (source: Barton Springs Edwards Aquifer District).

The logging transition from fresh to brackish groundwater generally results in a change in geophysical log curves that needs to be understood by the user. Figure 7-22 shows the relationship between the natural gamma, SP, resistivity, neutron, and neutron porosity logs. Groundwater chemical analysis was also performed, along with hydraulic conductivity testing, and actual total dissolved solids and hydraulic conductivity values were obtained from each interval, shown on the right side of the geophysical logs. For the interval from 615 to 643 feet within the Person Limestone, the natural gamma log has low radioactivity typical of a limestone, and the resistivity logs indicate relative low resistivity compared to the drilling mud and a moderately saline total dissolved solids concentration of 9,857 mg/L. Within the same 615 to 643 feet interval, the neutron log deflects left indicating low relative water content, and the neutron porosity log deflects right indicating higher porosity. For this particular log, the neutron curve does not provide much useful information about formation boundaries, but the SP log does, as shown by the deflection left at 643 feet marking the transition between the overlying limestone formation and harder regional dense member below 643 to 680 feet. Within the regional dense member, the neutron curve deflection right indicates more water content than the overlying Person Limestone, but it has less porosity as indicated with the neutron porosity log. Although no groundwater sample was collected from the regional dense member interval (probably because the hydraulic conductivity was so low a sample could not be collected), the resistivity curves indicate that the groundwater was likely saline, compared to the resistivity curves and the total dissolved solids groundwater concentrations from groundwater samples below 680 feet.

Figure 7-23 shows the relationship between the natural gamma, resistivity, and nuclear magnetic resonance logs. The natural gamma log provides a good indicator of the formation contact between the upper Ogallala Formation at approximately 286 feet and the underlying silty/sandy clay unit. The natural gamma log deflection left indicates less radioactivity within the Ogallala Formation sand unit and more radioactivity within the clay unit. The resistivity logs within the Ogallala Formation deflect right, as the (fresh) formation water has more resistivity than the drilling mud. The nuclear magnetic resonance curve indicates mobile (recoverable) fluids above approximately 286 feet, and increased clay-bound (not recoverable) fluids below approximately 286 feet.

Figure 7-24 shows the relationship between the natural gamma, conductivity, resistivity, sonic, and nuclear magnetic resonance logs within a brackish groundwater zone. The natural gamma log deflections above approximately 800 feet and between approximately 910 to 925 feet indicate sand formations within the Dockum Formation. The resistivity logs are not particularly useful for discerning formation changes within the interval from approximately 900 to 930 feet, as the formation water and drilling mud have similar electrical resistance. However, the resistivity logs show greater separation from each other within the more permeable Dockum Formation sand from approximately 910 to 925 feet (separation between the single point resistance, lateral resistivity, 16-inch normal resistivity, and induction resistivity logs). The separation indicates more permeability within the 910 to 925 feet interval. A low-permeability (often called tight) zone would ordinarily be hard to discern from the natural gamma, resistivity, and conductivity curves. However, the nuclear magnetic resonance and sonic logs show good representation of a low-permeability zone from approximately 802 to 808 feet because the nuclear magnetic resonance log shows a drastic reduction in water content and the sonic log shows a denser interval. Higher conductivity (higher total dissolved solids concentrations) is indicated by the conductivity deflection right within the Dockum Formation interval from approximately 912 to 922 feet.

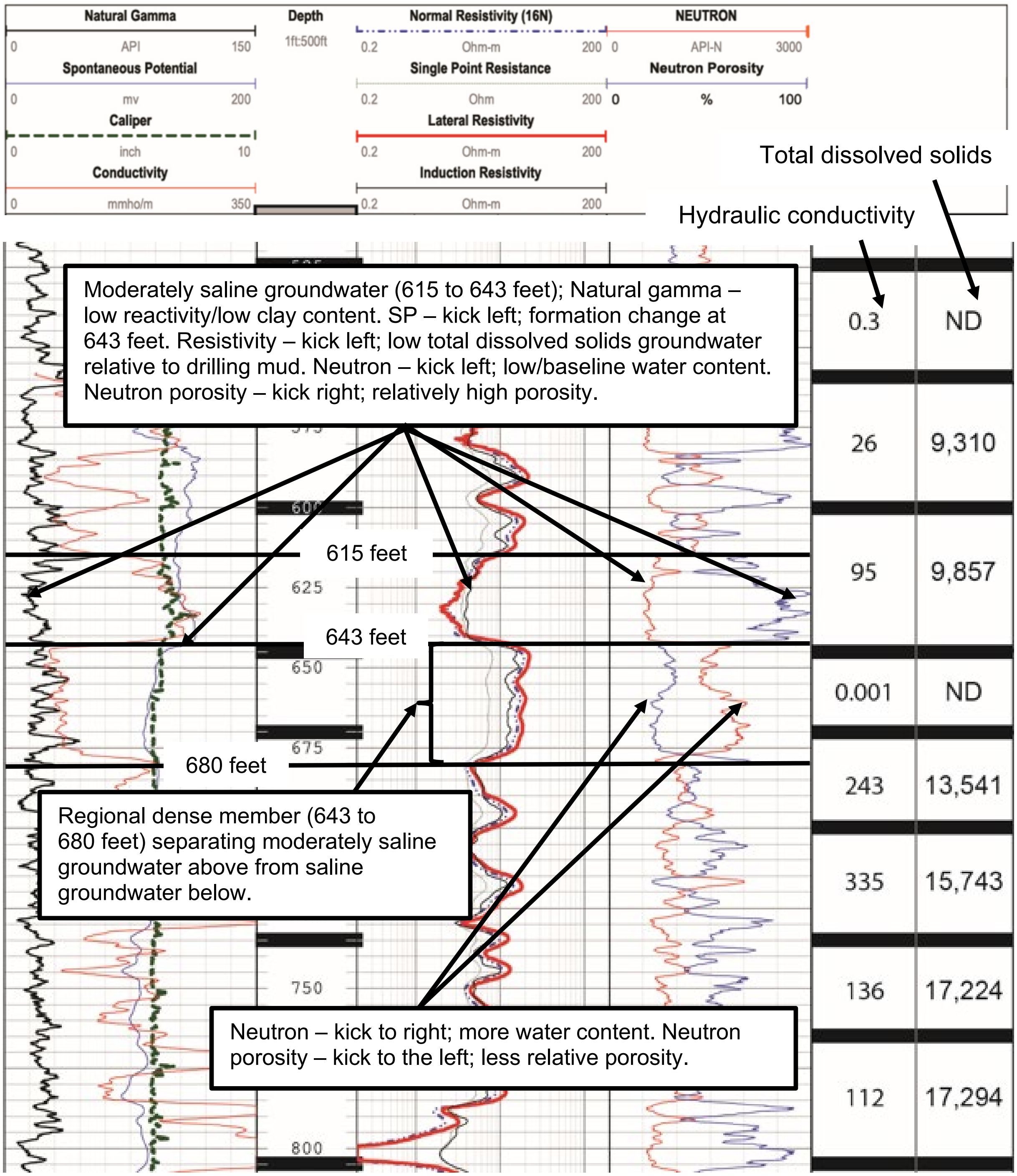


Figure 7-22. Log showing various log responses within a transition zone of a limestone interval (source: Barton Springs Edwards Aquifer District).

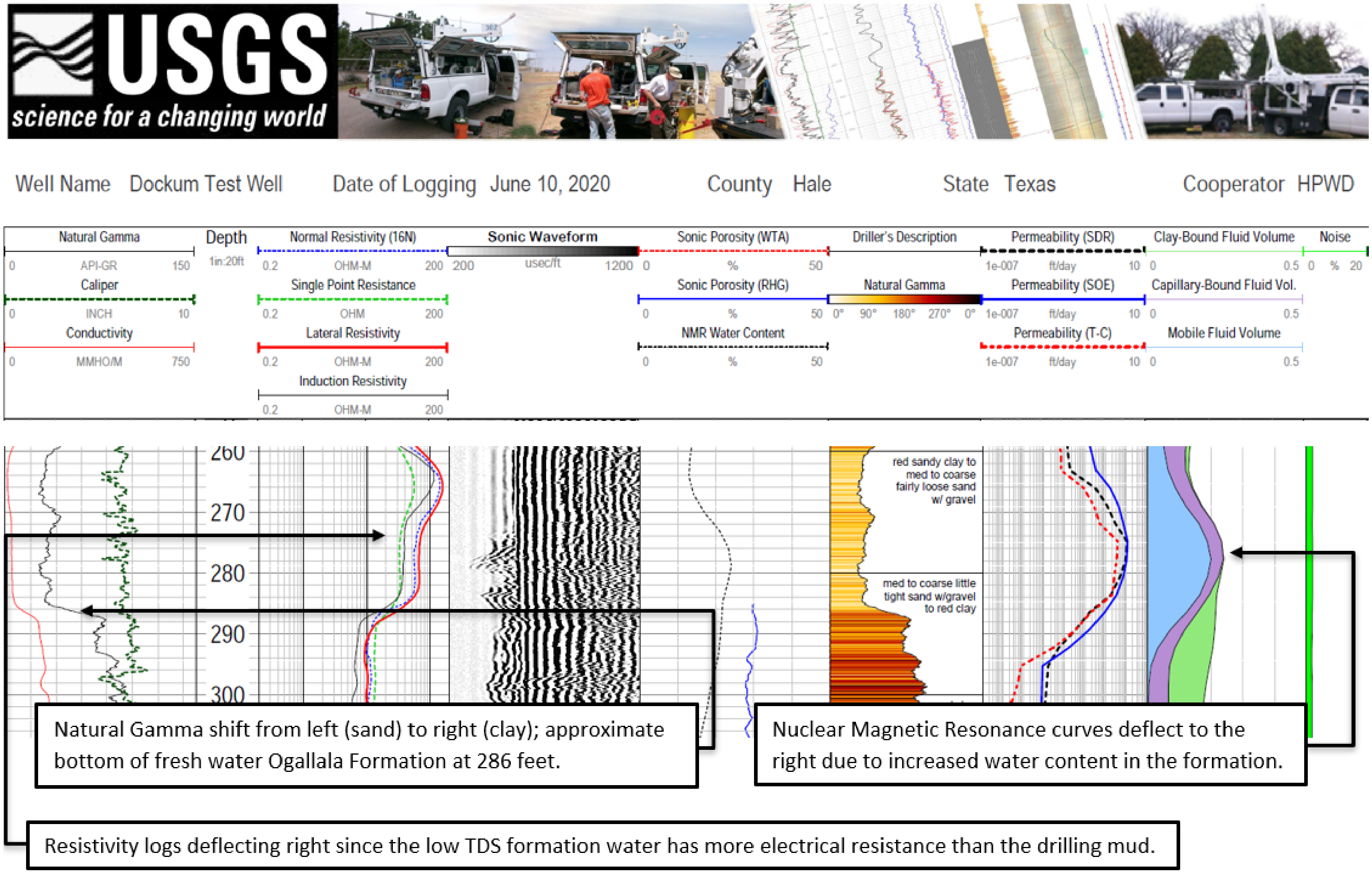


Figure 7-23. **Log of borehole drilled in unconsolidated formation materials within a fresh groundwater zone showing natural gamma ray, resistivity, induction log, and nuclear magnetic resonance characteristics (source: High Plains Underground Water Conservation District).**

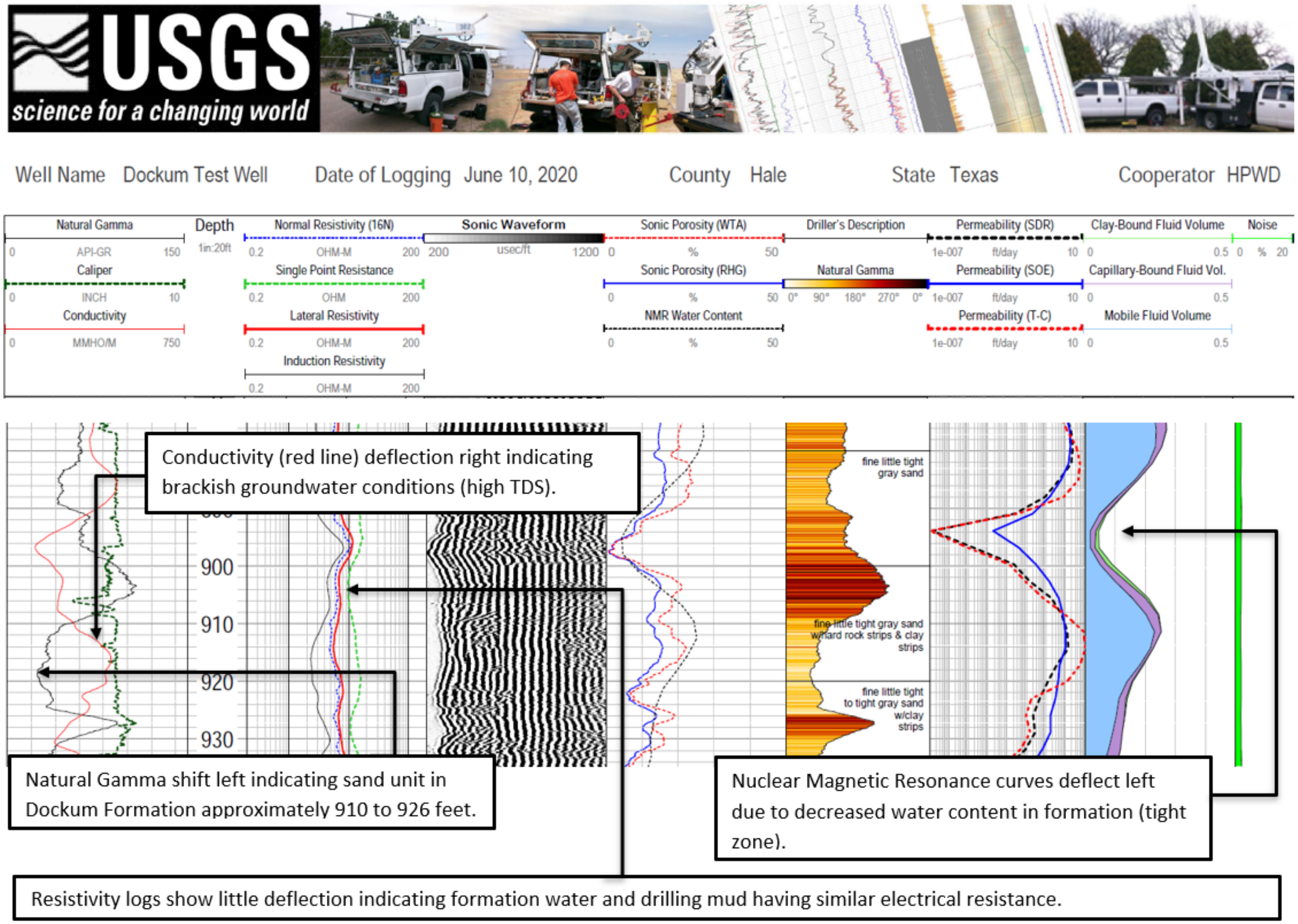


Figure 7-24. Log of borehole drilled in unconsolidated formation materials within a brackish groundwater zone showing natural gamma ray, conductivity, resistivity, and nuclear magnetic resonance characteristics (source: High Plains Underground Water Conservation District).

Figure 7-25 shows the relationship between the caliper, natural gamma, resistivity, and sonic logs within a brackish groundwater zone. The natural gamma log shows a sand unit from approximately 1,066 to 1,082 feet, and the caliper log shows a sand washout interval within the upper portion of the sand, from approximately 1,066 to 1,070 feet. The sonic log shows the density change between the overlying clay unit and the sand where the washout occurred.

Figure 7-26 shows idealized log responses relative to groundwater salinity in unconsolidated formations for resistivity and SP logs.

Figure 7-27 shows the relationship between optical, caliper, resistivity, temperature, and flow logs within a limestone formation. The optical log provides a direct image of the borehole sidewall, and the solution cavity at approximately 55 feet is confirmed by the caliper log showing a relative change of borehole diameter from 4 to 8 inches. The resistivity logs do not provide a direct indication of the solution cavity, but the temperature log shows about 1°F of temperature change, from 70.5°F to 70°F, below the solution cavity. The flow meter log at approximately 49 feet indicates water flow within the formation that is slightly downward above the solution cavity, which might indicate that the solution cavity is draining water from the borehole.

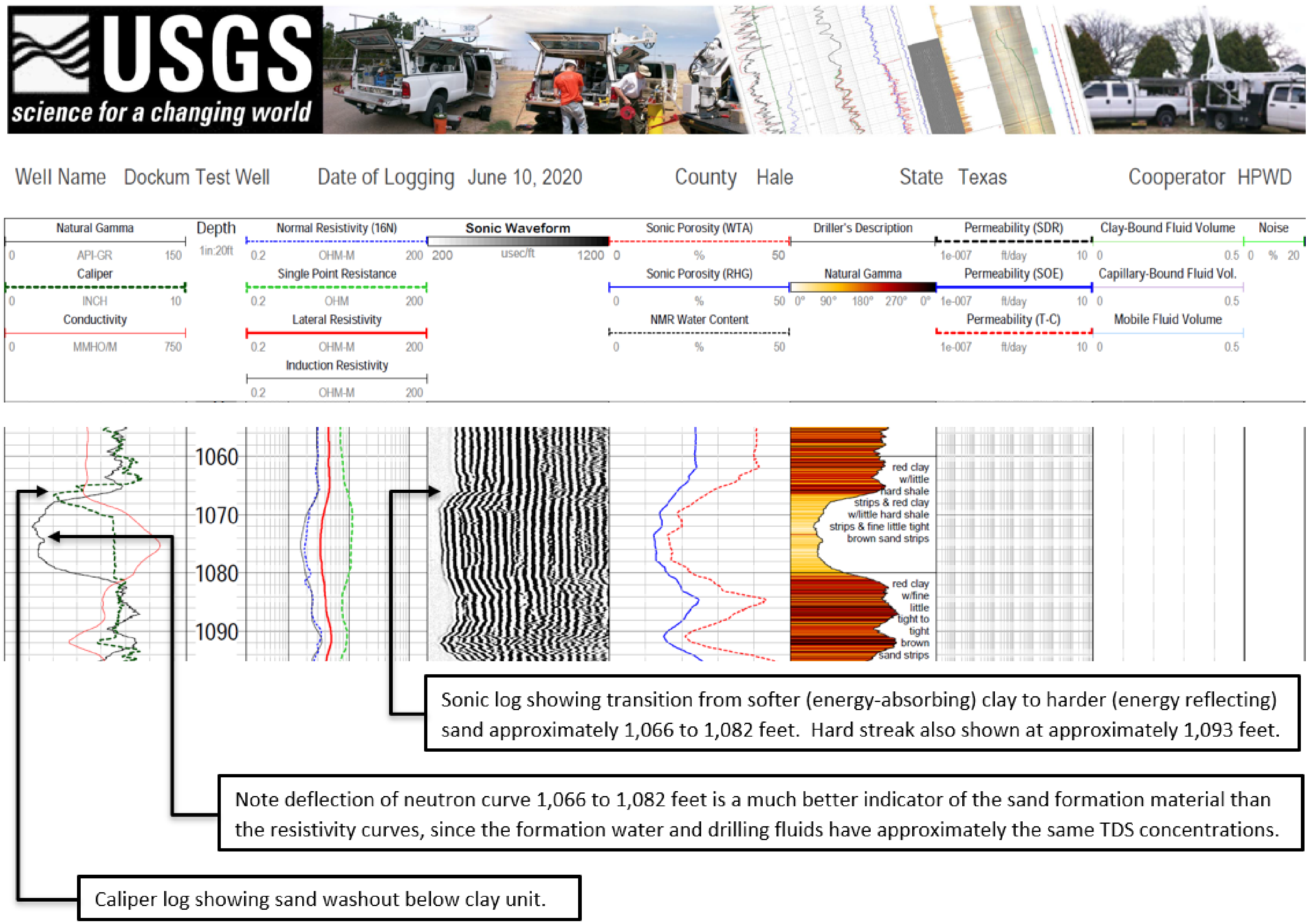


Figure 7-25. Log of borehole drilled in unconsolidated formation materials within a brackish groundwater zone showing caliper, sonic, and resistivity characteristics (source: High Plains Underground Water Conservation District).

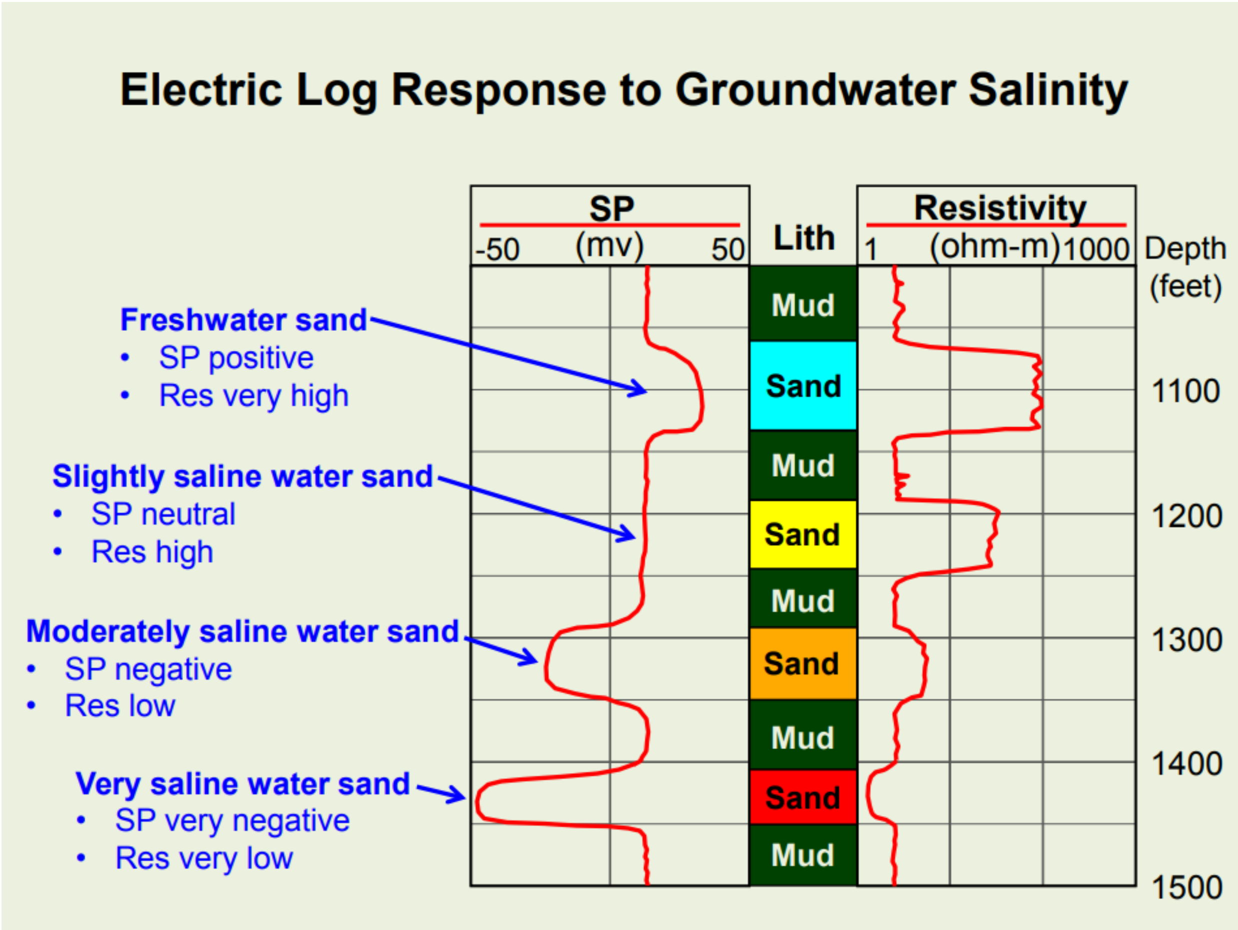


Figure 7-26. Schematic showing idealized SP and resistivity characteristics in unconsolidated formation materials under various salinity conditions (source: Introduction of TWDB Groundwater Availability Modeling Program, Queen City, Sparta, and Carrizo-Wilcox Aquifers).

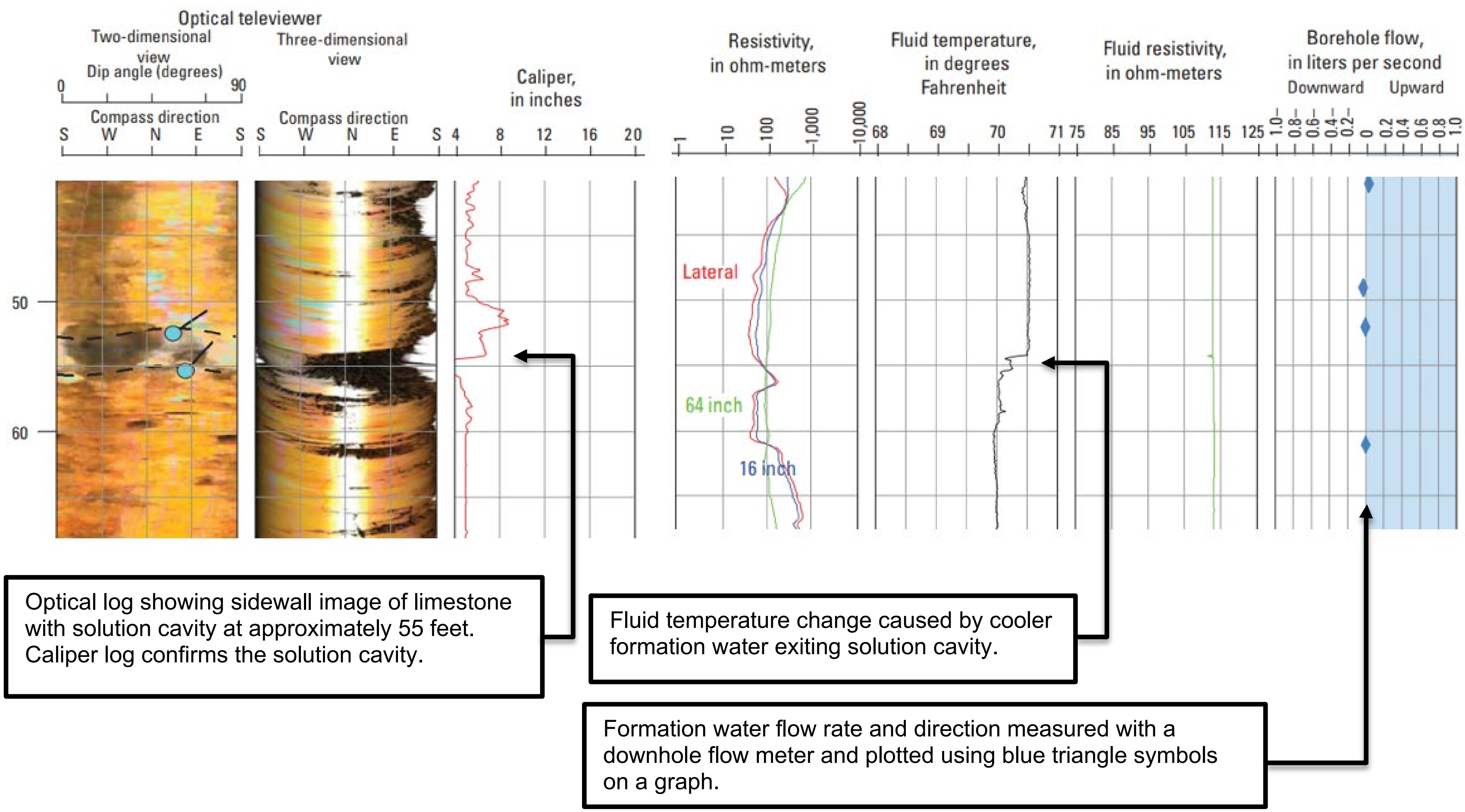


Figure 7-27. Optical, caliper, and fluid temperature logs used with a borehole flow graph to study flow characteristics within a well (source: Clarke and others, 2011).

7.7.2 Total Dissolved Solids Calculations from Geophysical Logs

Some modern geophysical logs automatically calculate (estimate) the formation total dissolved solids concentration and provide a continuous log curve of total dissolved solids concentrations relative to depth. The total dissolved solids concentration determines the groundwater salinity, which is a major component of brackish groundwater investigations. If available, geophysical methods that provide automatic calculation of total dissolved solids concentrations are recommended for brackish groundwater investigations; they can save significant time and effort by removing the need for manual calculations and will likely provide more accurate results. Automatic total dissolved solids calculations from modern geophysical logs use resistivity readings from the mud, mud filtrate, flushed zone, transition zone, uninvaded zone, temperature, and shale volume data from other logs run simultaneously during the logging operation.

In some cases, however, a more sophisticated geophysical logging suite may not be available or the project budget may not allow use of tools that automatically calculate total dissolved solids concentrations, and manual calculations may be required. There are numerous corrections that are applied to total dissolved solids calculations from geophysical logs based on the known groundwater chemistry (bicarbonate- vs. sodium chloride-dominated), types of resistivity tools used, tool calibration, tool electrode spacing, and formation temperature. This section describes a method for roughly estimating resistivity and corresponding total dissolved solids concentration assuming that no specific known total dissolved solids values are available in the study area (i.e., the initial pre-drilling data collection process described in Section 5 revealed no water quality data from the aquifer for comparison to the geophysical log).

Several brackish groundwater studies have been completed, and results of the investigations are available on the BRACS Program website (www.twdb.texas.gov/groundwater/bracs/index.asp). These reports provide total dissolved solids concentration estimates based on geophysical log values that provide the resistivity of the uninvaded zone.

Most resistivity and SP logs and many induction (conductivity) logs report results of water resistivity (R_W), sometimes called true resistivity, in units of ohm-m. Conductivity values (from induction logs) can be converted to resistivity values. The relationship between specific conductance (C_W) and R_W can be expressed in the following equation:

$$C_W\ (\mu\text{mhos/cm}) = 10{,}000/R_W\ (\text{ohm-m}) \qquad \text{Equation 7-1}$$

The resistivity ratio method (Alger and Harrison, 1998) is recommended for evaluation of total dissolved solids during brackish groundwater investigations intended for field use or use in the office shortly after geophysical logging is performed where no previous total dissolved solids information is available for the exploration interval.

The resistivity ratio method is practical for use in the field, although potentially less accurate if the formation is relatively thin (less than 10 feet) and contains abundant shale. The resistivity ratio (Alger and Harrison, 1989) compares the resistivity of the flushed zone (R_{X0}) with the resistivity of the uninvaded zone (R_0), knowing the resistivity of the mud filtrate (R_{mf}):

$$R_W = R_{mf} / (R_{X0}/R_0) \qquad \text{Equation 7-2}$$

For this method, no temperature, porosity, degree of cementation, pore structure, or surface conductance corrections are needed (Collier, 1993). The following steps are needed to calculate R_W:

Step 1: Calculate the resistivity of the drilling mud filtrate (R_{mf}). The resistivity of the drilling mud (R_m) may be recorded on the geophysical log header. If not, the mud weight may be recorded on the geophysical log header, and a conversion of mud resistivity (R_m) based on mud weight can be calculated. The weight of the drilling mud can be measured in the field using a mud scale (Figure 7-28). Measuring the mud weight on a daily basis is recommended, as the drilling mud weight and resistivity change during the drilling process.

Figure 7-28. Mud scale (source: DBS&A).

R_{mf} can be calculated from R_m using the conversion factor developed by Overton and Lipton (1958) explained by Collier (1993), based on (water-based) mud weight:

$$R_{mf} = K_m (R_m)^{1.07} \qquad \text{Equation 7-3}$$

where K_m = a constant derived from a table developed by Overton and Lipton (1958) (reproduced as Table 7-2)

Table 7-2. K_m values for various mud weights (source: Overton and Lipton, 1958).

Mud Weight (pounds/gallon)	K_m
10	0.847
11	0.708
12	0.584
13	0.488
14	0.412
16	0.380
18	0.350

For mud weights less than 11 pounds per gallon, K_m values were determined to be more variable (Lowe and Dunlap, 1986). Approximate K_m values for lighter muds are presented in Table 7-3.

Table 7-3. K_m values for various lighter mud weights (modified from Lowe and Dunlap, 1986).

Mud Weight (pounds/gallon)	Approximate K_m
8	1.01
9	0.94
10	0.84
11	0.76

Step 2: Determine the resistivity of the invaded zone (R_{X0}) and the uninvaded zone (R_0). Choose the interval of interest from the geophysical log, and record the values of R_{X0} and R_0 directly from the geophysical log (Figure 7-29). Specialized geophysical tools (focused pad microelectrode tools) are best for obtaining resistivity readings in the invaded zone, but are rarely used for groundwater exploration. If they are available, they should be used, but if not, the shallow-and deep-reading resistivity curves can be used (Collier, 1993).

If the formation is shaley, then R_0 and R_{X0} must be corrected (Alger and Harrison, 1998):

$$(R_{X0}/R_0)^{1/1-Vcl)} = (R_{X0}/R_0)_{clean} \qquad \text{Equation 7-4}$$

where R_{X0}/R_0 = log values uncorrected for shale (read directly from the geophysical log)

Vcl = clay volume (calculated or estimated from the SP curve or the gamma ray curve)

$(R_{X0}/R_0)_{clean}$ = log values corrected for shale

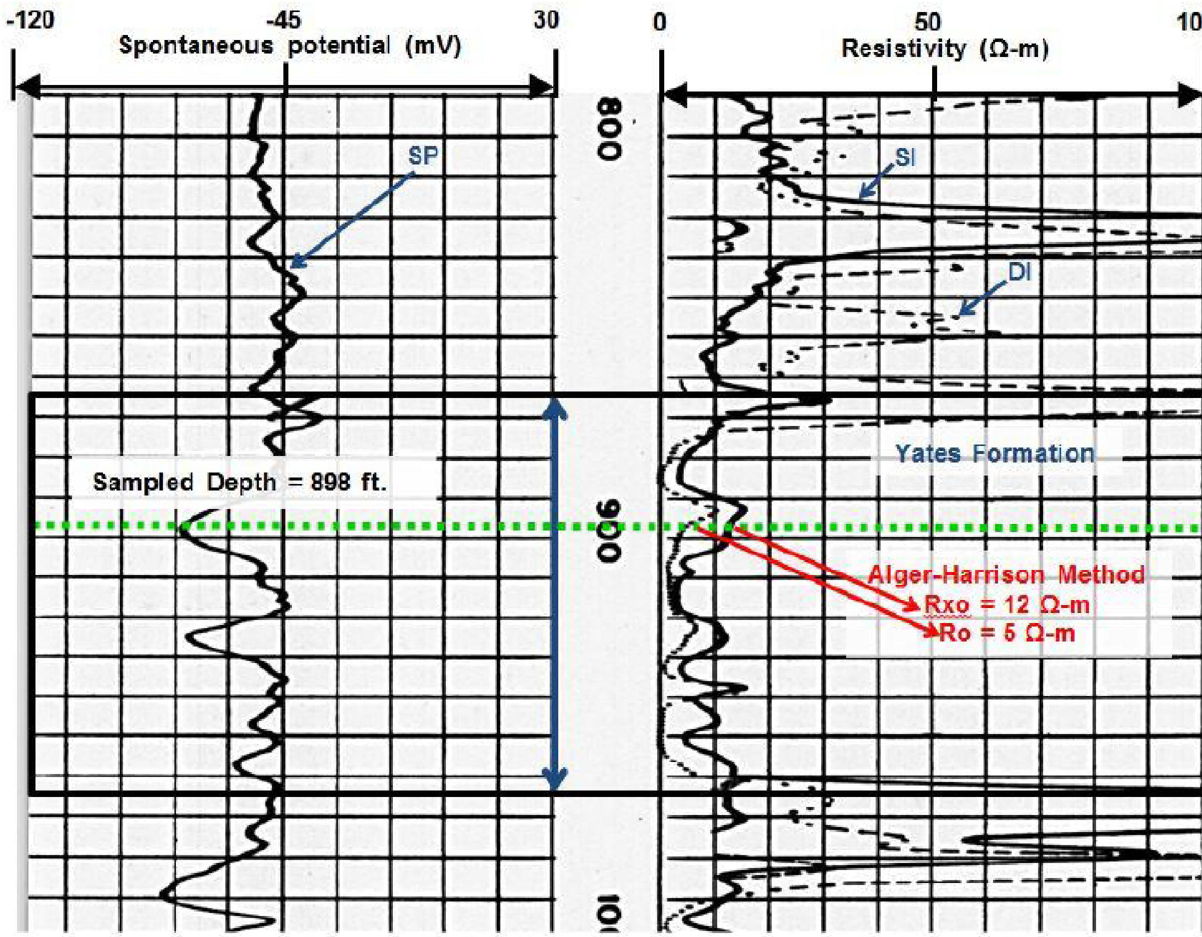


Figure 7-29. SP deflection to the left indicates a sand with a thickness greater than 10 feet. The corresponding shallow resistivity curve R_{X0} shows a resistivity reading of 12 ohm-m and the deep resistivity curve R_0 shows a resistivity reading of 5 ohm-m (source: Robinson and others, 2018).

Step 3: Calculate R_W (Equation 7-2) using the values calculated for R_{mf} (Step 1) and R_{X0} and R_0 (Step 2).

$$R_W = R_{mf} / (R_{X0}/R_0)$$

If the formation is shaley, substitute $(R_{X0}/R_0)_{clean}$ for (R_{X0}/ R_0) (Equation 7-4).

Calculate CW using the value of R_W (Step 3) in Equation 7-1:

$$C_W\ (\mu\text{mhos/cm}) = 10{,}000/R_W\ (\text{ohm-m})$$

The ct conversion factor represents the total dissolved solids concentration divided by the specific conductance, and is typically determined empirically from water quality samples. The ct conversion factor has a range of 0.55 to 0.75 for waters of ordinary composition up to total dissolved solids concentrations of a few thousand mg/L (Hem, 1985). However, for exploratory brackish groundwater investigations where there are no known previous data regarding the aquifer total dissolved solids concentration, a mean value of 0.65 can be used as an approximation.

Calculate the total dissolved solids concentration using the mean ct value (0.65) described above and the C_W value from Equation 7-1:

Total dissolved solids (mg/L) = ct (unitless) x C_W (µmhos/cm) Equation 7-5

7.8 Geophysical Log Correlation

Log correlation is the process of comparing two or more geophysical logs to each other and selecting formation tops and bottoms or zones of similar geologic composition, such as sand or limestone units. Geophysical log correlation may be useful during the pre-drilling data acquisition phase of a brackish groundwater investigation to estimate the depths to formations that might be desirable for exploitation. If the brackish groundwater source being investigated is large and the region of interest includes multiple exploratory boreholes, geophysical logs from the boreholes may be correlated across the study area to help define the subsurface formations. Using the example in Figure 7-30, if a new exploration boring or well were desired to be completed within the Carrizo Formation between the Guadalupe River and US 90 Alternate (highway), the depth of drilling could be estimated by correlating the Carrizo Formation between wells MWCZ-7 and MWCZ-3.

In this example, the gamma curve on the left side of the geophysical log and the resistivity curves on the right side of the geophysical log were used to correlate the bottom of the Carrizo Formation. It is generally better to use clay or shale strata for correlation markers because they are more likely to be regionally extensive (low energy depositional environments) than sand units, which are likely to be less regionally extensive. Clay or shale units often provide a more pronounced “signature” over larger correlation distances than sand units.

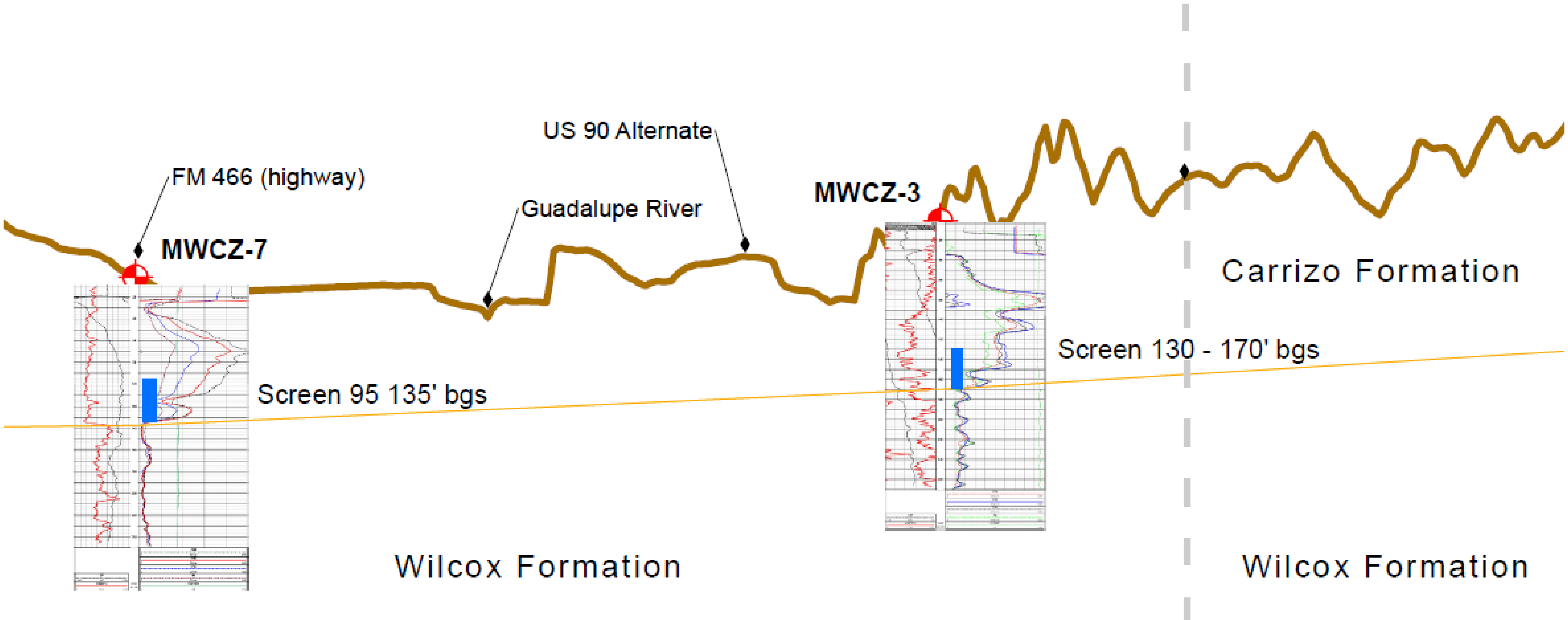


Figure 7-30. Example of log correlation (source: Gonzales County Underground Water Conservation District).

8 Data Collected After Well Completion

As described in previous sections, preliminary testing data are typically obtained during the installation of a brackish groundwater exploration borehole or well to obtain a general estimate of the brackish groundwater interval for potential production. However, after a brackish well has been installed and developed, additional testing should be performed to evaluate the brackish groundwater production zone water levels, water quality, and aquifer hydraulic properties in a more precise manner. In addition, long-term monitoring may also be conducted, where water levels and water quality are monitored over time. Long-term monitoring is performed because during production and over time, water levels, chemical composition, and hydraulic properties can change within a brackish groundwater production zone or within overlying and underlying aquifers.

The potential for impacting adjacent fresh water aquifers through the production of brackish groundwater may exist, depending on the location and hydraulic characteristics of the brackish aquifer, the fresh water aquifer(s), and the geologic formations or units that exist between them. The potential impact can be reduced by ensuring that suitable geologic confining formations separate the fresh water aquifer(s) from the brackish groundwater production zone, or that the brackish groundwater production zone is located a sufficient distance from the fresh water aquifer.

Brackish groundwater exploration investigations may include installation of monitor wells within fresh groundwater aquifers and may require a groundwater monitoring program for water level and water quality. Monitor wells may also be installed within low permeability confining zones to evaluate the effectiveness of the confining zones in limiting the hydraulic communication between the brackish aquifer and fresh water zones.

Some fresh water aquifers are not separated from a brackish groundwater aquifer by confining units. This may occur, for example, where fresh water occurs in an aquifer near recharge areas at or near land surface, but brackish water occurs in the same aquifer unit at depth, downdip and downgradient of the fresh water portion of the aquifer. In this situation, water level monitoring in the fresh water portion of the aquifer is needed. Long-term changes in water levels in the fresh water portion of the aquifer can be evaluated to determine whether the water level declines were caused by brackish groundwater production or if they were caused by pumping within the fresh water portion of the aquifer. Such assessments require (1) water level data in both the brackish and fresh water portions of the aquifer, (2) the production rates from the brackish groundwater project, and (3) groundwater production rates in the fresh water aquifer, which may also cause water level declines that can be misinterpreted to be caused by production from the brackish aquifer.

Groundwater models can be a valuable tool for evaluating both groundwater production from a brackish groundwater aquifer and the impact of the production on adjacent fresh groundwater resources. However, it is important to understand that this type of model requires a significant amount of data and can be challenging to construct, especially in areas where little data exists. The construction and use of groundwater models is beyond the scope of this document.

Long-term monitoring of water quality is also important for brackish groundwater projects. Groundwater production from a brackish groundwater resource may induce the migration of groundwater into the produced aquifer from formations above or below the production zone, or laterally from portions of the aquifer beyond the well field area. Groundwater that moves into the production zone over time may be of a different chemical quality than the groundwater evaluated when the test well was installed. Because source water quality is very important in brackish groundwater treatment system design and operation, it is important to understand whether changes in water quality are occurring. Figure 8-1 presents an example of regional chloride concentrations monitored over a period of 16 years at five well locations.

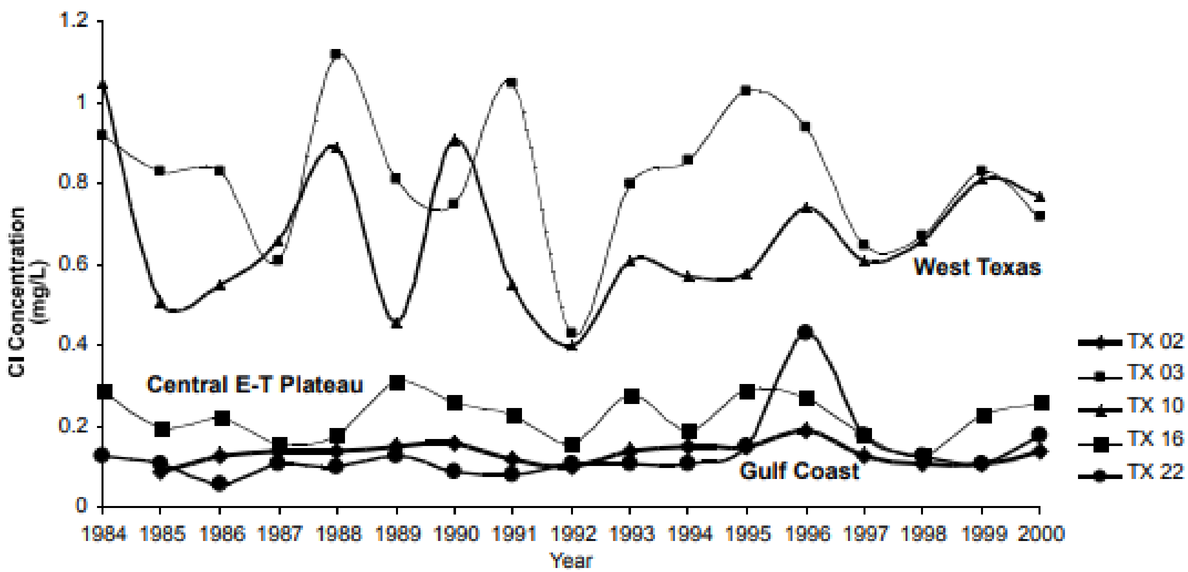


Figure 8-1. Example of groundwater chemical concentration monitoring over time (source: Mace and others, 2004).

8.1 Water Levels

A Field Manual for Groundwater-Level Monitoring at the Texas Water Development Board (Hopkins and Anderson, 2016) provides an excellent guide for collecting water level measurements. Water levels within exploration boreholes or wells can be measured accurately (within the closest 0.01 foot) using an electronic water level meter (Figure 8-2).

Figure 8-2. Electronic water meter. The probe is lowered down the well until the water level is reached, at which point the alarm (beeping noise) will be triggered (source: Solinst, 2021).

In unconfined aquifers, water levels within a well represent the depth in the formation where saturated, or "water table" conditions occur. In deeper aquifers overlain by confining (low-permeability) geologic formations, overburden pressure and other factors causes water levels in wells to rise above the top of the aquifer unit, often by a substantial amount. This situation is called a "confined aquifer," and water levels are said to occur under "confined aquifer conditions." In either case, the water level in the exploratory brackish well should be measured and recorded along with the date and time of the measurement. The point from which the depth to water was measured should also be clearly marked on the wellhead and recorded.

Water levels can also be recorded using a pressure transducer and data logger. A pressure transducer is installed in a well below the water level and measures the pressure at the transducer location attributable to the overlying water column and atmosphere. Transducers with "vented" cables can be used to eliminate the influence of changes in atmospheric pressure on the pressure reading. Transducers come with internal programs or external processing programs to convert the pressure readings to water levels (hydraulic head). Some transducers are constructed with a cable that connects to a data logger or computer at the ground surface (Figure 8-3), and others are small, self-contained, wireless (Bluetooth) units (less than 1 inch in diameter and about 4 to 5 inches long), that are pre-programmed and installed inside the well to the desired depth using thin suspension cables (Figure 8-4). The second type (no data cable from the transducer to the surface) needs to be extracted from the well to obtain the recorded data.

Figure 8-3. Pressure transducer with data cable being installed in a shallow monitor well (source: In-Situ, 2021).

Figure 8-4. Self-contained pressure transducer with built-in data logger. Suspension cable not shown. This type of transducer must be removed from the well in order to retrieve the recorded data (source: In-Situ, 2021).

Transducers can record thousands of data points at time intervals specified by the user. The use of pressure transducers is critical when a series of water level data points is needed over short periods of time, such as at the beginning of a falling head test or pumping test, when water levels change rapidly. Data collected by the data logger can be downloaded and used to prepare hydrographs (plots of water levels through time) for a variety of applications.

Noting the level of groundwater within separate production zones within multiport and nested wells during construction can provide clues about the quality of well construction. If the bentonite seals or inflatable packers between zones are not constructed or deployed properly, water can migrate between zones. If this happens between two production zones, for example, the water levels will stabilize to one "composite" level not representative of either zone. Hydraulic communication between two production zones may also occur naturally through faults or stratigraphic conduits. Poor construction practices of exploration wells can also allow groundwater seepage between overlying or underlying permeable zones to the screened interval(s) or open hole zone(s) of targeted production. Confirming the presence or lack of seepage between a given production interval and overlying or underlying aquifers in an exploration well can be difficult if nearby wells completed in the same zone are not available for comparison.

If a pump test is performed in an area where clustered or nested test wells have been installed, pressure transducers can be placed within each well (pumping well and adjacent monitoring wells) to evaluate the response of each production zone and/or overlying/underlying aquifers while pumping. Water level changes in production zones or aquifers that are not pumped during the test might indicate hydraulic communication between the production zones or aquifers. If monitoring of multiple aquifers or production zones is performed, transducer readings should be collected for as long as possible (at least a week is recommended) before and after pumping is performed to establish pre- and post-test trends. Also, the barometric pressure at the site should be monitored and recorded during the test, as changes in barometric pressure can influence water levels in wells.

Water levels collected over a limited period of time (if possible, within a single day) in multiple wells in an area or region can be used to construct a map of the water table (for unconfined aquifers) or the potentiometric surface (for confined aquifers). If at least three wells are completed within the same hydrologic zone, the direction of groundwater flow can be determined using the elevation of the static water levels in each well. The more wells that are measured, the more accurate the water level map becomes. After the water level map is constructed, the hydraulic gradient (slope of the water levels) can be measured. The direction of groundwater flow is often determined by drawing a line perpendicular to the potentiometric contours, with the direction of groundwater flow occurring from the high contour to the low contour. However, this approach may not be accurate in fractured or karst production zones. Knowledge of the groundwater flow direction can be useful for resource planning and better understanding groundwater quality.

Monitoring of water levels in the production well(s) can be used to predict potential future maintenance schedules to improve efficiency, as well efficiency typically decreases with time due to a variety of factors. Water levels collected from production well(s) can be used to calculate specific capacity (pumping rate divided by the change in water level during pumping) and available drawdown, both of which often change through time.

Water levels can also be monitored by creating hydrographs to assess changes in water storage in an aquifer over time. Hydrographs are graphs of water level changes over time. An example of multiple hydrographs for wells within the Dockum Aquifer is presented in Figure 8-5.

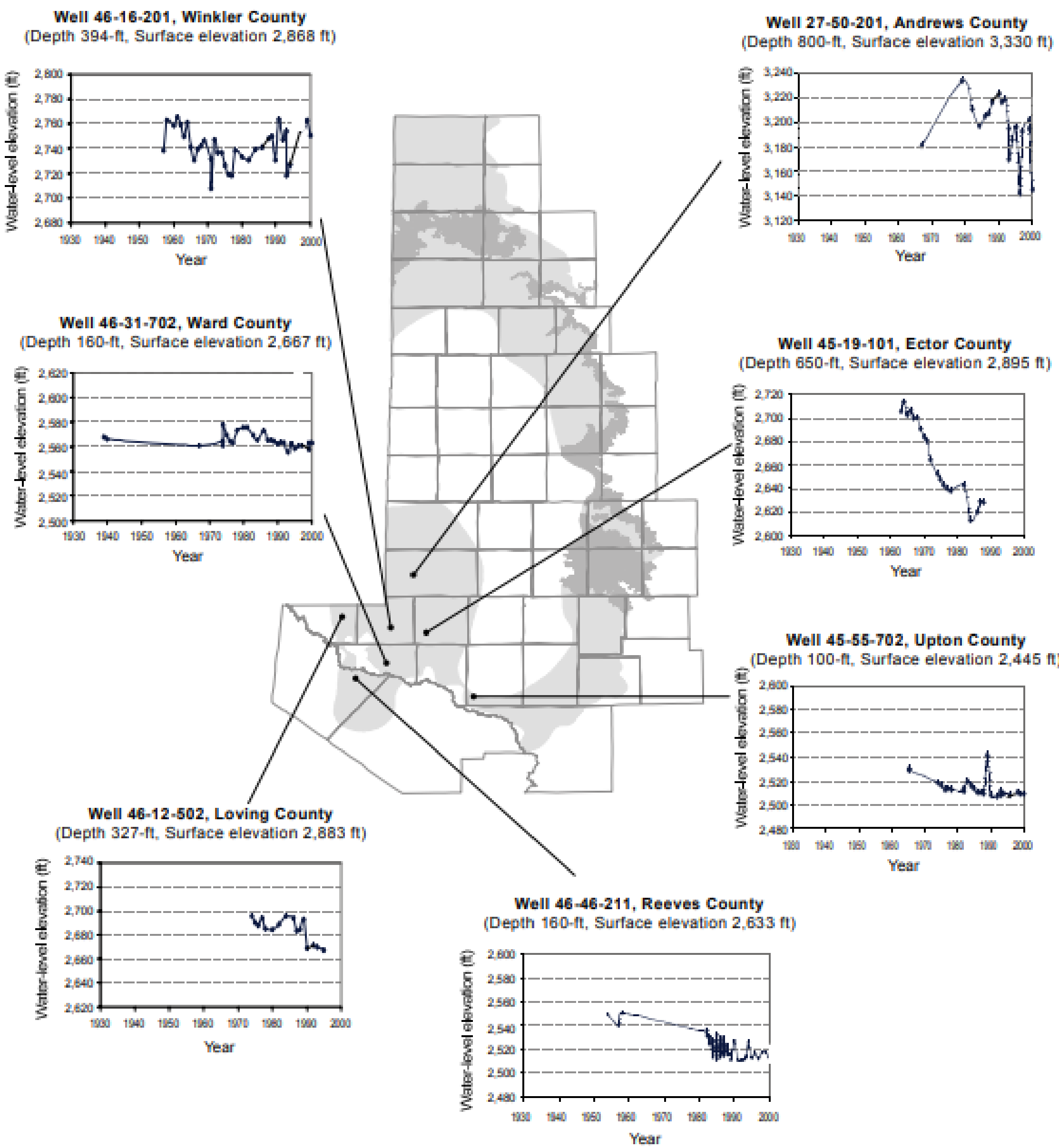


Figure 8-5. Example of hydrographs (source: Bradley and Kalaswad, 2003). These plots were used as a visual aid to evaluate water level trends in the Dockum Aquifer wells over long time periods.

8.2 Aquifer Hydraulic Testing

Complete well development of the desired production interval should be conducted before aquifer testing is performed (Section 3). If complete well development has not been accomplished prior to aquifer testing, the well will continue to develop during the test, and non-representative data will be collected. Falling head tests are simple and relatively short-duration methods for obtaining approximate hydraulic data, while pump tests are more complex and longer-duration methods for obtaining more accurate hydraulic data. Both types of aquifer testing methods evaluate the change in water levels through time, which can be evaluated using mathematical calculations to determine the aquifer hydraulic conductivity (K), transmissivity (T), specific capacity (SC), and well yield.

8.2.1 Falling Head Test

Falling head tests, or slug tests, are performed by introducing an instantaneous "slug" of water into the aquifer through a drill pipe/eductor setup (for zonal testing during drilling operations) or directly into a well casing from the ground surface in a completed well. Introduction of the slug causes the water level in the well to increase almost instantaneously, and the subsequent water level decline (fall) over time is measured. An alternate method of performing a slug test is to construct a solid cylinder of material (heavier than water with a known displacement volume) attached to a cable that is quickly lowered into the well to displace water in the well and raise the water level. The use of a solid cylinder also allows a "slug-out" evaluation of the water level response over time after the solid cylinder is removed (lowering the water level). Measurement of time and water level changes while performing falling head tests can be performed using a pressure transducer or an electronic water level meter and stop watch. Falling head tests can typically be performed in about two hours per zone tested.

8.2.2 Pump Tests

Pump tests can be performed in exploratory wells if the diameter of the casing is large enough to accommodate the necessary-sized pump, drop pipe, electrical leads, transducer/cable, and electronic water level meter probe. The transducer and cable are sometimes installed through a separate small-diameter access tube, and a separate access tube is sometimes installed such that a water level meter can be used to manually confirm water levels during the test. The access tubes prevent the transducer and water level meter from becoming tangled with other downhole components, and also lessen the effects of turbulence caused by the pump on the water level measurements. Aquifer testing using a pump can produce more accurate hydraulic test results than a falling head test described above because the pumping affects a greater volume of aquifer adjacent to the well bore. Pump tests for fresh water production wells where disposal of the pumped water is readily accommodated are typically performed for periods ranging from 8 to 72 hours or longer, and the tests are often conducted at pumping rates approaching maximum well capacity. However, for brackish well testing, disposal of the pumped water must be more carefully planned because the water may need to be fully captured and contained due to its quality. To reduce the cost of containing the pumped water, the pumping rate and/or pumping duration of the test may be reduced. Longer-duration pump tests generally provide more accurate aquifer test data. Step tests and constant rate tests are two types of pump tests.

8.2.2.1 Step Test

The purpose of a step test (sometimes referenced as a step-drawdown test) is to determine well efficiency and select an appropriate pumping rate and pump setting for both the constant rate pumping test and long-term production from the well.

To perform a step test, a well is pumped at progressively higher discharge rates for a time period sufficient for the observed drawdown rate to become approximately constant during each step. The well is pumped at a constant rate for a set period of time. After the specific period of time has elapsed, the pumping rate is increased and pumping continues for the same interval of time, and so on until all of the stages have been completed. Most step tests are performed with three to five stages. At least three stages of the step test are required to calculate well efficiency. It is common that one or more of the later stages cannot be conducted, or might only partially be conducted, because water levels in the well may approach the top of the pump intake.

Example results of a step test are provided in Figure 8-6. The step pumping rates were performed at 200 gpm incremental pumping rates, including 700 gpm, 900 gpm, 1,100 gpm, and 1,300 gpm. Each step pumping duration was 200 minutes (or 2 hours and 40 minutes), and the well was pumped at each of the rates listed above for the duration of each step.

To determine the target flow rate of the constant rate aquifer test and the long-term operational flow rate of the well, step test data are used to calculate the available drawdown and the specific capacity of the well. Available drawdown is the length of water column that the water level can drop below the static water level without damage to the pump motor. This length is typically from the depth to the static water level to a depth of about 20 feet above the top of the pump intake. Figure 8-7 presents the example step test water levels relative to ground surface and the top of the screened interval in the well. It is desirable to maintain the water level in the well above the top of the screened interval when possible.

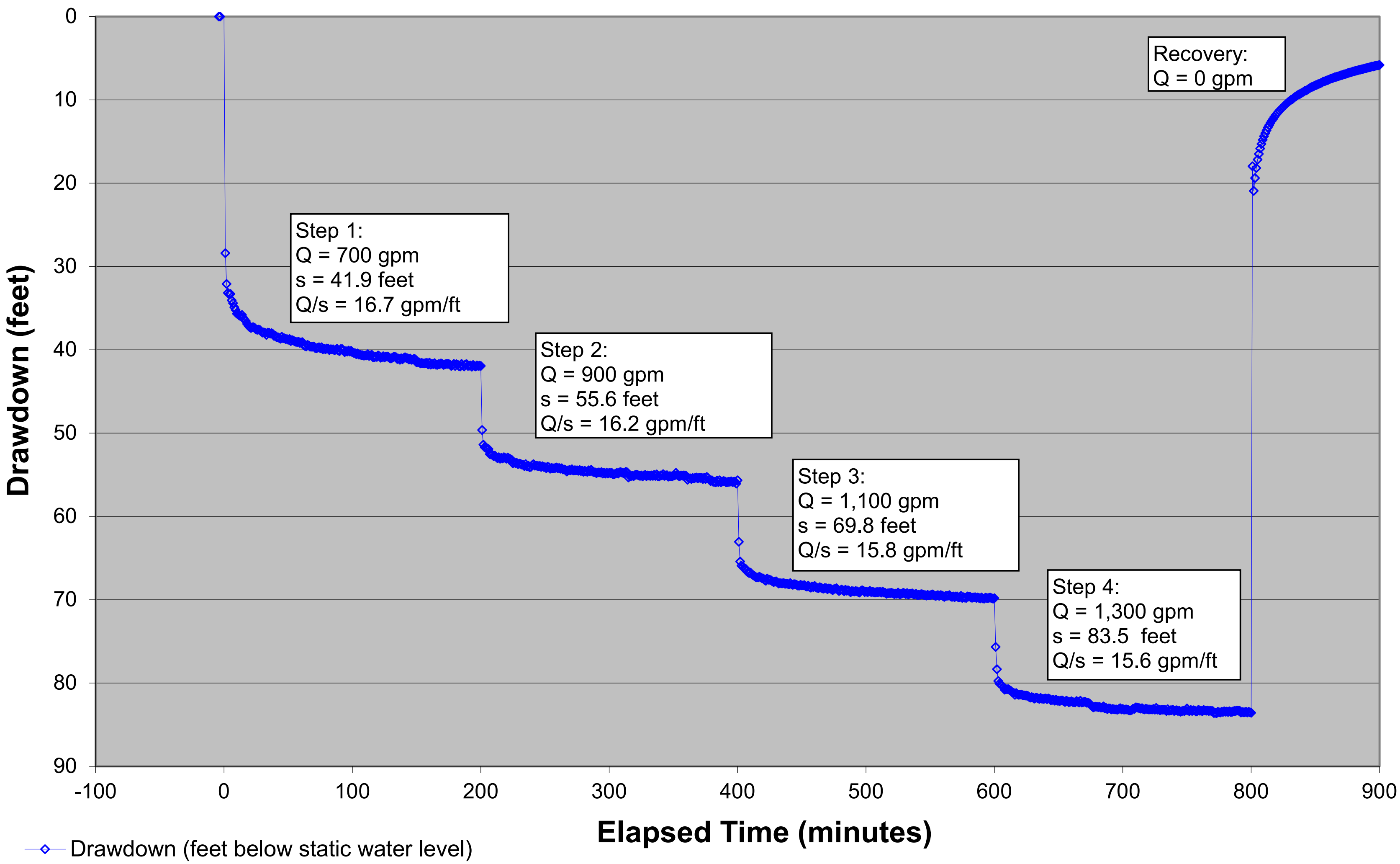


Figure 8-6. Example of a step drawdown test plot of drawdown versus time (source: DBS&A).

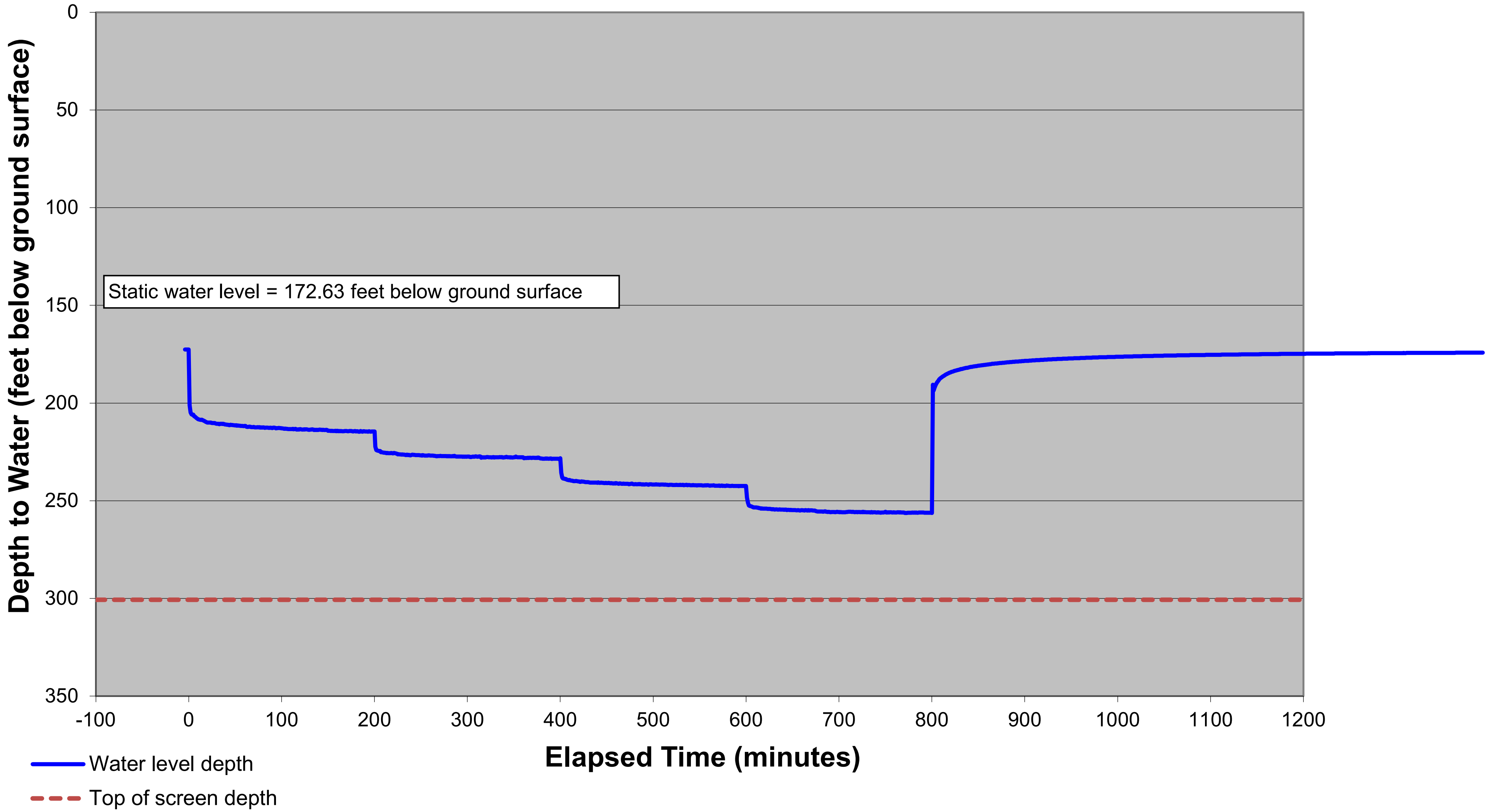


Figure 8-7. Example step drawdown data showing the water level depth versus time relative to a near-surface measuring point and the top of the screen interval (source: DBS&A).

The minimum water column required above the pump intake of about 20 feet is required to avoid cavitation (pumping of water mixed with air); the exact value can vary by pump and is listed on the pump curve. For example, if the depth to the pump is 290 feet and the depth to groundwater is 172 feet, the available drawdown would be 290 feet, minus 20 feet to avoid cavitation, minus 172 feet, or 98 feet.

Specific capacity is calculated and compared for each step of the test. Specific capacity is defined as follows:

$$SC = Q/s \qquad \text{Equation 8-1}$$

where SC = specific capacity (gallons per minute per foot [gpm/ft])
Q = discharge rate (gpm)
s = drawdown or change in hydraulic head while pumping (feet)

For the first stage of the step test example (Figure 8-6), the specific capacity is 16.7 gpm/ft. Specific capacity generally decreases when the rate of discharge is increased due to higher well losses. For example, for the last step of the example step test, the specific capacity is 15.6 gpm/ft.

The next step would be to calculate the maximum pump rate that would lead to the maximum available drawdown over the desired constant pump test duration. This calculation is conducted as follows:

$$\text{Maximum pump rate} = (\text{lowest specific capacity}) \times (\text{available drawdown}) \qquad \text{Equation 8-2}$$

which, in the current example, would be as follows:

$$\text{Maximum pump rate} = 15.6 \text{ gpm/ft} \times 118 \text{ feet} = 1{,}529 \text{ gpm}$$

The constant rate pump test flow rate will often be less than the maximum possible calculated pumping rate, although the pumping rate should be as high as feasible based on well and site conditions. If possible, the selected test rate should always be at least as high as, or higher than, the anticipated operational pumping rate.

8.2.2.2 Constant Rate Test

After the step test is performed and the target pumping rate for the constant rate pumping test is determined, a constant rate test is conducted by producing water at a constant rate and recording the changes in the water level during and after the test. The purpose of a constant rate test is to determine values for aquifer properties such as transmissivity, hydraulic conductivity, and storage coefficient; these properties are needed to determine the long-term production capability of the well over periods of years or decades. The constant rate test can also be used to identify potential hydrologic boundaries, such as faults, that impede the flow of groundwater.

The data collected during the constant-rate test are evaluated by plotting drawdown versus time. Figure 8-8 presents an example of a constant rate pump test.

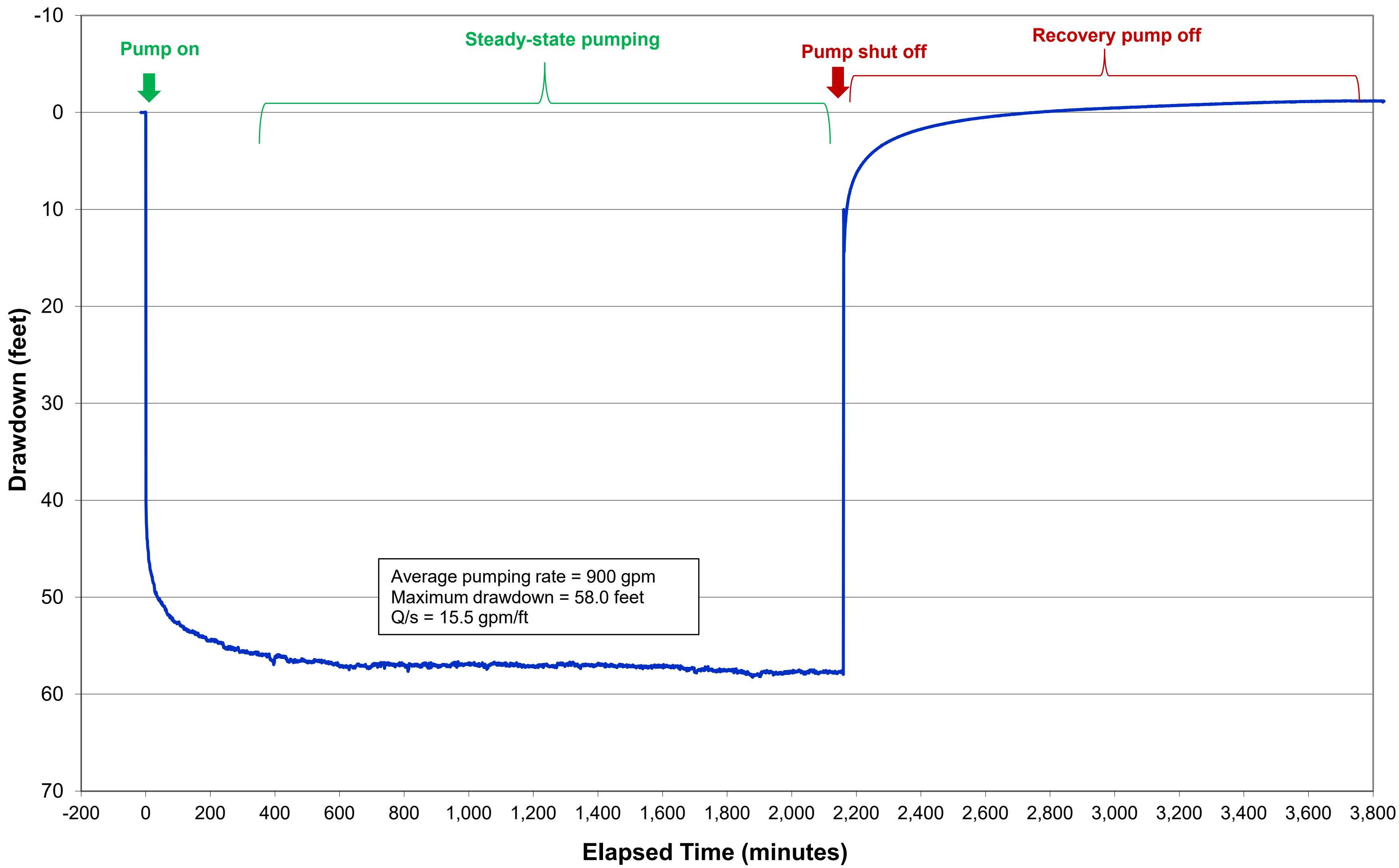


Figure 8-8. Example of a constant rate pumping test drawdown plot (source: DBS&A).

Frequent measurements during the early portion of the test (i.e., during the first several minutes after starting the pump) are particularly useful in determining aquifer properties. Collection of these early-time data is greatly facilitated by use of a pressure transducer. Test durations are commonly 24 to 72 hours. The duration of the pumping period is typically estimated prior to the constant rate test based on the data needs, available budget, and logistical factors such as water disposal. The water level recovery period is the period of time immediately after the pump is turned off. Water levels should be monitored during the recovery period until the pre-test level, or a value close to the pre-test level, is reached.

Groundwater professionals use the observed water level decline and recovery data to estimate aquifer hydraulic properties based on mathematical equations of groundwater flow. Explanation of these procedures is outside the scope of this document.

8.3 Water Quality Sampling

8.3.1 Groundwater Sampling Suite Selection

The type of water quality sampling needed to characterize brackish groundwater resources will depend on the intended use of the water. Brackish groundwater intended for human consumption will require treatment to meet state and federal drinking water standards. Table 8-1 provides a list of potential chemical and physical testing parameters that might be included in the sampling suite.

Table 8-1. Physical and chemical parameters of concern for desalination (modified from Meyer and others, 2011)

Physical Parameters	Chemical Parameters		
	Cations	Anions	Other
• Conductivity • pH • Silt Density Index • Temperature • Turbidity	• Aluminum • Arsenic (III) • Arsenic (V) • Barium • Calcium • Copper • Ferrous iron • Ferric iron • Potassium • Magnesium • Manganese • Sodium • Ammonium • Nickel • Strontium • Zinc	• Chlorine • Carbonate • Fluoride • Bicarbonate • Nitrite • Nitrate • Hydroxide • Sulfate	• Alkalinity • Boron • Dissolved oxygen • Hydrogen sulfide • Hardness • Pesticides • Radionuclides • Dissolved silica • Total dissolved solids

8.3.2 Groundwater Sampling

A Field Manual for Groundwater Sampling (Boghici, 2003) provides an excellent guide for groundwater sampling. Groundwater quality samples should be collected following development of the well using the methods described in Section 3 and near the end of the constant rate aquifer test. If only one sample is collected, then collecting a sample near the end of the constant rate aquifer test is best. If for some reason water sampling is not scheduled immediately after development or during aquifer testing, the well will need to be purged prior to groundwater sampling. After determining the suite of analysis needed to meet the project objectives, a sample “kit” should be obtained from a State of Texas accredited analytical laboratory prior to the collection of samples. The sample kit typically consists of a thermally insulated cooler, sample containers (bottles, jars, vials, etc.), sample labels, chain of custody (COC) forms, COC seals, and a heavy-duty plastic bag to contain the samples during shipping. If the sample location is relatively close to a laboratory, the samples can be hand-delivered rather than shipped, and some of the special packaging precautions for shipping can be reduced. The sample containers are typically certified “clean” by the laboratory, and should only be handled in clean environments and with the sample team’s hands covered with nitrile gloves to avoid contamination of the samples.

Some sample containers will likely contain a small quantity of acid preservatives. The sample collection team should be aware of these preservatives and avoid skin and eye contact. Also, the sampling team should avoid overfilling the sample containers such that the preservatives are washed out. It is generally best to collect water samples directly from the discharge stream of the well through a sampling port.

Some laboratories provide sample labels pre-attached to the sample containers, and some laboratories provide loose labels that can be completed and attached to the containers after the water samples are collected. For labels that are pre-attached, it is useful to fill out the sample information before sampling begins using an indelible ink pen, such as a fine Sharpie™, as adding information to the label after water samples are collected might be difficult if the label becomes wet. This is not generally an issue if loose labels are provided and are kept in a dry location. During the sample labeling process, the chain of custody form should also be completed.

When sampling is complete, all samples should be placed within the heavy-duty plastic bag with as much ice as possible, and then placed in the thermal cooler. The cooler must arrive at the laboratory at a temperature below 4 degrees Celsius (°C) (39.2°F). The unused portion of the plastic bag should be twisted as tightly as possible and tied to prevent it from leaking during shipping. After the sampler’s copy of the chain of custody form is signed and retained, the remaining pages of the chain of custody form are contained within a large zip-lock bag and taped to the inside lid of the cooler. The sample cooler custody seals are attached to the cooler where the cooler lid meets the cooler body, and the entire package is taped securely with multiple layers of tape, such that the cooler will not open during transportation. The final step is to transport the cooler to a shipping facility for expedited delivery to the laboratory, or deliver by hand. Samples with ice must be shipped overnight for arrival the next day to maintain the required temperature.

9 Miscellaneous Issues

There are other issues that should be considered when planning an exploratory brackish test well program not covered in the previous sections. Some of these issues can be significant, potentially increasing the cost of the project substantially.

9.1 Drilling Site Selection and Preparation

The size of the drilling site will depend on the size of the drilling equipment needed, which will depend on the anticipated depth of drilling and nature of the formations penetrated. Larger drilling rigs may require mobilization in individual components, and include a rig pad/drill floor, mud pits and shale shakers for removing drill cuttings, water truck, pipe rack, air compressors, well supplies/supply trailers, generators, backhoe or all-terrain forklift for digging pits and moving materials, driller's quarters, and support vehicles. For larger drilling rigs, a site approximately 1 acre in size may be needed to stage and move the equipment and materials. For smaller truck-mounted drilling rigs with minimal support vehicles, equipment, and materials, a site approximately 100 feet square may be adequate. Temporary access roads and gates may also need to be constructed. The drilling contractor can provide drill pad size requirements.

Drilling is an inherently messy operation, and moving large equipment around can cause damage to the ground surface, either to unimproved land or to asphalt or concrete. Provisions for complete site restoration should be calculated into the project budget, including removal of drill cuttings and waste materials, leveling and site grading, re-sodding or landscaping, and repaving broken or damaged asphalt or concrete.

Subsurface and overhead utilities must be identified prior to mobilization of drilling equipment. Overhead utilities may need to be moved or shielded from potential contact with drilling equipment.

9.2 Permits and Regulations

Special permits may be required for drilling exploratory boreholes and wells. Depending on the location of the site, drilling permits from a city, county, or groundwater conservation district may be required prior to initiation of drilling operations. There are approximately 100 groundwater conservation districts in Texas, each with a different set of rules governing permitting. A recommended approach for ensuring compliance with exploration activities within a groundwater conservation district would be to contact the district office and discuss the brackish groundwater project being considered, and inquire about their regulations. It is important to include the local district in the planning stages of a brackish groundwater exploration project, as they are a very good source of information on the groundwater resources in their jurisdictions, and will have a good understanding of a variety of other issues that may arise during a brackish groundwater exploration project (Section 5).

Larger drilling rigs typically use work crews that work in non-stop shifts, continuously drilling during the day and night. A review of local ordinances should be performed to confirm authorization for non-stop work in relation to noise and possibly light restrictions. Special city and/or county permits may be needed for drilling. Special permits for hauling heavy equipment to the site may also be needed, including a traffic control plan. Authorization and payment for use of public water may be needed for preparation of drilling fluids. Emergency response and community notification plans should be prepared if drilling through potential pressurized natural gas zones or zones with potential sour gas.

9.3 Waste Disposal

Brackish groundwater exploration could potentially generate large volumes of drilling mud (if mud-rotary drilling methods are used) and/or brackish groundwater produced during drilling, well development, and aquifer testing. When drilling and testing a fresh groundwater well, disposal of produced groundwater may be possible on-site. However, due to the nature of brackish groundwater exploration, produced brackish groundwater likely cannot be disposed of on-site, and therefore consideration must be given to where and how disposal of this water will be conducted. Disposal costs can be very expensive depending on where the water will be disposed of and how the water will be transported to the disposal site; therefore, the calculation of waste characterization, transportation costs from the site to the disposal facility, and the cost per gallon for disposal should be considered. For example, for the Brown County Water Improvement District case study included in Appendix C, flowing artesian conditions were encountered during drilling, and an additional $100,000 was required to transport this fluid to the disposal facility.

The disposal facility identified for a project may be an oilfield disposal well. Oilfield disposal well operators are somewhat particular about the fluids that are disposed of in their wells, and chemical analysis of the fluids may be necessary before the fluids are accepted for disposal. In some cases, fluids that are brackish and not saline or brine could damage the disposal well injection zones (through clay or shale swelling). Before a drilling project begins, it is important to be aware of potential restrictions associated with the disposal facility identified.

10 Acknowledgements

We acknowledge and thank the following individuals and their organizations for providing information and explanation regarding their brackish groundwater characterization, drilling, and monitoring projects.

- Mr. Jason Coleman, General Manager, High Plains Underground Water Conservation District, Lubbock, Texas.
- Mr. Brian Smith, Principal Hydrogeologist, Barton Springs/Edwards Aquifer Conservation District, Austin, Texas.
- Mr. John Allen, General Manager, Brown County Water Improvement District, Brownwood, Texas.

The contributions of these individuals and their organizations added significantly to the content of this document.

Hypothetical drilling and well installation pricing described in Section 4 was requested from nine companies, and four provided pricing despite their busy schedules. We wish to thank Harrison & Cooper Inc., Stewart Brothers Drilling Company, Yellow Jacket Drilling Services, and a fourth company that wished to remain anonymous.

11 References

Alger, R.P. and C.W. Harrison, 1998, Improved fresh water assessment in sand aquifers utilizing geophysical well logs: *The Log Analysis* 30(1): 31-44.

Australian Drilling Industry Training Committee Limited, 1997, Drilling: The manual of methods, applications, and management: CRC Press, Boca Raton, Florida.

Bradley, R.G. and S. Kalaswad, 2003, The groundwater resources of the Dockum Aquifer in Texas: Texas Water Development Board (TWDB) Report 359, December 2003.

Boghici, R., 2003, A field manual for groundwater sampling: TWDB User Manual 51, March 2003.

Clarke, J.S., M.D. Hamrick, and O.G. Holloway, 2011, Borehole geophysical and flowmeter data for eight boreholes in the vicinity of Jim Woodruff Lock and Dam, Lake Seminole, Jackson County, Florida: U.S. Geological Survey Open-File Report 2011–1254, 25 p.

Collier, H.A., 1993, Borehole geophysical techniques for determining the water quality and reservoir parameters of fresh and saline water aquifers in Texas: TWDB Report 343, June 1993.

Conger, R.W., 1998, Evaluation of geophysical and borehole video logs at the Lehigh Electric Superfund Site, Lackawanna County, Pennsylvania: U.S. Geological Survey Administrative Report prepared for the U.S. Environmental Protection Agency.

Dewan, J.T., 1983, Essentials of modern open-hole log interpretation: PennWell Books.

Driscoll, F.G., 1986, Groundwater and wells, Second edition: Johnson Screens, 1089 p.

Gilmore, T.J., 1989, The installation of a multiport ground-water sampling system in the 300 Area: Prepared by Pacific Northwest Laboratory for the U.S. Department of Energy under Contract DE-AC06-76RLO 1830, June 1989.

Glotfelty, M.F., 2019, The art of water wells: Technical and economic considerations for water well siting, design, and installation: National Ground Water Association Press, 174 p.

Great West Drilling, 2021, Images of Becker hammer drilling on company website, Accessed July 2021, <https://www.greatwestdrilling.com/becker_hammer_drilling.php> and <https://www.greatwestdrilling.com/becker_hammer_drilling_method.php>.

Hem, J.D., 1985, Study and interpretation of the chemical characteristics of natural water, Third edition: U.S. Geological Survey Water-Supply Paper 2254.

Hopkins, J. and B. Anderson, 2016, A field manual for groundwater-level monitoring at the Texas Water Development Board: TWDB User Manual 52, September 2016.

In-Situ, Inc., 2021, Product images from company website, Accessed July 2021, <https://in-situ.com/en/>.

LBG-Guyton Associates (LBG-Guyton), 2003, Brackish groundwater manual for Texas regional water planning groups: Prepared in association with NRS Consulting Engineers for the TWDB, February 2003.

LBG-Guyton, 2008, Brackish groundwater exploration guidance manual: Prepared in association with Freese and Nichols, Inc. for the Upper Colorado River Authority and TWDB, April 2008.

Lowe, T.A. and H.F. Dunlap, 1986, Estimation of mud filtrate resistivity in fresh water drilling muds: The Log Analysis 27(2): 77-84.

Mace, R.E., C. Ridgeway, and J. Sharp, 2004, Groundwater is no longer secret and occult—A historical and hydrological analysis of the East case: TWDB Report 361, Conference Proceedings 100 Years of Rule of Capture: From East to Groundwater Management.

Meyer, J.E., M.R. Wise, and S. Kalaswad, 2011, Pecos Valley Aquifer, West Texas: Structure and brackish groundwater: TWDB, September 6, 2011.

Nicot, J.-P., S. Walden, L. Greenlee, and J. Els, 2006, A desalination database for Texas: Prepared for TWDB under Contract No. 2004-483-021, Bureau of Economic Geology, University of Texas at Austin, Austin, Texas, Initial Issue October 2005, Revised October 2006.

Nielsen, D.M. (Ed.), 1991, Practical handbook of ground-water monitoring: CRC Press.

Overton, H.L. and L.B. Lipson, 1958, Correlation of electrical properties of drilling fluids with solids content: Transactions of AIME 213: 333-336.

R.W. Harden & Associates, Inc. 2013. Guidance manual: Fiberglass casing use in Texas public supply wells: Prepared in association with Norris Leal PLLC for the TWDB, April 2013.

Rider, M., 1996, The geological interpretation of well logs: Rider-French Consulting, Ltd.

Robinson, M.C., M.L. Webb, J.B. Perez, and A.G. Andrews, 2018, Brackish groundwater in the Lipan Aquifer Area, Texas: TWDB Report 384, January 2018.

Solinst, 2021, Product images for water level indicator, Accessed July 2021, <https://www.solinst.com/products/level-measurement-devices/102-water-level-indicator/images/102-p10.jpg>.

Sterrett, R.J. (Ed.), 2007, Groundwater and wells, Third edition: Smyth Co Inc.

Texas Water Development Board (TWDB), 2020, The future of desalination in Texas: 2020 biennial report on seawater and brackish groundwater desalination in Texas: 87th Texas Legislative Session, December 1, 2020.

Texas Water Development Board (TWDB), 2021, Water for Texas- 2022 State Water Plan; adopted by the TWDB on July 7, 2021.

WDC Exploration & Wells, Undated, Brochure describing air rotary casing hammer system, Downloaded from <wdcexploration.com>.

Westbay Instruments, 2021, Brochure: “Westbay System,” Accessed July 2021, <https://westbay.com/wp-content/uploads/2017/05/WestbaySystemBrochure20155.pdf>.

Winslow, A.G. and L.R. Kister, 1956, Saline-water resources of Texas: One state's reserves of saline water – A potential water reserve: U.S. Geological Survey Water-Supply Paper 1365.

Appendix A. Exploratory Borehole Case Study: High Plains Underground Water Conservation District

With Ogallala Aquifer water levels declining throughout much of the Texas high plains, many landowners and public water suppliers have shown interest in the Dockum Aquifer, which lies beneath the Ogallala Formation in much of the southern High Plains region. Although groundwater in the Dockum Aquifer is brackish in most of the region, there are portions of the aquifer that produce better quality water. Consequently, the Dockum Aquifer is increasingly being viewed as a potential source of groundwater to serve municipal, industrial, and irrigation uses. In 2015, the High Plains Underground Water Conservation District No. 1 (HPUWCD) Board of Directors approved a study to evaluate the Dockum Aquifer within the district. This ongoing, multi-faceted study includes the Dockum Aquifer Partnership Program, a program in which the HPUWCD provides funding for Dockum Aquifer exploratory test borings and test wells throughout the district. The District has so far funded four brackish groundwater exploration borings and test wells, and an additional two are scheduled to be drilled in 2021. These exploration borings and test wells are specifically designed to determine the character of the Dockum Aquifer and the quantity and quality of the groundwater contained in the aquifer within the HPUWCD boundaries.

The fourth site evaluated under the program was at a dairy in Hale County. At this site, located about 4 miles west of the Town of Edmonson in northwestern Hale County, an exploration test boring was drilled to collect data on the brackish Dockum Aquifer. The following description of the project is based on personal communication with Jason Coleman of the HPUWCD in April 2021, and a summary of the project given in a presentation to the HPUWCD board of directors.

This project consisted of only a test boring; no test well was planned. In June 2020, a 6-inch, 1,320-foot test boring was drilled by Hydro Resources to the base of the Dockum Aquifer. Cuttings were collected every 5 feet for evaluation by on-site geologists. After the test hole was drilled to its total depth, geophysical logging was conducted by the U.S. Geological Survey (USGS). This logging consisted of the USGS's standard suite of geophysical logs—natural gamma, caliper, conductivity, and resistivity—as well as sonic and nuclear magnetic resonance (NMR) logs. The full length of the borehole was logged with the geophysical tools with the exception of the NMR tool, which could not be lowered past 935 feet in the boring. Even though the borehole was subsequently cleaned out, the 3.5-inch-diameter, 14-foot-long NMR tool was still unable to pass the 935-foot depth. This was most likely due to the length of the tool, combined with a borehole that likely deviated from vertical and/or possibly had swelling clays. Upon completion of testing and logging, the exploratory test borehole was plugged.

Cuttings samples collected during drilling and geophysical logging of the boring showed that the Dockum Aquifer at the test location has low sand content overall. Geophysical logging showed a few cleaner sand zones present:

- A thin sand zone about 15 feet thick is present at a depth of approximately 518 to 533 feet, which was estimated to only be able to support a minimal amount of groundwater production.
- Additional sand zones were identified starting at a depth of approximately 800 feet that are thicker than the shallower zone at 520 feet, but these zones were also estimated to have relatively limited water production potential capacity.

Overall, the zones identified in this boring were deemed insufficient to support high groundwater production; the production capacity of a well completed as this location was estimated to be less than 200 gallons per minute (gpm).

Geophysical logging results of electrical conductivity were used to determine the presence of slightly saline groundwater (less than 3,000 milligrams per liter [mg/L] total dissolved solids) within permeable zones at depths of less than 1,000 feet, and several permeable zones of moderately saline groundwater (likely greater than 4,000 mg/L total dissolved solids) at depths greater than 1,000 feet. One of HPUWCD's objectives includes gathering information in strategic areas so that water quality delineations may be pursued.

This exploratory test boring showed that the Dockum Aquifer contains very little sand and is relatively unproductive at this location, and it also showed the presence of slightly to moderately saline groundwater within the aquifer. Although these data did not indicate that this area could be used as a productive source of brackish groundwater, it did provide the HPUWCD with valuable information on the nature of the Dockum Aquifer and the quality of the groundwater within it in this part of the District.

HPUWCD manager Jason Coleman, P.E. stated: "We know that rapid advancements in water treatment technology will continue. In fact, HPUWCD is funding several studies that address cost-effective treatment of higher TDS source water. Exploratory test borings and the data we are collecting should help us understand where the application of this technology is well suited." The total cost of the project was approximately $36,000, which included drilling costs of approximately $24,000 and the geophysical logging cost of approximately $24,000. The HPUWCD contributed all of the cost of the logging and $15,000 of the drilling cost under its Dockum Aquifer Partnership Program cost-sharing program. This exploratory test boring provided a significant amount of data on the nature of the Dockum Aquifer at this location at a far lower cost than would have been expended to drill, complete, and test a test well.

The purpose of the Dockum Aquifer study being conducted by the HPUWCD is to collect data and develop an understanding of the quality and quantity of groundwater within the Dockum Aquifer in the HPUWCD boundaries. This study has included identifying Dockum Aquifer wells within the district, conducting geophysical logging on selected existing wells, collecting water level measurements in wells and establishing a water level observation network, collecting water quality samples from wells producing from the Dockum, and approving funding for research projects on the Dockum. These research projects are typically for cost-share assistance for the drilling of exploratory test borings and/or the drilling of exploration test borings or test wells in the Dockum Aquifer. Exploratory test borings such as the Hale County exploratory test boring described here provide such data, and are invaluable in developing a regional understanding of the character of the Dockum Aquifer.

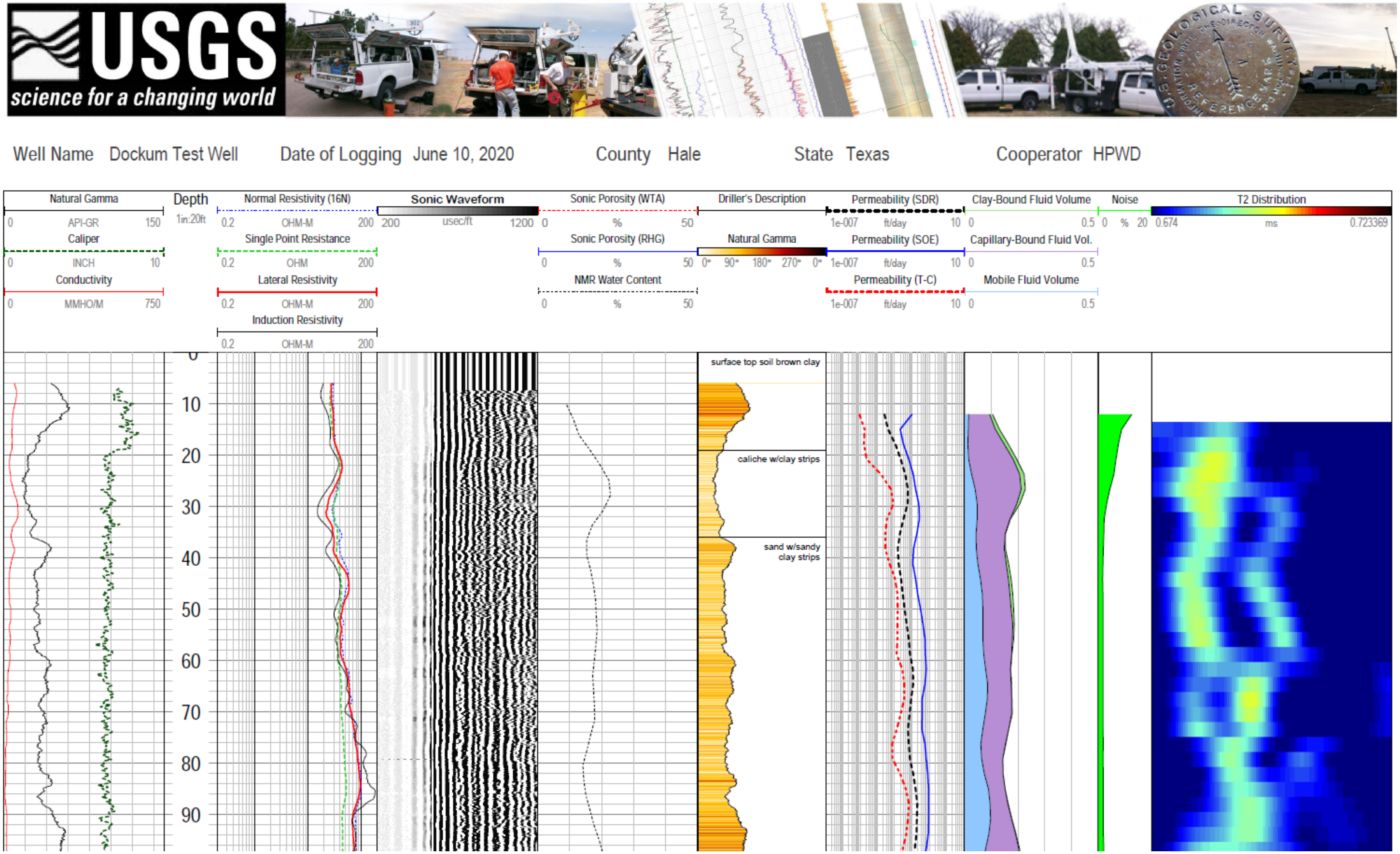


Figure A-1. Geophysical log from the exploratory test boring.

Figure A-2. The Dockum exploratory test boring drilling site.

Figure A-3. Examining exploratory test boring drill cuttings.

Figure A-4. Geophysical logging truck at the drilling site.

Figure A-5. Preparing a logging tool for use in the exploratory test boring.

Appendix B. Exploratory Test Well Case Study: Brown County Water Improvement District

An example of an exploratory brackish test well is presented in a project completed for the Brown County Water Improvement District (BCWID) in 2013 (DBS&A, 2013). This project involved the installation of an exploratory test well drilled into the Ellenburger and Hickory aquifers near Brownwood, Texas (Figure B-1). This well is located downdip of the official extent of both the Ellenburger and Hickory aquifers as delineated in a cross section prepared by the TWDB (Figure B-2). The Bureau of Economic Geology (BEG) conducted a study for the BCWID in 2012 in which they considered all of the geologic formations known to exist in the county, and evaluated the potential for each to serve as a public drinking water supply (Nicot and others, 2012). The Ellenburger and Hickory Formations were identified as prime targets for brackish groundwater development due to their known ability to produce significant quantities of groundwater at other locations, and because they contain the most extensive groundwater resources in the county.

An exploratory brackish test well was chosen by the District as the best way to assess the Ellenburger and Hickory aquifers as potential water supply alternatives. Two locations were initially considered, and after a site was selected, an approximately 3,600-foot-deep test well was installed through the Ellenburger Aquifer to the base of the underlying Hickory Aquifer. Well design, cost estimates, and bid documents were developed based on the information provided in Nicot and others (2012). Gamma, normal resistivity, fluid resistivity, spontaneous potential, temperature, neutron, sonic, caliper, and deviation logs were run upon completion of the boring to the base of the Hickory Aquifer. Information obtained from the geophysical logs was used to finalize the well completion and screened intervals. After the well was installed and developed, step-drawdown and constant-rate pumping tests were performed to determine aquifer properties and expected well yield, and packers were set to collect groundwater quality samples from specific intervals within the well. Finally, a video log was conducted prior to sealing and capping the well so that well conditions were documented.

Results from the testing indicated that several distinct zones, from approximately 1,800 to 2,800 feet below ground surface, contributed the majority of the potential groundwater production from the well; the estimated porosity of these zones ranged from 6 to 10 percent. Aquifer testing indicated that the overall (average) hydraulic conductivity of the aquifer units was very low because most of the rock adjacent to the well bore consists of a solid, massive limestone lacking significant void spaces and open fractures. Water that could be produced from the well was derived from a very small thickness of the formation that contains open, interconnected fractures.

Water quality sampling performed during zonal testing indicated that the total dissolved solids concentration of the Hickory Formation water was approximately 78,000 milligrams per liter (mg/L), more than two times the salinity of seawater. Total dissolved solids concentrations in the Ellenburger Aquifer ranged from approximately 14,000 to 22,000 mg/L, which is considered saline. Therefore, while the testing indicated that limited water productivity might be an issue that could be overcome with wells that intersected zones of increased fracturing, the water quality in both the Ellenburger and Hickory aquifers was too poor to exploit as a water source due to the cost of water treatment.

This test well allowed District staff to determine that the brackish groundwater from the Ellenburger and Hickory aquifers was not economically feasible to develop as a drinking water supply for the District, and that other water supplies needed to be pursued. The advantage of this type of exploratory well was the ability to obtain higher quality aquifer productivity and water quality data than would have been possible in an exploratory test boring. This means that higher-quality engineering data are available on which to base any future potential well field buildout.

The well was sealed and capped and kept as a potential future resource should the costs of desalinating water decline in the future. The District considers this project to have been a success, in that they determined that water is present in these deep units in significant quantities, but the water is too expensive to treat using current technology, although this constraint might change in the future (John Allen, personal communication, 2021).

The overall project cost was approximately $1,050,000. The drilling costs accounted for approximately $700,000 of the cost, and the disposal of wastewater from the drilling and testing operations cost an additional $100,000. The remainder of the costs (about $250,000) were expended on geophysical logging, analytical costs for water quality analyses, and consultant costs, including drilling oversight. This project is a good example of the types of information that can be obtained from an exploratory brackish groundwater well, especially when evaluating a potential resource or area where little to no data exist prior to drilling. The results of a test well may be that the resource is not viable as a water supply for a variety of reasons. However, without the installation of exploratory test wells, the determination of the suitability of an aquifer for brackish groundwater development cannot be made. In this case, the hydrogeologic, geophysical, and chemical data provided the information necessary for decision making.

References

Allen, J., 2021, Personal communication between John Allen, Brown County Water Improvement District, and Daniel B. Stephens & Associates, Inc.

Daniel B. Stephens & Associates, Inc. (DBS&A), 2013, Exploration well installation report, Ellenburger/Hickory Exploration ELL-1 well construction, Brown County, Texas: Prepared for Brown County Water Water Improvement District No. 1, Brownwood, Texas, December 10, 2013.

Nicot, J.-P., Y. Huang, A.R. Standen, R.A. Costley, B.D. Wolaver, and A. Valens, 2012, Brown County brackish-water project: Ellenburger and Hickory aquifers as a public water supply: Prepared for the Brown County Water Improvement District No. 1, September, 2012.

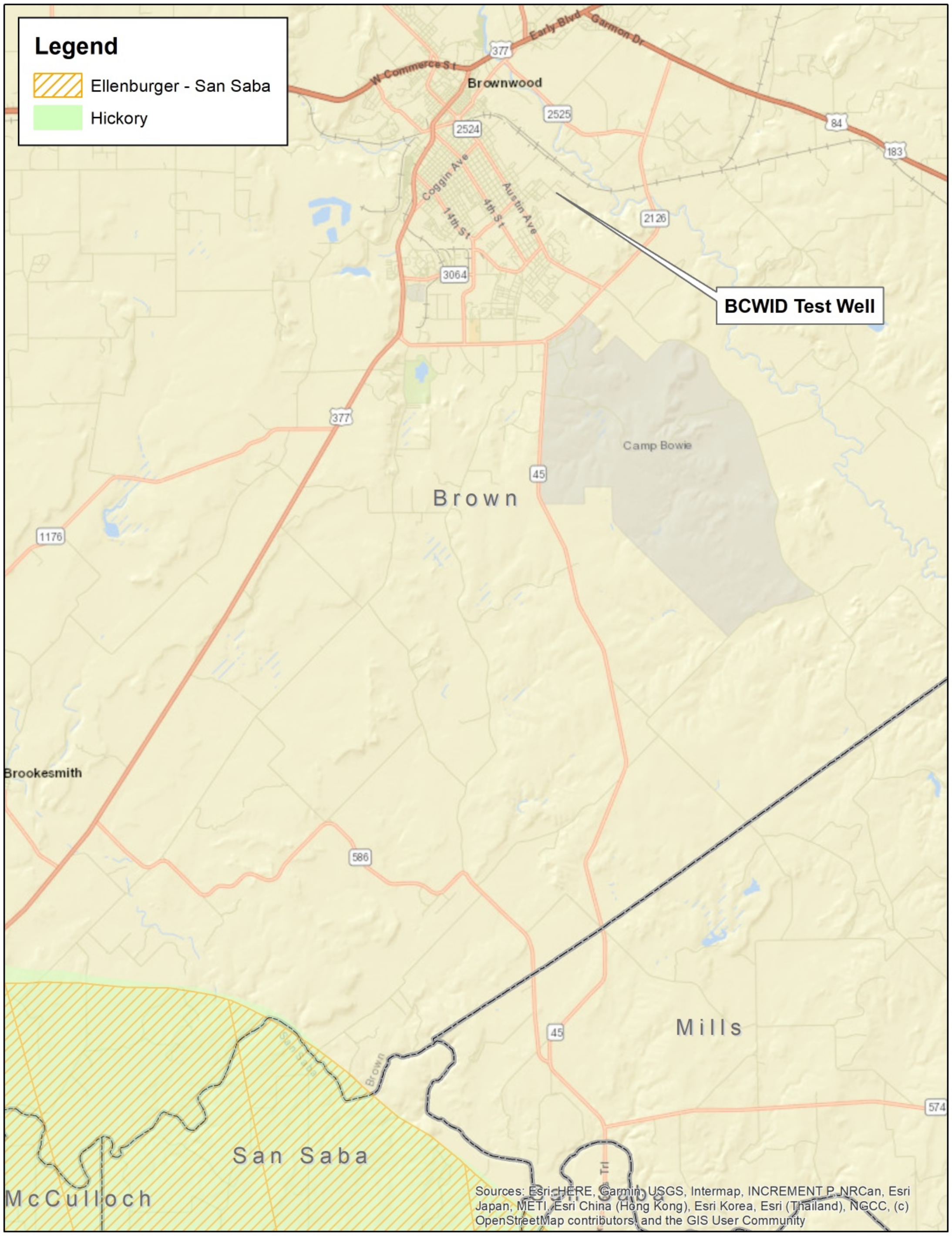


Figure B-1. Location of the BCWID test well relative to mapped aquifer extents.

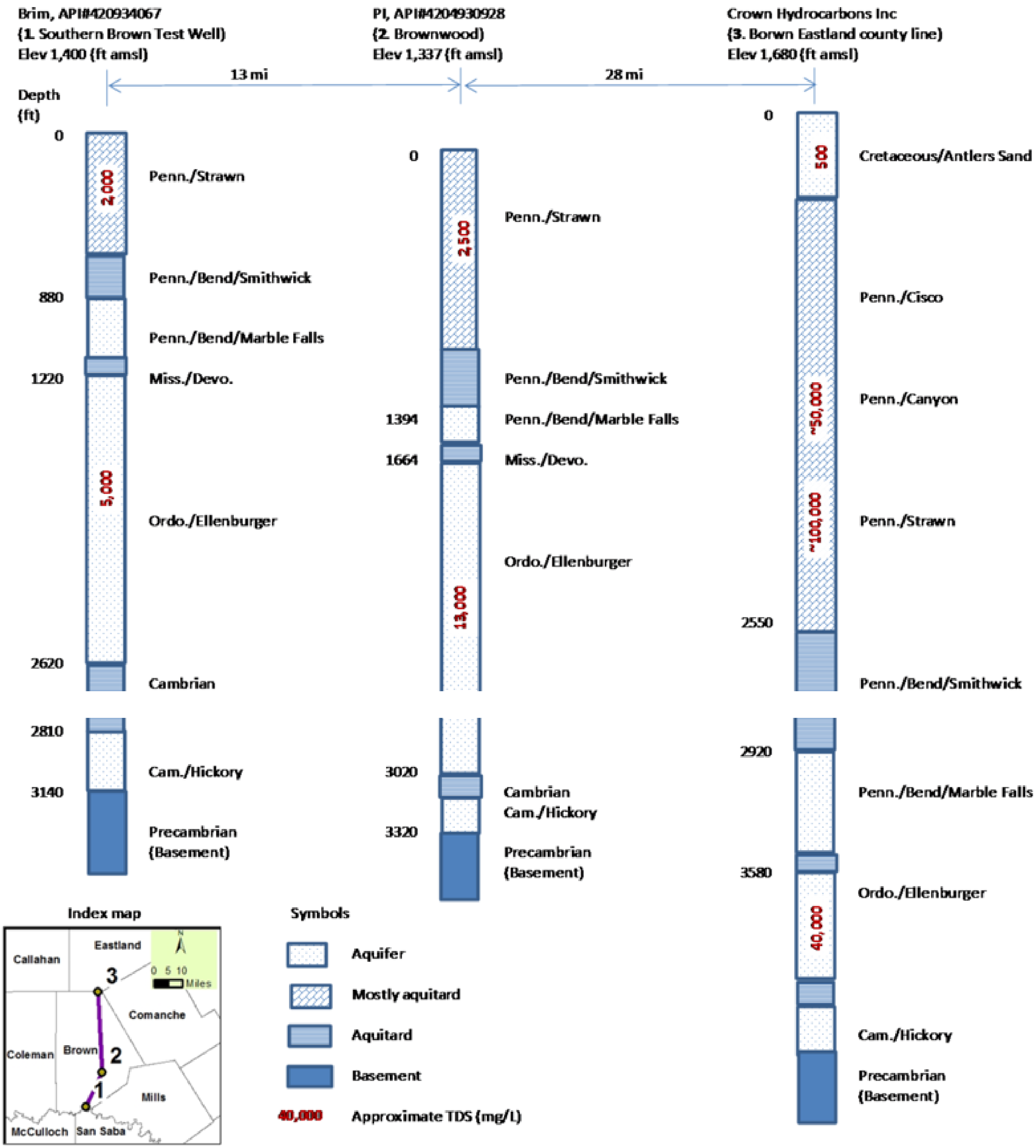


Figure B-2. Cross-section of the Ellenburger and Hickory aquifers (source: Nicot and others, 2012).

Appendix C. Multiport Well Case Study: Barton Springs/Edwards Aquifer Conservation District

The Barton Springs/Edwards Aquifer Conservation District (BSEACD) has been studying the saline portion of the Edwards Aquifer and the relationship between the Edwards and underlying brackish Trinity Aquifers for more than 15 years. To date, these long-term studies have included the installation of three clustered well sets, six multiport wells, and two nested wells. The clustered wells involved the installation of multiple shallow Edwards Aquifer monitor wells adjacent to existing Middle Trinity Aquifer monitor wells. The nested wells were constructed with one or two piezometers completed in the annular space above the production zone of water-supply wells. The multiport wells consist of multiport sampling and measurement zones isolated vertically by packers in a single borehole. The multiport wells were completed in a dedicated borehole drilled specifically for groundwater monitoring purposes.

The BSEACD's preferred groundwater monitoring approach relative to the type of wells selected is based on the cost of each type of well for a given location. The clustered wells approach (multiple monitor wells in close proximity completed at different depths) is the District's preferred method for shallower depths of investigation less than about 600 feet. For monitoring deeper aquifers or portions of aquifers, the District prefers multiport or nested wells to reduce costs, as only one borehole is drilled.

In 2016, the first BSEACD multiport monitor test well was installed into the saline (brackish) Edwards Aquifer in Travis County to evaluate the potential of the Edwards Aquifer for aquifer storage and recovery (ASR) and/or desalination (Carollo, 2018). This test well is located in South Austin, downdip of the edge of the official extent of the Edwards-Balcones Fault Zone (BFZ) Aquifer (Figures C-1 and C-2). This multiport monitor well was drilled to a depth of 1,100 feet, and geophysical logging was conducted using caliper, natural gamma, long and short normal resistivity, spontaneous potential, fluid temperature, conductance, electromagnetic induction conductivity/resistivity, and neutron tools.

A Westbay Instruments™ (Westbay) multiport well was designed and installed with 19 packers, forming 18 distinct (isolated) sampling zones to characterize confining units and potential production zones. The multiport well system was designed after reviewing drill cuttings and geophysical logs, and considering the stratigraphy and hydrostratigraphy of the study area. A caliper log was run to measure the diameter of the borehole so that the packers could be placed within relatively smooth sections of the borehole walls where cavities were not prominent. This approach improved the likelihood that upon inflation the packers would provide effective seals in the boring and not allow water to flow into the sampled zone from overlying or underlying zones. Figures C-3 and C-4 show photographs of the Westbay system component layout and installation, respectively.

Well development, water quality sampling, and aquifer testing using the slug test method were performed in each of the test zones using the sampling and pumping ports of the Westbay system. Following well development, groundwater samples were collected from each isolated zone. Water quality data were used as input to a desalinization model of the aquifer water to evaluate treatment cost if the brackish water were to be used as a drinking water supply. The hydraulic head within each sample interval was measured using pressure transducers installed through the sample port. Pressure readings were subsequently adjusted to freshwater equivalent water levels based on the water density and temperature. With this information, the District was able to evaluate water levels and water chemistry, and was also able to estimate hydraulic conductivity and a production capacity for each zone of the multiport well. The collected data were also used to evaluate the amount of vertical groundwater flow in the aquifer between zones (Figure C-5).

The District noted many advantages for using multiport wells. The most significant benefit is that multiport monitor wells can provide more detailed information and understanding of complex aquifers relative to a single monitoring point. A significant amount of data obtained is from wells that were installed for water supply purposes, not aquifer characterization purposes, meaning that the well is constructed with an open hole or screened interval over much of the thickness of an aquifer. These data are then evaluated to represent the entire aquifer. In complex aquifers like the Edwards, the ability to evaluate the vertical variation in the hydrogeologic units provides a more detailed understanding of the aquifer. These multiport wells can be installed in a single borehole, which saves on drilling costs.

The District also notes some negative aspects of multiport monitor wells. First, they can be much more complicated to install and operate relative to other types of wells, and are therefore more expensive than traditional monitor wells. Specialized equipment is needed to collect data from the wells, and staff need to be trained to operate and maintain this equipment. The BSEACD had a Westbay technician on-site to assist with installation of the well.

The cost of the multiport well installed by the BSEACD was approximately $200,000. Approximately half of this amount included drilling costs. The Westbay equipment cost for this well was approximately $70,000, with an additional $20,000 incurred for the Westbay technician and equipment rental. The remainder of the project costs were associated with site preparation and geophysical logging. Additional costs that might be associated with this type of project, such as hydrogeologic consulting/oversight and sampling equipment costs, were borne internally by the BSEACD and were not itemized (Smith, 2021).

To date, the BSEACD has installed six Westbay multiport wells. The key goal of most of these wells is to understand the potential for a hydraulic connection between the Edwards Aquifer and the underlying Trinity Aquifer. Monitoring results from these wells indicate that the Edwards Aquifer is hydraulically separated from the underlying Trinity units except for the uppermost section of the Upper Glen Rose Limestone. Significant water level and water quality differences between the various Trinity units were also observed in data collected from these wells.

Although the BSEACD is not developing brackish groundwater resources itself, they have strived to better understand the relationship of the Edwards Aquifer to the underlying brackish Trinity Aquifer, as well as the saline portion of the Edwards Aquifer that occurs close to the freshwater section. Use of the multiport wells has provided valuable insight into the hydrogeology of the groundwater system, and has allowed the District to better understand the complex relationship between the Edwards and Trinity Aquifers, which in turn allows for improved management of the resource. Based primarily on the information obtained from these wells, the BSEACD determined that the Trinity Aquifer could be managed separately from the Edwards Aquifer because there is very limited seepage between aquifers.

References

Carollo, 2018, Barton Springs Edwards Aquifer Conservation District desalination/ASR feasibility assessment report: Prepared for the Barton Springs/Edwards Aquifer Conservation District, March 2018.

Smith, B., 2021, Personal communication between Brian Smith, Barton Springs/Edwards Aquifer Conservation District, and Daniel B. Stephens & Associates, Inc.: April 2021.

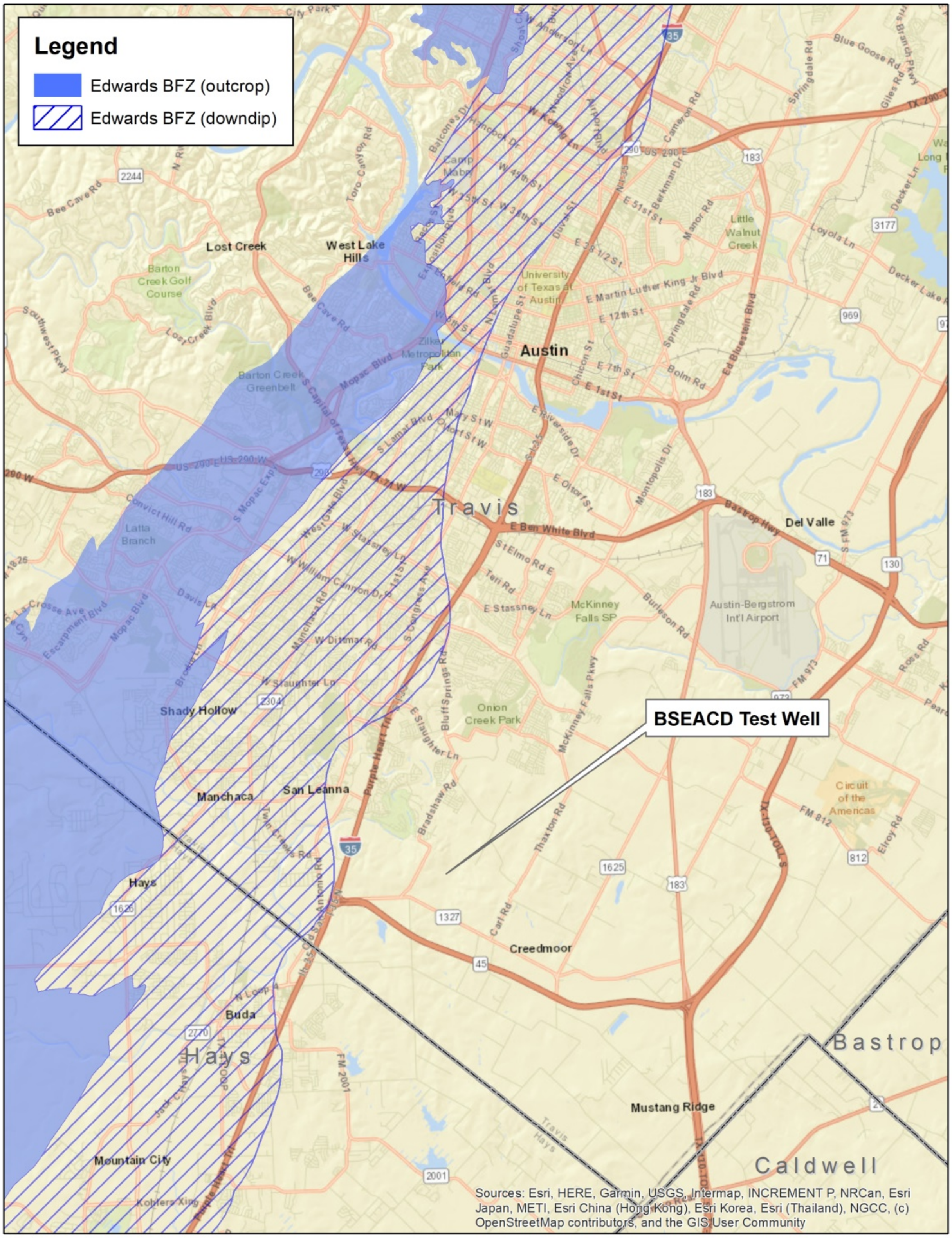


Figure C-1. Location of saline Edwards test well.

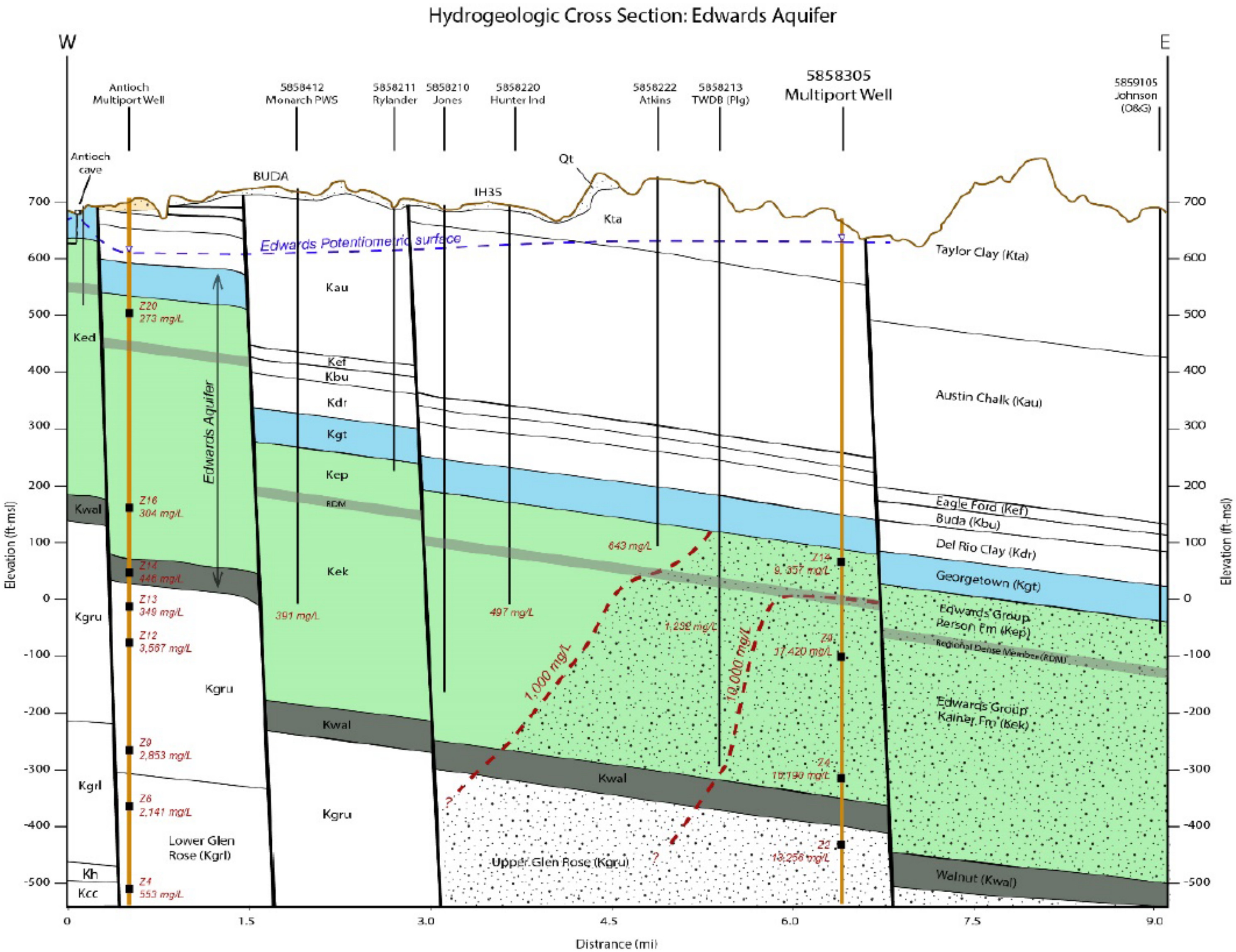


Figure C-2. **Cross section of the Edwards and Trinity Aquifers (source: Carollo, 2018).**

Figure C-3. Layout of Westbay equipment prior to installation of the multiport well.

Figure C-4. Multiport well apparatus installation.

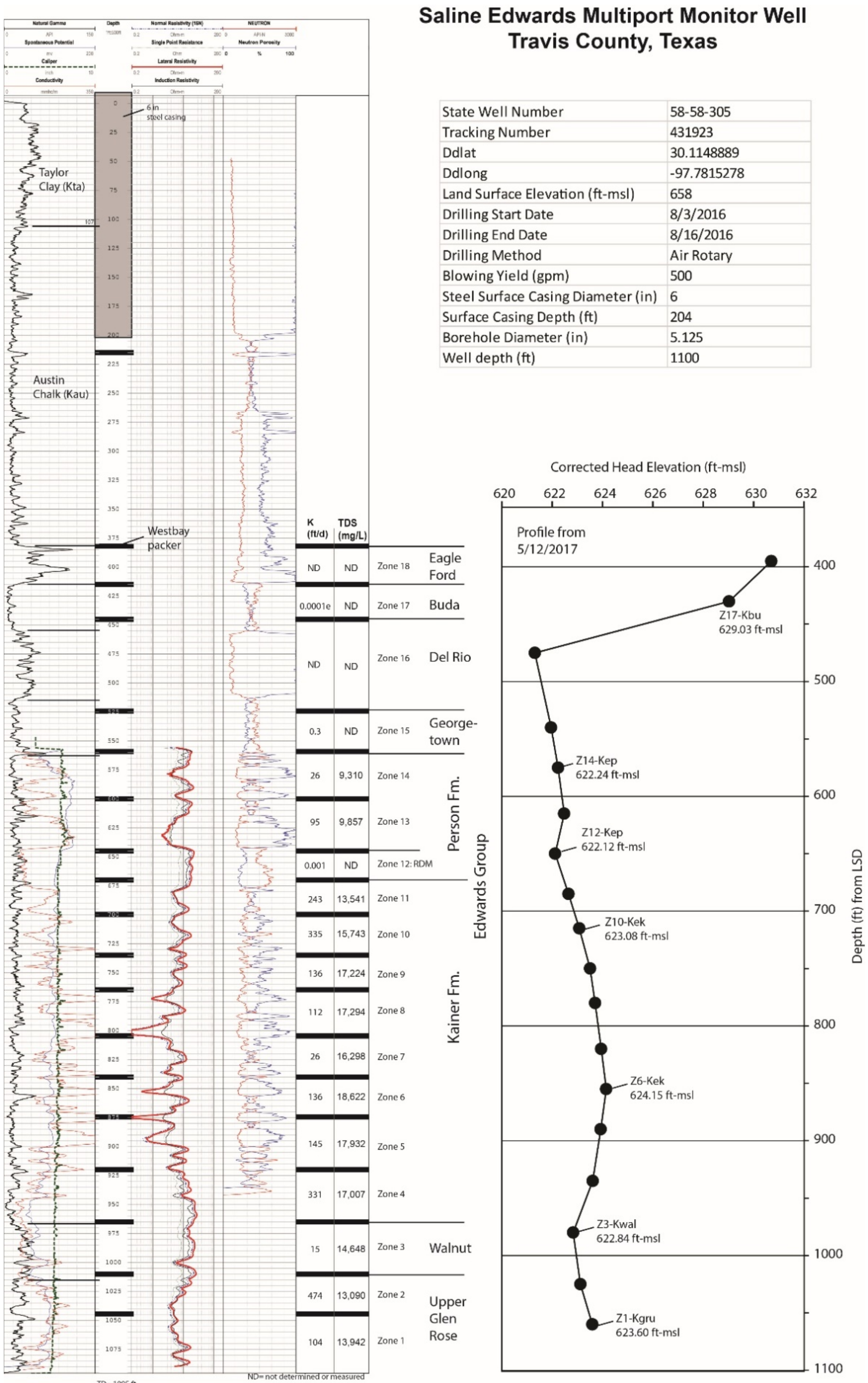


Figure C-5. Saline Edwards multiport monitor well (source: Carollo, 2018).

Appendix D. Nested Well Case Study: Deer Valley Water Treatment Plant, Phoenix, Arizona

In 2014, Clear Creek Associates, LLC (Clear Creek) designed, permitted, and managed the installation of a deep nested well during an aquifer storage and recovery (ASR) investigation at the City of Phoenix Deer Valley Water Treatment Plant in Phoenix, Arizona. The nested well was installed to measure and evaluate water level changes relative to a nearby municipal water well. Initially, consideration was given to the installation of three clustered wells, but due to space limitations the client opted for the nested well option. Installation of the nested well required over 4 months to drill and install in several stages.

After an initial 16-inch pilot borehole was drilled, geophysical logging was conducted, including magnetic deviation log, caliper log, natural gamma ray log, electric log (long normal, short normal, SP, single point resistivity), guard log (laterolog), and sonic log. Upon completion of the geophysical survey, zonal testing of the borehole was performed in seven zones. A 20-foot-long eductor pipe (perforated pipe with a bottom cap) was attached to the drill pipe and lowered to the lowermost test interval. A tremie pipe was used to install a filter pack to a depth approximately 10 feet above the eductor pipe, and then a 5-foot-thick layer of bentonite chips was installed above the filter pack. The test zone was then developed for approximately 12 hours. Zonal testing was performed in each of the remaining six successively shallower zones using the methods described above by pulling the eductor pipe up the borehole and repeating the process at other test zone depths.

After zonal testing on the 16-inch borehole was completed, the pilot borehole was reamed to 22 inches to its total desired depth of 1,221 feet. A second geophysical survey of the reamed borehole was performed using caliper and deviation tools to better determine the actual borehole diameter for annular volume calculation purposes and to determine the straightness of the borehole. Following the second geophysical survey, construction of the nested test well was performed in two stages. First, the outer casing and outer annular filter pack were installed, followed by the three inner casing strings and inner filter pack (Figures D-1 and D-2). An as-built diagram of the completed nested piezometers is presented in Figure D-3.

All filter pack, bentonite seals, and grout were installed by pumping through a tremie pipe near the annulus bottom. Bentonite seals of approximately 10-foot thickness were installed above and below filter packed intervals to hydraulically isolate them from one another and from the formation stabilizer used over blank intervals. After the outer casing and screen sections were installed, a downhole video survey was performed to visually confirm and determine the exact screened interval depths needed to construct the inner nested wells.

Three individual nested piezometers (wells) were then constructed inside the large borehole. Installation of the inner nested wells took six days, and required careful measurement of components prior to installation. The nested wells were installed to depths of 1,205 feet, 955 feet, and 313 feet, hung in suspension from the drill rig mast while the filter pack, bentonite seals, and grout were installed through a tremie pipe. Potable water was introduced to the wells during construction to cool the PVC casings such that heat caused by curing of the polyacrylate grout would not distort the casings. Special care had to be made to ensure that all downhole materials (filter pack, bentonite seals, and grout) were completely placed where specified because the presence of three separate PVC casings and the specialized centralizers required to place them inside the borehole significantly increased the chance that downhole materials might bridge, which would potentially compromise the integrity of the individual wells. After completion, each nested well was developed using a 2-inch-diameter, 30-foot-long PVC bailer actuated by the drill rig's sand line. Groundwater parameters were monitored until developed groundwater stabilized, and groundwater samples were collected for chemical analysis.

The overall project cost was approximately $1 million. One of the advantages of nested wells is that if land availability is very constrained, this type of well allows for the collection of data from selected depths from a single well location. The disadvantages of a nested well are that it involves an overly complex well design and the actual installation of the well can be extremely challenging and time-consuming. Handling all of the casing strings suspended in the well bore can be difficult for the driller, and accidents may occur that can damage these well materials. The placement of completion materials, including filter pack, seals, and grout, must be done carefully to ensure that these materials do not bridge because of all of the well materials in the borehole. If the nested well is not completed properly, the integrity of the individual zones may be compromised, and the data collected would therefore be questionable. Finally, the cost of a nested well far exceeds the cost of a cluster of equivalent individual wells.

Ultimately, the Deer Valley nested well was successfully installed and met its intended purpose. However, the complexity of installing a nested well resulted in a significantly higher project cost than would have resulted from three clustered wells being installed at the same location.

Figure D-1. Lowering the surface casing into the borehole.

Figure D-2. Installation of the three individual nested piezometers for the Deer Valley nested well.

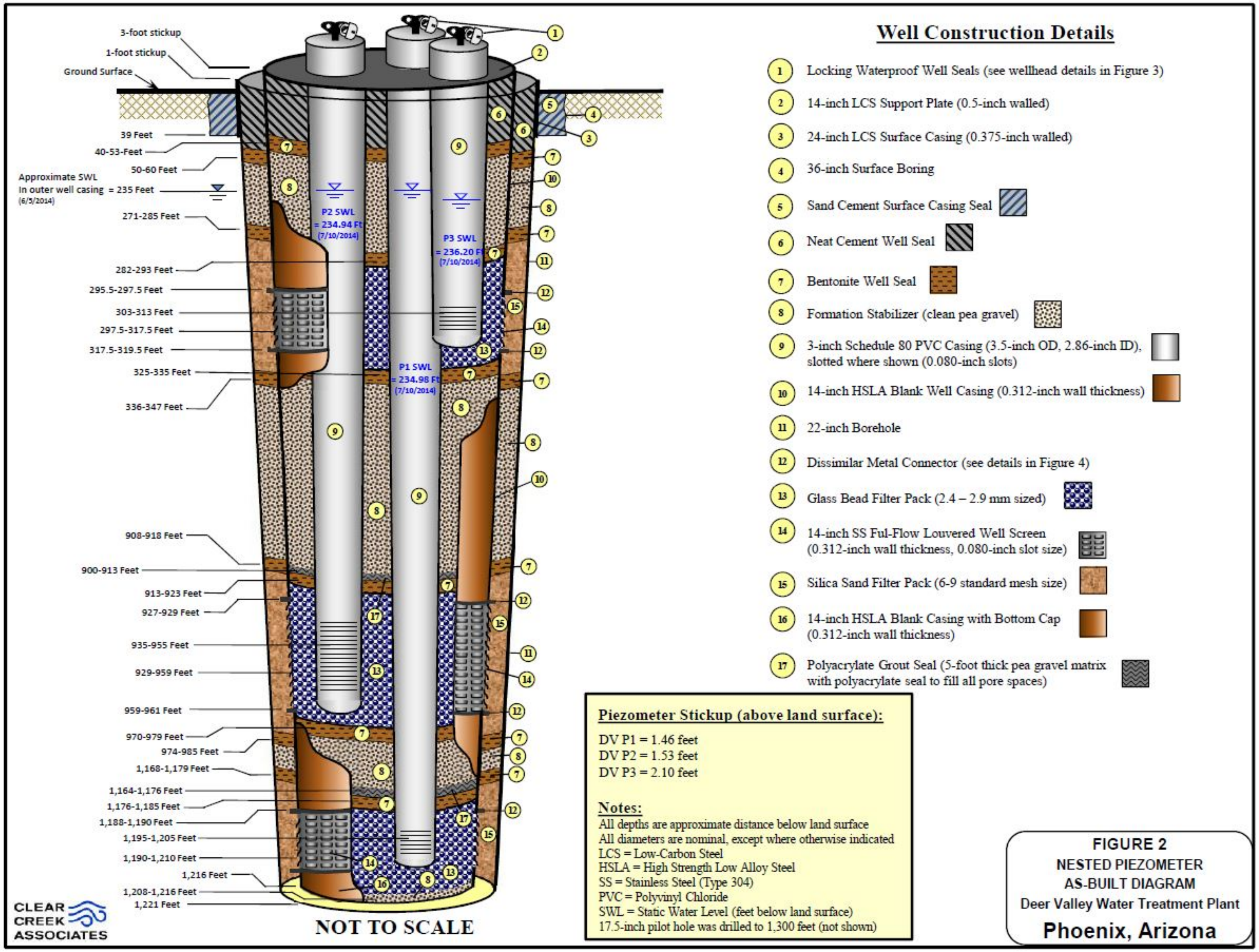


Figure D-3. As-built diagram of Deer Valley nested well.

Appendix E: General Geophysical Logging Resources

General Logging Resources

Collier, H.A., 1993, Borehole geophysical techniques for determining the water quality and reservoir parameters of fresh and saline water aquifers in Texas: Texas Water Development Board (TWDB) Report 343, June 1993.

Keys, W.S., 1990, Borehole geophysics applied to ground-water investigations: U.S. Geological Survey Techniques of Water-Resources Investigation.

ASTM D5753-18 Standard Guide for Planning and Conducting Geotechnical Borehole Geophysical Logging.

Williams, J.H. and J.W. Lane, 1998, Advances in borehole geophysics for ground-water investigations: U.S. Geological Survey Fact Sheet 002-98.

Ellis, D.V. and J.M. Singer (Eds.), 2007, Well logging for earth scientists: Springer, Dordrecht, The Netherlands.

Keys, W.S. and L.M. MacCary, 1975, Location and characteristics of the interface between brine and fresh water from geophysical logs of boreholes in the Upper Brazos River Basin, Texas: U.S. Geological Survey Professional Paper 809-B.

Rittgers, J., 2019, Refining well log interpretation techniques for determining brackish aquifer water quality: U.S. Bureau of Reclamation Research and Development Office, Science and Technology Program, Final Report ST-2018-7106-01.

https://www.usgs.gov/centers/ny-water/science/borehole-geophysics?qt-science_center_objects=0#qt-science_center_objects

https://archive.epa.gov/esd/archive-geophysics/web/html/index-12.html

Electrical Resistivity Log Resources

Collier, H.A., 1993, Borehole geophysical techniques for determining the water quality and reservoir parameters of fresh and saline water aquifers in Texas: Texas Water Development Board (TWDB) Report 343, June 1993.

Keys, W.S., 1990, Borehole geophysics applied to ground-water investigations: U.S. Geological Survey Techniques of Water-Resources Investigation.
https://www.usgs.gov/centers/ny-water/science/borehole-geophysics?qt-science_center_objects=0#qt-science_center_objects

https://www.usgs.gov/media/images/geophysical-logs-single-point-resistance-logs

https://en.wikipedia.org/wiki/Resistivity_logging

https://superpetrophysics.com/blog/8495/the-six-ko-ko-rules-for-well-log-interpretation https://www.slb.com/-/media/files/oilfield-review/defining-log-interpretation.ashx

https://petrowiki.spe.org/Resistivity_and_spontaneous_(SP)_logging

https://wiki.aapg.org/Open_hole_tools#Resistivity

Electrical Induction (Conductivity) Log Resources

Collier, H.A., 1993, Borehole geophysical techniques for determining the water quality and reservoir parameters of fresh and saline water aquifers in Texas: Texas Water Development Board (TWDB) Report 343, June 1993.

Keys, W.S., 1990, Borehole geophysics applied to ground-water investigations: U.S. Geological Survey Techniques of Water-Resources Investigation.

https://www.usgs.gov/media/images/geophysical-logs-electromagnetic-induction-log

https://petrowiki.spe.org/Induction_logging

https://www.smu.edu/-/media/Site/Dedman/Academics/Programs/Geothermal-Lab/Conference/PastPresentations/2015/Schick_SMU_GeoConference_Poster_2015.pdf?la=en

https://wiki.aapg.org/Open_hole_tools#Induction

Spontaneous Potential Log Resources

Collier, H.A., 1993, Borehole geophysical techniques for determining the water quality and reservoir parameters of fresh and saline water aquifers in Texas: Texas Water Development Board (TWDB) Report 343, June 1993.

Keys, W.S., 1990, Borehole geophysics applied to ground-water investigations: U.S. Geological Survey Techniques of Water-Resources Investigation.

https://en.wikipedia.org/wiki/Well_logging#Self/spontaneous_potential

https://en.wikipedia.org/wiki/Spontaneous_potential_logging

https://petrophysicsblogcom.wordpress.com/2018/09/07/sp-log/

https://www.usgs.gov/media/images/geophysical-logs-spontaneous-potential-log

https://petrowiki.spe.org/Spontaneous_(SP)_log

https://www.smu.edu/-/media/Site/Dedman/Academics/Programs/Geothermal-Lab/Conference/PastPresentations/2015/Schick_SMU_GeoConference_Poster_2015.pdf?la=en

https://wiki.aapg.org/Open_hole_tools#Spontaneous_potential

Natural Gamma Ray Log Resources

Collier, H.A., 1993, Borehole geophysical techniques for determining the water quality and reservoir parameters of fresh and saline water aquifers in Texas: Texas Water Development Board (TWDB) Report 343, June 1993.

Keys, W.S., 1990, Borehole geophysics applied to ground-water investigations: U.S. Geological Survey Techniques of Water-Resources Investigation.

https://en.wikipedia.org/wiki/Gamma_ray_logging

https://petrowiki.spe.org/Gamma_ray_logs

https://www.usgs.gov/media/images/geophysical-logs-gamma-logs

https://petrophysicsblogcom.wordpress.com/2018/11/19/gamma-ray-gr-log/

https://www.smu.edu/-/media/Site/Dedman/Academics/Programs/Geothermal-Lab/Conference/PastPresentations/2015/Schick_SMU_GeoConference_Poster_2015.pdf?la=en

https://wiki.aapg.org/Open_hole_tools#Gamma_ray

https://wiki.aapg.org/Cased_hole_tools#Gamma_ray_tool

Gamma-Gamma (Density) Log Resources

Collier, H.A., 1993, Borehole geophysical techniques for determining the water quality and reservoir parameters of fresh and saline water aquifers in Texas: Texas Water Development Board (TWDB) Report 343, June 1993.

Keys, W.S., 1990, Borehole geophysics applied to ground-water investigations: U.S. Geological Survey Techniques of Water-Resources Investigation.

https://en.wikipedia.org/wiki/Density_logging

https://petrowiki.spe.org/Density_logging

https://www.smu.edu/-/media/Site/Dedman/Academics/Programs/Geothermal-Lab/Conference/PastPresentations/2015/Schick_SMU_GeoConference_Poster_2015.pdf?la=en

https://wiki.aapg.org/Density-neutron_log_porosity

Neutron Log Resources

Collier, H.A., 1993, Borehole geophysical techniques for determining the water quality and reservoir parameters of fresh and saline water aquifers in Texas: Texas Water Development Board (TWDB) Report 343, June 1993.

Keys, W.S., 1990, Borehole geophysics applied to ground-water investigations: U.S. Geological Survey Techniques of Water-Resources Investigation.

https://petrowiki.spe.org/Glossary:Neutron_log

https://en.wikipedia.org/wiki/Formation_evaluation_neutron_porosity

https://petrowiki.spe.org/Neutron_porosity_logs

https://wiki.aapg.org/Cased_hole_tools#Compensated_neutron_tool

https://wiki.aapg.org/Open_hole_tools#Compensated_neutron

https://en.wikipedia.org/wiki/Well_logging#Neutron_porosity

https://www.smu.edu/-/media/Site/Dedman/Academics/Programs/Geothermal-Lab/Conference/PastPresentations/2015/Schick_SMU_GeoConference_Poster_2015.pdf?la=en

Nuclear Magnetic Resonance (NMR) Log Resources

Keys, W.S., 1990, Borehole geophysics applied to ground-water investigations: U.S. Geological Survey Techniques of Water-Resources Investigation.

https://en.wikipedia.org/wiki/Well_logging#Nuclear_magnetic_resonance

https://en.wikipedia.org/wiki/Nuclear_magnetic_resonance_logging

https://petrowiki.spe.org/Nuclear_magnetic_resonance_(NMR)_logging

https://petrowiki.spe.org/NMR_logging_tools

Caliper Log Resources

Collier, H.A., 1993, Borehole geophysical techniques for determining the water quality and reservoir parameters of fresh and saline water aquifers in Texas: Texas Water Development Board (TWDB) Report 343, June 1993.

Keys, W.S., 1990, Borehole geophysics applied to ground-water investigations: U.S. Geological Survey Techniques of Water-Resources Investigation.

https://en.wikipedia.org/wiki/Caliper_log

https://petrowiki.spe.org/Openhole_caliper_logs

https://wiki.aapg.org/Open_hole_tools#Calipers

https://www.usgs.gov/media/images/geophysical-logs-caliper

Acoustic (Sonic) Log Resources

Collier, H.A., 1993, Borehole geophysical techniques for determining the water quality and reservoir parameters of fresh and saline water aquifers in Texas: Texas Water Development Board (TWDB) Report 343, June 1993.

Keys, W.S., 1990, Borehole geophysics applied to ground-water investigations: U.S. Geological Survey Techniques of Water-Resources Investigation.

https://en.wikipedia.org/wiki/Sonic_logging

https://petrowiki.spe.org/Acoustic_logging

https://wiki.aapg.org/Open_hole_tools#Sonic

Borehole Camera Resources

https://www.usgs.gov/media/images/geophysical-logs-television-logs

https://inis.iaea.org/collection/NCLCollectionStore/_Public/48/050/48050366.pdf

https://en.wikipedia.org/wiki/Well_logging#Borehole_Imaging

https://en.wikipedia.org/wiki/Borehole_image_logs

https://petrowiki.spe.org/Borehole_imaging

Temperature Log Resources

Keys, W.S., 1990, Borehole geophysics applied to ground-water investigations: U.S. Geological Survey Techniques of Water-Resources Investigation.

https://petrowiki.spe.org/Temperature_logging

https://www.usgs.gov/media/images/geophysical-logs-temperature-logs

Flow Meter Resources

Keys, W.S., 1990, Borehole geophysics applied to ground-water investigations: U.S. Geological Survey Techniques of Water-Resources Investigation.

https://www.usgs.gov/media/images/geophysical-logs-flowmeter-logs

https://water.usgs.gov/ogw/bgas/flowmeter/

https://wiki.aapg.org/Data:_sources#Production_logs

https://wiki.aapg.org/Production_logging

https://petrowiki.spe.org/Continuous_and_fullbore_spinner_flowmeters