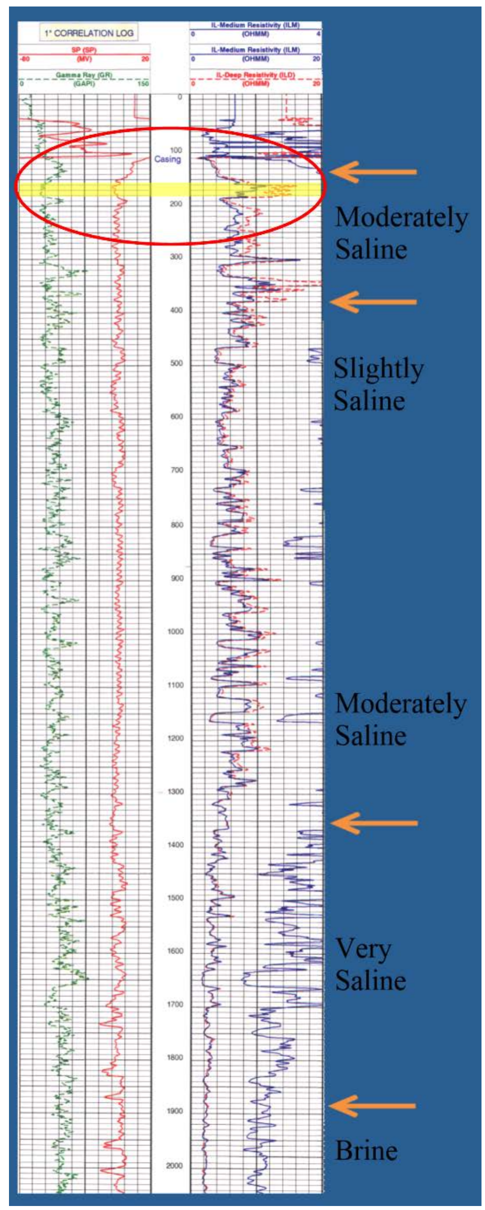
RECLAMATION

Managing Water in the West

Refining Well Log Interpretation Techniques for Determining Brackish Aquifer Water Quality

Final Report
Research and Development Office
Science and Technology Program
Final Report ST-2018-7106-01



U.S. Department of the Interior
Bureau of Reclamation
Research and Development Office

September 2019

REPORT DOCUMENTATION PAGE		*Form Approved* OMB No. 0704-0188
T1. REPORT DATE: September 2019	**T2. REPORT TYPE:** Research	**T3. DATES COVERED** 2017-2019
T4. TITLE AND SUBTITLE Refining Well Log Interpretation Techniques for Determining Brackish Aquifer Water Quality		**5a. CONTRACT NUMBER** RR4888FARD170010003 (8) **5b. GRANT NUMBER** **5c. PROGRAM ELEMENT NUMBER** 1541 (S&T)
6. AUTHOR(S) Nahjee Maybin Jong Beom Kang Justin B. Rittgers		**5d. PROJECT NUMBER** ST-2018-7106-01 **5e. TASK NUMBER** **5f. WORK UNIT NUMBER** 86-68330
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Justin B. Rittgers and Nahjee Maybin Seismology, Geomorphology, and Geophysics Group Jong Beom Kang Concrete, Geotechnical, and Structural Laboratory Group Technical Service Center U.S. Department of the Interior, Bureau of Reclamation P.O. Box 25007, Denver CO 80225-0007		**8. PERFORMING ORGANIZATION REPORT NUMBER**
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) **Research and Development Office** **U.S. Department of the Interior, Bureau of Reclamation,** **P.O. Box 25007, Denver CO 80225-0007**		**10. SPONSOR/MONITOR'S ACRONYM(S)** **R&D:** Research and Development Office **BOR/Reclamation:** Bureau of Reclamation **DOI:** Department of the Interior **11. SPONSOR/MONITOR'S REPORT NUMBER(S)** ST-2018-7106-01

12. DISTRIBUTION / AVAILABILITY STATEMENT
Final report can be downloaded from Reclamation's website: https://www.usbr.gov/research/

13. SUPPLEMENTARY NOTES

14. ABSTRACT *(Maximum 200 words)* There is an increasing need to better characterize brackish groundwater resources throughout the United States, and geophysical well log analysis offers great value and challenges to this effort. In this Science and Technology Research Project, we conducted a literature and technology review of standards of practice to characterize aquifer water quality using bore geophysical logging. This report summarizes parameters and approaches to assess existing log data, identifies common data gaps, discusses challenges related to analysis of log data, discusses various opportunities for addressing data gaps and for future research efforts, provides lists of key contacts for potential future collaborations and partnerships, and provides extensive information on both borehole geophysical logging techniques and surface and airborne geophysical data types applicable to hydrogeologic studies and groundwater quality assessment.

15. SUBJECT TERMS Brackish aquifer, water quality, desalination, geophysical well logs

16. SECURITY CLASSIFICATION OF: U			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**	U	191	Justin B. Rittgers **19b. TELEPHONE NUMBER** 303-445-3010
U	U	U			

S Standard Form 298 (Rev. 8/98)
P Prescribed by ANSI Std. 239-18

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Mission Statements

Protecting America's Great Outdoors and Powering Our Future

The Department of the Interior (DOI) conserves and manages the Nation's natural resources and cultural heritage for the benefit and enjoyment of the American people, provides scientific and other information about natural resources and natural hazards to address societal challenges and create opportunities for the American people, and honors the Nation's trust responsibilities or special commitments to American Indians, Alaska Natives, and affiliated island communities to help them prosper.

The mission of the Bureau of Reclamation is to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American public.

Bureau of Reclamation

Research and Development Office
Science and Technology Program
Engineering Geology and Geophysics Group, 86-68320
Geotechnical Laboratory and Field Support Group, 86-68550
Final Report ST-2018-7106-01

Refining Well Log Interpretation Techniques for Determining Brackish Aquifer Water Quality

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Acronyms and Abbreviations

AAPG	American Association of Petroleum Geologists
ADWR	Arizona Department of Water Resources
AEM	airborne electromagnetic
AMP	Aquifer Mapping Program
AWT-BOR	Advanced Water Treatment Research Group, Reclamation
AZGS	Arizona Geologic Survey
AZ OGCC	Arizona Oil and Gas Conservation Commission
AZWSC	Arizona Water Science Center
B	equivalent conductance per cation
BGNDRF	Brackish Groundwater National Desalination Research Facility
BRACS	Brackish Resources Aquifer Characterization System
Caltrans	California Department of Transportation
CAWSC	California Water Science Center
CO-DWR	Colorado Division of Water Resources
COGG	California Oil, Gas and Groundwater
COHYST	Cooperative Hydrology Study
DOM	dissolved organic material
DWR	Department of Water Resources (CA)
EC	electrical conductivity
ENWRA	Eastern Nebraska Water Resources Assessment
GAMA	California Groundwater Ambient Monitoring and Assessment Program
GIS	Geographic Information System
IGRAC	International Groundwater Resources Assessment Centre
m	cementation factor
MERAS	Mississippi Embayment Regional Aquifer Study
n	saturation exponent
NaCl	sodium chloride
NASA	National Aeronautics and Space Administration

NAWQA	National Water-Quality Assessment Program
NGGDPP	National Geological and Geophysical Data Preservation Program
NM-BWWG	New Mexico – Brackish Water Working Group
NMBGMR	New Mexico - Bureau of Geology and Mineral Resources
NM-OCD	New Mexico Oil Conservation Division
NOAA	National Oceanic and Atmospheric Administration
NRCS	Natural Resources Conservation Service
NWS	National Weather Service
PEST	Model-Independent Parameter Estimation & Uncertainty Analysis (PEST)
PRRC	Petroleum Recovery Research Center
Qv	cation exchange capacity
RASA	Regional Aquifer Systems Analysis
Reclamation	Bureau of Reclamation
RISA	Regional Integrated Sciences and Assessments
Rm	resistivity of drilling mud
Rmf	mud filtrate resistivity
Rt	true resistivity
R_w	groundwater resistivity
R_{wa}	resistivity water apparent
R_{we}	water resistivity equivalent in the formation
SIR	Scientific Investigations Report
SP	spontaneous potential
SSP	static spontaneous potential
S&T	Science and Technology
Sw	water saturation
SWRCB	California State Water Resources Control Board
Sxo	flushed zone saturation
TEM	transient electromagnetic
TDS	total dissolved solids
TDEM	time-domain electromagnetic

TEM	transient electromagnetic
Tf	formation temperature
TSC	Technical Service Center
TWDB	Texas Water Development Board
UGS	Utah Geological Survey
USDA	U.S. Department of Agriculture
USGS	U.S. Geological Survey
USGS WSC	USGS Water Science Centers
WSWC	Western States Water Council
α	tortuosity factor
Φ	porosity
M	connectivity exponent
χw	water connectivity correction index

Executive Summary

Purpose and Need

In recent decades, it has become increasingly apparent that groundwater is one of the most important and limited natural resources in the United States. Demand for fresh water has steadily increased over time, mainly due to sustained or increasing municipal usage, commercial and industrial developments that require large amounts of fresh water, and a lack of adequate recharge rates. As a result of the demands placed on fresh groundwater supplies, there is a growing national interest in and need to characterize and quantify brackish groundwater resources throughout the Nation. There is a critical need to supplement or replace freshwater sources and increase the Nation's water security.

In order to move forward with developing brackish groundwater resources, it will be necessary to identify priority zones that contain the highest available water quality (e.g., relatively low salinity and total dissolved solids [TDS]). In addition, the specific spatial distributions and quantities of groundwater resources must be understood so that well-informed water management decisions can be made. With identified priority zones and a good understanding of the location, type, and amount of available groundwater, communities will be equipped to identify brackish groundwater that can be treated for irrigation, potable drinking water supply, and other beneficial uses throughout the United States in an economically viable manner.

Although stakeholders have not widely adopted the practice of using existing geophysical well logs to interpret groundwater distributions, interest in doing so has been steadily increasing. In particular, using existing geophysical well logs to assess and characterize brackish groundwater quality could help address the critical water resource quality and sustainability challenges affecting the Nation, particularly in arid regions.

A 2016 Bureau of Reclamation (Reclamation) Science and Technology (S&T) Program scoping research project (ID 2924) revealed that Texas was the only State actively engaged in characterizing the water quality of the brackish waters in its domain. The Texas Water Development Board (TWDB) has been at the forefront of the research into, and the application of, borehole geophysical techniques and methods to identify and characterize brackish groundwater resources. For example, in 2009, TWDB established the Brackish Resources Aquifer Characterization System (BRACS) program. The BRACS program was designed to map and delineate brackish groundwater and promote desalination projects in Texas.

Before existing geophysical well log data can be used to assess, evaluate, interpret, and characterize brackish groundwater to help meet the Nation's growing water crises, a number of correction factors must be applied. These correction factors must be based on local geology, well details, and many other confounding factors. Moreover, existing information is most often sparse and incomplete, which makes calibration and reliable interpretation of well logs difficult.

This report focuses on the general challenges related to geophysical well log analysis applications, and it presents various technology and research opportunities to help address these various interpretation challenges.

Study Scope and Methodology

Reclamation's 2016 S&T Program scoping research project provided an initial literature and technology review to examine potential methods to interpolate existing data and state of the effort and science with regard to using well logs to characterize brackish groundwater. The 2016 research project formed a foundation upon which the current 2017 S&T Program research effort was based.

This 2017 research effort expanded the literature review to evaluate the current state of the practice, define specific log analysis options, and identify future research areas that will help support geophysical log interpretation for water quality in brackish aquifers. The 2017 research effort helps answer the following questions:

- Are there any existing geophysical well log analysis techniques in addition to alternative techniques that can better characterize brackish aquifers given existing log data?

- Are there any specific aspects or challenges to standard analysis techniques and workflows that warrant significant and focused research in the future?

- How can well log analysis techniques be improved or made more robust by incorporating additional data types for addressing current challenges or limitations?

- Who are some of the key working groups or specific researchers recently and currently studying or implementing geophysical well log analysis for brackish groundwater characterization?

Summary of Results

This 2017 S&T Program research effort identifies which geophysical well log data types are most critical and useful for brackish groundwater characterization (table ES-1). It specifies the well log data gaps that commonly exist for well log analysis. In addition, it presents and discusses several techniques, analysis workflows, and alternative processes applicable to improving brackish aquifer characterization (table ES-2).

Specific findings from this research project include the following:

- **Water sample testing is the primary approach to mapping and characterizing brackish groundwater aquifers.** Geophysical well log analysis generally plays a secondary role in brackish groundwater assessment efforts. Recently, however, interest in using geophysical well log analysis to address water sampling data gaps is growing, and its use is becoming more frequent.

- **Various well log data gaps are common and can be addressed with advanced analysis techniques.** Existing data may be in hard copy, handwritten, or other nondigitized formats. Existing digitized data may be spatially sparse or limited in depth coverage. As a result, advanced analysis techniques are necessary to obtain critical well log information that is currently missing.

- **Cross-validation of various techniques can help identify areas of poorly-constrained water quality estimates.** The most frequently used techniques include Archie's equation using resistivity water apparent (R_{wa}) minimum method, spontaneous potential (SP) method, resistivity ratio method, and the connectivity equation. An analyst will usually use just one of these methods. The advantages and disadvantages of each method are presented in table ES-1. It may be possible to ground-truth and calibrate salinity or TDS estimates if water quality samples can be obtained from a nearby water wells, but this is not always possible. Without ground-truth water quality samples available nearby, quality assurance of results can be reduced, depending on hydrogeologic and geoelectric variability between a given well log data set and the nearest ground-truth. In this scenario, using a combination of techniques enables the cross-validation necessary to test the accuracy of results.

- **Incorporation of additional supplementary data types can help the analysist fill data gaps.** Additional data types can be incorporated in the analysis to help fill in or compensate for existing well log data gaps; however, co-located data types required for certain analysis processes may be limited. Appendix A, "Additional Data Types and Complementary Well Log Interpretative Techniques for Brackish Groundwater Characterization," provides detailed information on various applicable surface and airborne geophysical techniques to acquire supplemental data and more spatially comprehensive data coverage within shallow to intermediate depths. Appendix A also suggests opportunities and techniques to acquire applicable well log data within existing cased wells, such as inactive oil and gas wells. Table ES-2 provides a condensed summary of these supplemental data types.

Table ES-1. Advantages and Disadvantages of Existing Brackish Groundwater Well Log Interpretation Methods

Method	Advantages	Disadvantages
Archie's method	Useful in sandstone aquifers. Variety of methods to fine-tune Archie's parameters.	Shale content in the lithology causes a breakdown in the empirical equation. Without water samples and necessary well logs (resistivity, gamma ray, SP, neutron porosity, and density), the amount of assumptions can greatly increase the error margin when calculating TDS.
SP	Only requires SP log. Enables quick interpretation.	Assumes all solids in solution are NaCl. Aquifer must be clay free. Not applicable in oil-based muds.
Resistivity ratio	Only requires shallow and deep resistivity logs. Enables quick interpretation.	Not applicable in vuggy fractured layers. Shallow log can be unreliable if conditions in hole changed after drilling.
Connectivity equation	Can be used in shales and clays to correct for shale effect on measured resistivity.	Relies on the same assumptions as Archie's method.

Table ES-2. Summary of Additional Data Types and Complementary Well Log Interpretative Techniques for Enhancing Brackish Groundwater Characterization

Data Type / Complementary Well Log Interpretative Technique	Summary
Data correlation and advanced spatial interpolation of missing and sparse data	Case studies that show how additional data can be used with existing well log data
Airborne-based geophysics	Airborne electromagnetic (AEM) most applicable to groundwater studies
Surface-based geophysics data	Complementary to SP or resistivity and induction logging
Existing cased wells: see-through casing technologies	Cased hole logging basics, cased hole gamma ray, cased hole spectral gamma ray, cased hole porosity, cased hole reservoir saturation log, cased hole dipole shear sonic, cased hole elemental capture spectroscopy, cased hole formation resistivity, cased hole formation density
Geophysical borehole logging techniques	Resistivity logs, borehole imaging logs, density (gamma gamma) logs, neutron porosity logs, sonic (acoustic) logs, gamma ray logs, spontaneous potential logs, caliper logs, nuclear magnetic resonance logs, spectral noise logging, logging while drilling and measurement while drilling

Next Steps and Future Research Opportunities

Various brackish groundwater stakeholders involved in the application and research of geophysical logging techniques can expand their capabilities by developing programmatic strategies to take advantage of the tools and techniques identified in this report and in appendix A.

Data analytics techniques and advanced spatial interpolation techniques can be used for correction factor calibration and tuning, and probabilistic modeling can be used to obtain a comprehensive analysis. Results from these methods, however, will never be completely accurate and will need to be updated and ground-truthed using directly measured water sample properties.

Incorporating additional data types or conducting cross-validation analysis (i.e., which involves leaving out a data point and comparing the analyses) will help to characterize the validity and accuracy of the analysis results. Integrating ground-based and airborne geophysical mapping and imaging technologies can help interpolate current sparse well log data and to address specific data gaps and challenges. Reclamation's Technical Service Center (TSC) has conducted several types of geophysical surveys applied to groundwater salinity characterization and mapping that have proven invaluable in better understanding various complex hydrogeologic situations.

A review of the literature search results led to the general conclusion that the most promising approach to addressing the challenges faced by well log analysts and stakeholders is to use a method that combines hybrid techniques that use a variety of different, yet complementary, technologies to assess and characterize brackish groundwater resources. These techniques and methodologies should be:

- Cost effective
- Adequately sensitive to physical and chemical properties and processes of interest
- Accurate and robust enough for routine assessments
- Applicable for use without impacting the resources themselves

Future research, and technical development strategies and priorities, should address methods and techniques to gather and use existing data, acquire additional data, and optimize data analysis methods. Other potential data analysis techniques should be sought out that can best utilize existing data and help bridge current data gaps. Such research can be used to develop enhanced geophysical techniques, and examination of other fields, such as computer vision and optimization theory, can provide further insight into potential applicability and use of data. Suggested areas of research include:

- Pattern recognition to more effectively digitize existing well data
- Wireline technologies to use any accessible exploration wells to collect key types of data within relatively shallow brackish aquifers (i.e., "see-through-casing" well logging technologies).
- Data analysis tools and related areas of research such as advanced interpolation techniques, machine learning techniques and neural network theory, multivariate regression analysis, and advanced image-guided interpolation to further refine cross-validation results to more accurately interpret existing data

Further research should leverage industry and academia experts. Partnering with an academic institution could help determine more effective ways to organize and digitize existing data, as well as research and incorporate various data analytics and interpolation techniques to more effectively fill in existing data gaps and better support standard well log interpretation techniques.

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1. Background

1.1 Problem and Need

Groundwater is one of the Nation's most important water resources. Fresh groundwater resources are being depleted due to inadequate recharge rates coupled with continuous increases in usage demands such as groundwater pumping for many industrial uses (U.S. Geological Survey [USGS], 2013). This increased groundwater pumping is overtaxing many aquifers, resulting in groundwater aquifer depletion and even ground surface subsidence in certain areas of the United States. Increases in large-scale commercial agricultural and farming practices that involve flood and center-pivot irrigation techniques, flood-leaching of agricultural fields to remove built-up salts, pesticides and herbicides, and a continued need for environmental purposes (e.g., maintaining adequate riverflows to protect fisheries) have also contributed to groundwater quality and depletion challenges.

Brackish groundwater with a total dissolved solids (TDS) range of approximately 1,000 to 10,000 parts per million (ppm) (USGS, 2013) has recently become recognized as an important alternative water source and has garnered growing interest from stakeholders. According to Stanton et al. (2017), "Use of brackish groundwater could supplement or, in some places, replace the use of freshwater sources and enhance our Nation's water security." Stanton indicated, however, that there is a need to better understand how to locate and characterize brackish groundwater to expand development of the resource and provide a scientific basis for making groundwater management policy decisions.

In the United States, recent and ongoing Federal and State-level programs aimed at mapping and monitoring brackish groundwater resources have predominantly used directly sampled water quality data collected from existing water wells. To ensure future sustainable use and management of this limited resource, however, it will be critical to use additional subsurface mapping techniques capable of identifying the location, quantity, and quality of groundwater in brackish aquifers. To assess current availability of brackish groundwater resources across the United States and elsewhere, analysts must compile existing information, identify data gaps, use methods to interpolate existing data, and acquire additional data where needed. Specifically, the use of geophysical well logging data and analysis techniques can offer valuable information about groundwater conditions, especially when combined with complementary analysis techniques.

While geophysical well logging technologies have proven useful in fresh and brackish groundwater exploration and characterization efforts, various technical challenges related to quantitative brackish groundwater characterization remain. Advancement of existing well logging analysis techniques, as well as the development of new methods to acquire and utilize geophysical data and circumvent current data gap challenges, are needed to better quantify brackish groundwater resources for future use and management.

1.2 A Brief History of Geophysical Well Logging

Geophysical well logging is the practice of making a detailed record of a well's depth, temperature, and other properties over time. Research and development of geophysical well logging for use in general subsurface exploration and characterization has been ongoing for nearly a century within the Unites States. According to Johnson (1962), "the science of well logging, begun by Conrad Schlumberger in 1927 as an application of his work on resistivity measurements of the earth in surface exploration, has advanced further during the intervening thirty-three years than even its creator could have imagined." Johnson's publication offers a review of the early advances and developments of geophysical borehole logging techniques, and numerous other publications have provided extensive reviews of this subdiscipline of geophysics, including Spies (1996) and, more recently, Chopra et al. (2002). According to Stefan Luthi and others, well logging techniques extend back even further, where "Professor Forbes from the Edinburgh Observatory was perhaps the first person to make well log measurements, when, from 1837 to 1842, he lowered temperature sensors into three shafts up to 24 feet deep to record temperature variations with depth and time" (Luthi, 2001).

Since then, modern geophysical well logging has advanced to encompass much more complex instrumentation and analyses (e.g., focused sensing devices, electromagnetic induction tools, radioactive sources for density logging, passive radioactive techniques for inferring mineralogical properties of sediments and rocks, the measurement of acoustic properties via ultrasonic probes, etc.). Additionally, downhole (i.e., wireline) logging instruments have been developed to enable direct physical recovery of rock and fluid samples.

Historically, well-established logging techniques, including spontaneous potential (SP) and electrical resistivity profiling, have been utilized in oil and gas exploration and related stratigraphy and to map lateral variations in sedimentary facies within known hydrocarbon reservoirs (Thilagavathi et al., 2014). Accordingly, advancements in well logging technology have been driven by mineral and hydrocarbon exploration, as well as engineering and military application needs. However, the application of geophysical well logging specifically for brackish groundwater quality assessment and characterization has only recently become an increasing area of interest, especially in arid regions with persisting or developing groundwater quality and resources sustainability challenges.

A more detailed discussion of nationwide groundwater quality mapping and characterization efforts and findings, as well as recent research and applications related to the use of geophysical well logging for brackish groundwater characterization, is presented in Chapter 2, "General Efforts to Characterize Brackish Groundwater." Previous efforts conducted by Reclamation placed a focus on the Texas Water Development Board's (TWDB) efforts as TWDB has been at the forefront of the research into, and the application of, borehole geophysical techniques and methods to identify and characterize brackish groundwater resources. Examples of TWDB's recent work are discussed in detail in subsequent sections of this report.

1.3 Summary of Reclamation's 2016 Science and Technology Scoping Research

In 2016, the Bureau of Reclamation (Reclamation) conducted a scoping-level research effort focused on the state of the practice and methods. The information gained in the 2016 research effort then provided the building blocks upon which the 2017 research effort was based. This section of the report summarizes the 2016 research effort, and the 2017 research effort is discussed in the following section of this report.

The 2016 scoping research effort discussed generalities related to groundwater aquifer characterization techniques to either directly measure or infer hydrogeologic properties of interest based on measurements of other parameters which are correlative to the properties of interest. The main hydrogeological properties of interest were identified to include material type, intrinsic porosity, effective porosity, salinity, TDS, permeability, storativity, transmissivity, and vertical and lateral extent of a brackish aquifer. This list comprises a relatively comprehensive set of hydrogeological properties of primary interest to hydrologists and other stakeholders for any given groundwater aquifer, as they allow for evaluation of volumes of recoverable water and water quality.

The 2016 report also examined a general list of geophysical methods that can be used to help infer hydrogeologic parameters of interest, provide more comprehensive spatial coverage for use in extrapolation of in-situ properties estimated from borehole measurements, help infer the vertical and lateral extent, and map the distribution of variabilities of any given parameter for the aquifer system. However, this list primarily consisted of non-borehole geophysical methods and placed a greater emphasis on the need to employ and integrate multiple data types and data collection techniques beyond geophysical borehole logging techniques.

Furthermore, Reclamation's 2016 scoping effort included a preliminary literature search to identify previous work related to the use of geophysics for brackish groundwater characterization. While several publications were identified and briefly described, the reported literature predominantly involved the use of non-well logging geophysical surveys and data types. This trend in the use of surface-based and airborne geophysical methods versus borehole methods within previous work was also encountered in this 2017 research effort.

Finally, Reclamation's 2016 scoping effort identified potentially related and/or interested government entities for future research collaborations. Although these entities were generally closest in proximity to the state of Texas, by no means was the list all-inclusive or exhaustive. As reported, these entities included the following:

- USGS Water Science Centers (USGS WSCs)
- Reclamation's Brackish Groundwater National Desalination Research Facility (BGNDRF)
- Reclamation's Technical Service Center (TSC), Water Treatment Group
- New Mexico – Brackish Water Working Group (NM-BWWG)
- Petroleum Recovery Research Center (PRRC)
- California Department of Transportation (Caltrans)

From this list of potential partners, the most promising entities that have been or are actively involved in research specific to geophysical well logging for brackish aquifer characterization include USGS WSCs from various Southwestern and Western States, including Texas, New Mexico, Arizona, Colorado, Nevada, and California. Additionally, the most promising government entities for collaborating on data sharing or knowledge sharing include PRRC and potentially Caltrans. The NM-BWWG, while in its newly organized infancy, may prove useful for future research partnerships. Finally, although the Oklahoma Water Resources Board (OWRB) was not identified in the 2016 scoping effort, OWRB is currently embarking on a State-wide mapping of marginal quality waters effort that will also likely promote partnerships.

1.3.1 Future Improvements Identified in Reclamation 2016 Report

Future research should include efforts to reduce uncertainty regarding calibrating and correlating geophysical well log data with borehole physical properties. Additional research is needed to expand the techniques to other geophysical well log techniques.

1.4 Scope of 2017 Research Effort

This research project consisted of an expanded literature and technology review, and it defined specific research areas required to support geophysical log interpretation for water quality in brackish aquifers. This research effort provides a foundation to identify what specific types or aspects of geophysical well log data may be commonly missing or insufficient, and to delineate different data types, well log analysis techniques and workflows, and processes applicable to improving brackish aquifer characterization. Under this S&T Program research project, Reclamation:

- Performed a literature review and examined a database of pertinent metadata, log types, and locations for a representative subset of all available geophysical well logs throughout Texas (i.e., logs in the Great Plains Region) made available to Reclamation. This task involved accessing and examining a large number of geophysical well logs made accessible by TWDB's Groundwater Data Viewer at: https://www2.twdb.texas.gov/apps/waterdatainteractive/groundwaterdataviewer and visually identifying and assessing the following factors:
    - Relevant basins and aquifers
    - Common spatial distributions of geophysical well log data types within each area/aquifer
    - Typical depth-coverage of geophysical well log datasets
    - Typical quality and usability of digital copies of log files for subsequent interpretation techniques by means of accessing and inspecting a representative subset of well log files.
- Identified common data gaps that could prohibit the straightforward use of existing analysis techniques. The data gaps identified are listed in Chapter 5, "Data Gaps and Challenges."
- Developed a bibliography of selected literature. Specific references to geophysical characterization studies were sorted by publication date and are presented in Appendix B, "Summary of Bibliographic Entries and Key Inferred Parameters."
- Reviewed and summarized the methods currently being used or researched, and identified typical challenges encountered, such as data gaps and method limitations. Section 6, "Addressing Data Gaps Associated with Well Log Interpretation," discusses these methods.

- Reviewed and summarized applicable surface and borehole geophysical survey techniques. This work also identified non-well logging data collection methods that avoid the need for drilling more wells and that might be able to help fill or circumnavigate common geophysical well log data gaps. Additionally, available "see-through" steel casing well logging technologies were reviewed to identify options for addressing challenges related to the lack of availability of geophysical well log data within the uppermost several hundred feet of existing steel-cased oil and gas wells. Appendix A, "Additional Data Types and Complementary Well Log Interpretative Techniques for Brackish Groundwater Characterization," summarizes these technologies.

- Identified specific future technical research efforts needed to improve the applicability of identified state-of-the-art geophysical well log interpretation techniques for brackish groundwater stakeholders. Specifically, identified potential new interpretation techniques that could use existing data, despite gaps, and other non-invasive surface-based geophysical data types that could be used to help address challenges. These points are listed in Chapter 7, "Conclusions and Recommendations."

- Compiled a list of potential contacts for research and literature review. Canvassed the national and State-based USGS WSCs and laboratories, TWDB, several universities (e.g., Colorado School of Mines, Stanford University, University of Texas-Austin, and Texas A&M University), and other professional experts and compiled a list of reports related to groundwater quality in brackish aquifers. This list, along with the list generated from the scoping study, was used to contact authors to identify the methods used to characterize groundwater quality. To best characterize the area of interest, this effort focused on brackish water studies and reports that are relevant to Texas and other western/southwestern States that most commonly face brackish groundwater challenges. These contacts are listed in Chapter 8, "Researchers, Companies, and Contact Information."

Note that beyond this basic list of target properties, certain additional properties may be of interest, including the wettability of the host rock, and total dissolved organic material (DOM) concentrations within the aqueous fluid phase within multiphase aquifers (e.g., host rock containing more than one fluid type, such as oil and methane gas and water). Additionally, hydrochemical information, such as detailed constituent dissolved solids and ionic content profiles (assessed from direct testing of water samples) are often of interest, as this information can help inform the relationship and associated conversion factors between TDS and salinity (i.e., electrical conductivity or resistivity) of the groundwater. Here, only certain dissolved solids compounds add to the salinity (i.e., charged ions) which predominantly influence fluctuations in measured electrical conductivities (or resistivity) versus depth and lateral offset. Electrical resistivity logging therefore can offer a good proxy for inferring salinity but can fall short for inferring TDS if a significant amount of dissolved solids does not appreciably influence the measured resistivity values.

This S&T project expands upon the state of practice and methods outlined in the 2016 scoping level effort by delineating the confounding factors identified by that work and presenting research topics to resolve those factors. This current 2017 research effort has identified challenges related to existing geophysical well log data and available analysis techniques, as well as general future research directions or specific research topics that will help to address or solve these existing challenges. This work was aided by inputs from various stakeholders, including key partners identified in the scoping level effort, including: USGS, TWDB, NM-BWWG, and other State and Federal agencies.

2. General Efforts to Characterize Brackish Groundwater

2.1 Federal Efforts

Several Western States, including Arizona, California, Idaho, Kansas, Nebraska, North Dakota, Texas, Utah, and Washington, each host a USGS WSC. These WSCs are often involved in collaborative groundwater resources management and groundwater quality characterization and mapping efforts with State-based entities. These projects predominantly utilize data from water sampling programs and subsequent lab testing and interpolation/plotting of results. Very few of these efforts incorporate the use of geophysical well logging data. The USGS has, however, compiled a national catalog to access water resources data collated in all 50 States that includes depth to water and water quality metrics based on water well data (USGS, 2011). In fact, the Western States Water Council (WSWC), which is one of the main organizational entities involved in assessing conditions and managing groundwater resources in the Western States, including shallow brackish groundwater resources, relies on the use of USGS's National Water Information System.

In addition, several State and Federal government-based entities have recently been working in this focused application area, generally in a larger attempt to map and characterize groundwater resources throughout the United States, and to determine brackish groundwater resources, including a national effort completed by USGS in 2017, which is discussed in more detail below (Stanton et al., 2017). Specifically, the USGS has been actively leading an ongoing effort to assess nationwide groundwater resources and groundwater quality through its National Water-Quality Assessment Program (NAWQA). Recently, the USGS published Scientific Investigations Report (SIR) 2008–5227 and Circulars 1332 and 1360, which include more recent examples from several reports, providing a comprehensive national overview of 41 principal aquifers identified across the U.S., as shown in figure 1 (DeSimone et al., 2009, 2014; DeSimone 2009). These 41 aquifers are also grouped into 8 unique categories based on aquifer host rock/sediment types: (1) volcanic rock, (2) crystalline rock, (3) carbonate rock, (4) sandstone and carbonate rock, (5) sandstone, (6) semi-consolidated sand and gravel, (7) glacial sediments, and (8) unconsolidated sand and gravel (non-glacial).

Additionally, these 41 principal aquifers are divided into 9 categories based on each group's geographic location and geomorphological/depositional environments and conditions. Within these 9 categories, the Western and Southwestern States are observed to be predominantly affected by brackish groundwater conditions (higher TDS) within shallow to intermediate depths below ground surface that include the High Plains aquifers, the Southwestern

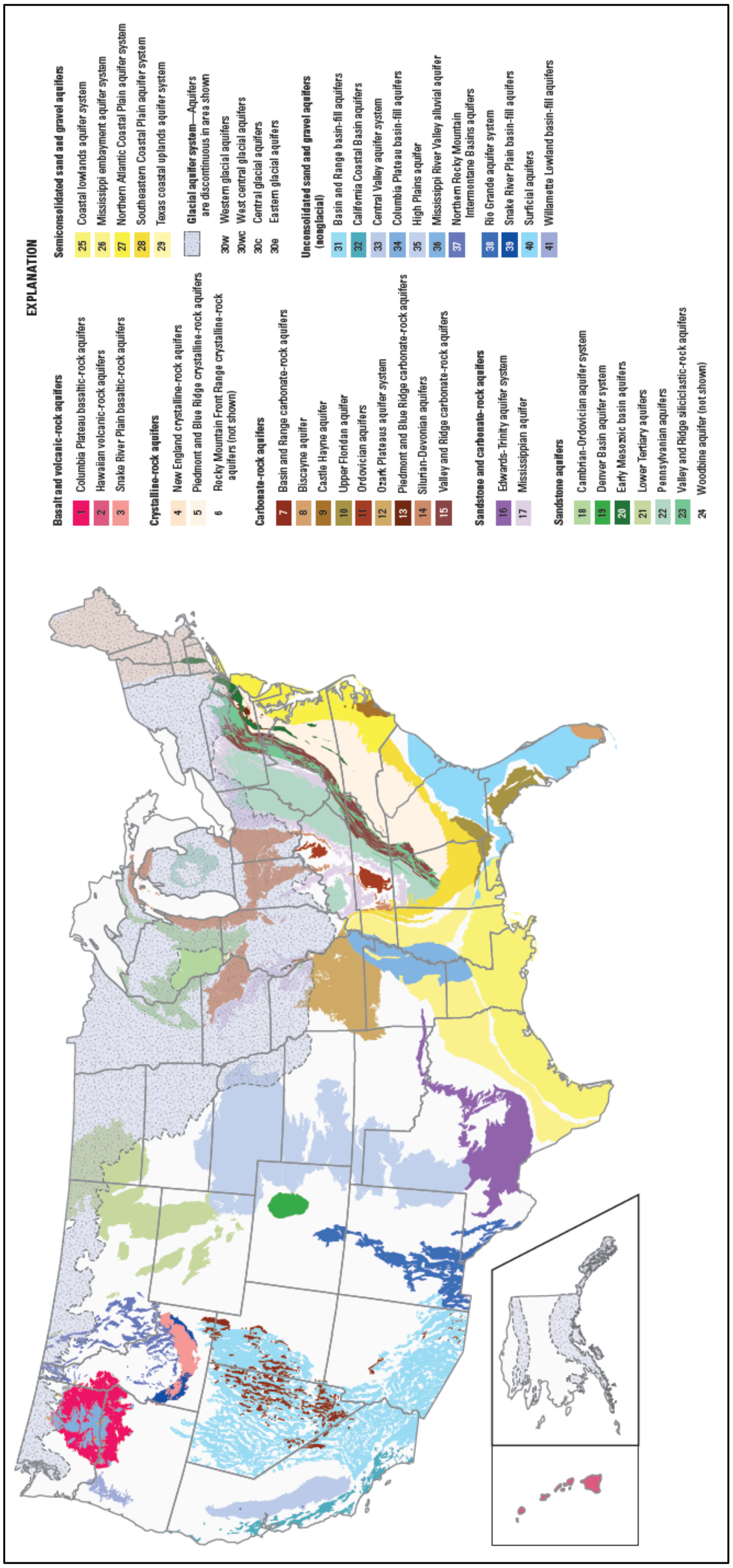


Figure 1. The quality of groundwater in 41 of the Nation's principal aquifers is described in this circular, based on groundwater samples collected between 1991 and 2010. The aquifers are grouped here according to rock or sediment type into categories with broadly similar hydrogeology. The map shows the uppermost regional aquifer in an area; parts of some aquifers are buried beneath other aquifers or geologic units. The principal aquifers shown here provide about 90 percent of the groundwater pumped for public supply. (Source: DeSimone et al., 2014)

basin-fill aquifers, the Mississippi embayment aquifer system, and the Texas coastal uplands aquifer system. Other regions of the United States are affected by brackish groundwater conditions that often result from overlying surface water interactions, irrigation infiltration processes, and oceanic salt water intrusion (see examples in figures 2 and 3).

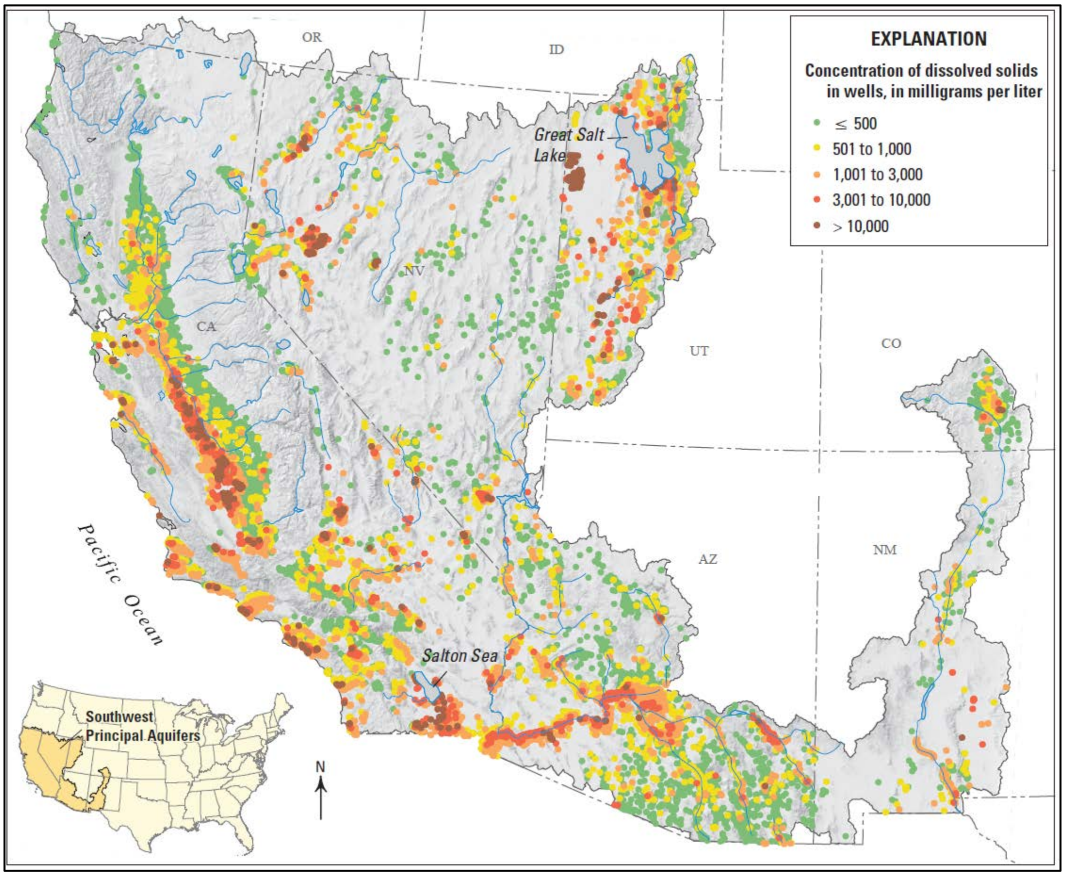


Figure 2. High concentrations of dissolved solids are common in the Southwest basin-fill aquifers. Dissolved solids concentrations shown on this map were measured in water from more than 21,000 wells, primarily water-supply wells, sampled for numerous USGS studies in the region. More than half of the wells had concentrations greater than the recommended upper limit of 500 milligrams per liter (mg/L). (Source: DeSimone et al., 2014)

Furthermore, Stanton et al. (2017) presented USGS Professional Paper 1833, which also encompasses a national perspective of groundwater resources and groundwater quality distributions. This work also predominantly relies on groundwater sampling from existing wells, and other miscellaneous data sources and partnerships, to help define hydrogeologic frameworks. This report serves as one of the most recent and comprehensive summaries of current assessments built upon prior efforts by the USGS. Through the identification of data gaps and limitations, it was inferred that the next challenge regarding possible development of brackish groundwater is to acquire detailed information for specific brackish groundwater aquifers. An exhaustive list of data sources and information obtained from prior USGS publications are presented in detail in tables 2 and 3 of the Stanton et al. (2017) Professional Paper.

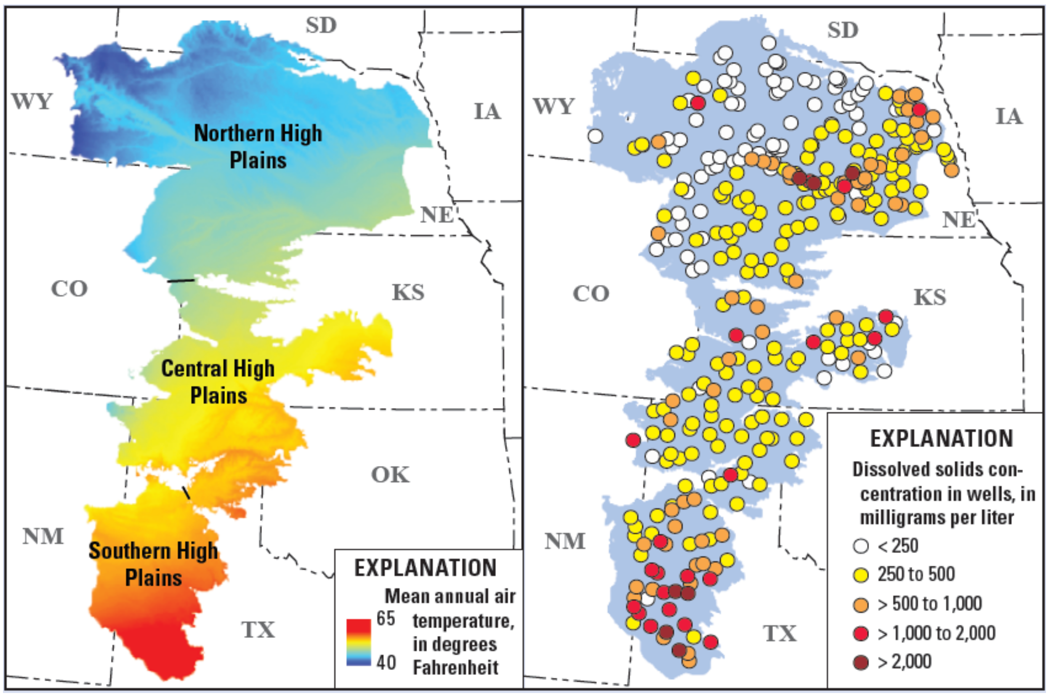


Figure 3. Dissolved solids concentrations in the High Plains aquifer increase from north to south, following broad regional patterns in climate. Data are derived from domestic wells in the Ogalalla aquifer, the primary hydrogeologic unit in the aquifer system. (Source: DeSimone et al., 2014)

Recent studies by the International Groundwater Resources Assessment Centre (IGRAC) and the USGS (depicted in figure 4) show that significant brackish groundwater resources are present within 1,000 to 3,000 feet below ground surface along much of the Eastern and Western United States and are present within 500 feet below ground surface throughout much of the Great Plains (Feth, 1965; Stanton et al., 2017). According to Stanton et al. (2017):

> "At the depth intervals studied, [brackish groundwater] was identified in every State except New Hampshire and Rhode Island. The most extensive occurrence of [brackish groundwater] is observed in a wide band in the central United States that extends from Montana and North Dakota in the north to Texas and Louisiana in the south. States along the Atlantic coast have the most extensive observation coverage; however,

> most of the groundwater in those States is fresh with little [brackish groundwater] except along the coastline. Other notable areas with extensive [brackish groundwater] are in Florida, eastern Ohio, West Virginia, Kentucky, western Pennsylvania, western New York, central Michigan, southern Illinois, northwestern and southern Iowa, northwestern Missouri, west-central Alabama, southern Mississippi, eastern and western Colorado, south-central and southeastern New Mexico, southwestern and northeastern Arizona, most of Utah, northwestern Nevada, and central and southeastern California."

Depth to these resources is an important factor when considering the feasibility and costs associated with developing these brackish aquifers. As a result of the current needs and distributions of brackish groundwater, most of the research and application of geophysical surveys and well-logging methods, as well as other more standard water sampling approaches, are being concentrated in Western States.

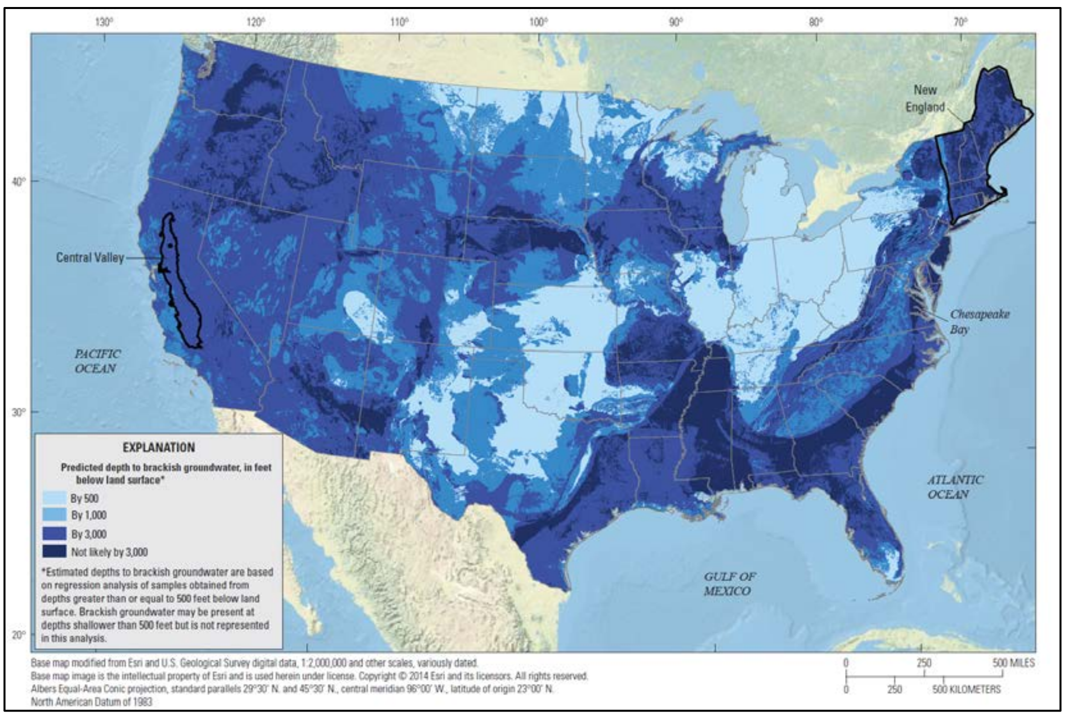


Figure 4. Predicted depth to brackish groundwater resources in the contiguous United States. (Source: Stanton et al., 2017)

2.2 State Efforts

In most cases, federal and state-based groundwater quality characterization studies identified during this literature and technology review focus on shallow to intermediate depths (e.g., approximately the uppermost 1,000 feet of the subsurface). This depth interval is most common for existing water wells that provide water sample data, and it corresponds to the approximate depth coverages of other relevant geophysical data. In some cases, data from oil and gas wells at a deeper depth (several thousand feet deep) are cited; however, groundwater at these depths is typically not of interest due to the economics involved in well development.

As mentioned above, several Western states host USGS WSCs that promote collaborative federal-state partnerships. For example, the Groundwater Ambient Monitoring Assessment Program (GAMA) Priority Basin Project provides an ongoing comprehensive assessment of statewide groundwater quality through a collaborative effort between the USGS, California Department of Water Resources (DWR), the USGS California Water Science Center (CAWSC), and the California State Water Resources Control Board (SWRCB). The overarching goal is to characterize California's groundwater resources within various priority basins identified throughout the State, as depicted in figure 5 (Bennett, 2018). The GAMA project is solely based on the use of well water sampling and monitoring. Well water samples were collected on a grid basis throughout the study area and interpolated to assess groundwater TDS distributions throughout the priority basin.

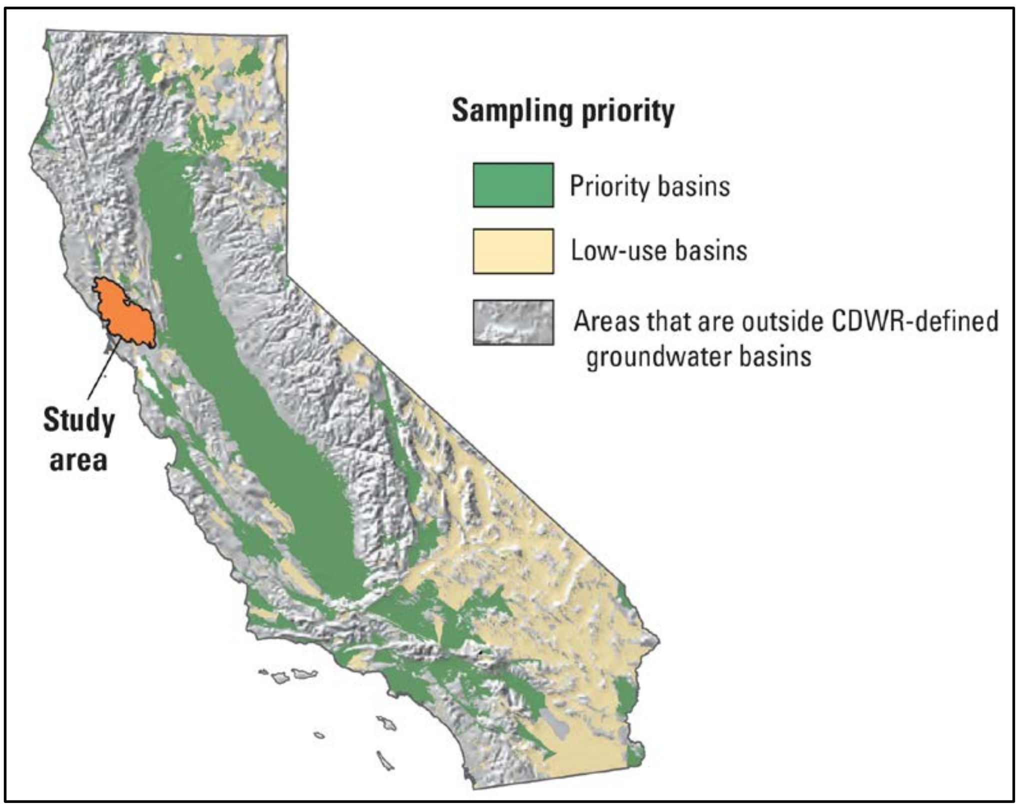


Figure 5. Map of California-based GAMA program's priority basins and the study area for the Bennett 2018 effort.

Nearly identical efforts exist throughout the other priority basins identified throughout California (CAWSC, 2018a). Related reports addressing the status, understanding, and trends of the water-quality assessments done by the GAMA Priority Basin Project are available from the USGS (http://ca.water.usgs.gov/gama/includes/GAMA_publications.html) (CAWSC, 2018a) and the SWRCB (http://www.swrcb.ca.gov/gama/) (SWRCB, 2018).

Other state-based government entities have engaged in similar efforts, including the Arizona Geologic Survey (AZGS) and Arizona Department of Water Resources (ADWR), as well as the New Mexico Bureau of Geology and Mineral Resources (NMBGMR), which is a division of the New Mexico Institute of Mining and Technology (Harris, 1999).

The NM-BWWG, a consortium of entities and agencies in New Mexico, was chartered by the state to identify, evaluate, and develop the brackish resources in New Mexico (NM-BWWG, 2016). In 2004, the NM-BWWG was established under the New Mexico Energy, Minerals and Natural Resources Department to

> "…identify ways to develop new sources of water, including treating brackish water reserves and treating wastewater to extend the life of existing water supplies… identify water-related infrastructure and management investment needs and opportunities to leverage federal and other funding... promote collaboration with and strategic focusing of the research and development of the state's national laboratories and research institutions to address the state's water challenges."

The NM-BWWG has many of the same goals and objectives as the TWDB but has not been in existence very long and is still in the phase of developing proposals and securing funding. Despite its relative newness, a Reclamation (2016) publication notes, "The NM-BWWG has expressed interest in working with TSC, TWDB [and similar stakeholders] for this research." In addition, the NM-BWWG has produced a number of position papers and informational presentations. For example, water quality data and geologic logs were collected for developing a hydrogeologic framework of the Village of Peña Blanca, New Mexico (Rinehart, 2016).

The NMBGMR performed a similar study, assessing the brackish groundwater resources in the Eastern Tularosa Basin of New Mexico. The study was performed predominantly with the use of water quality sampling and interpolations. The NMBGMR study also identified large spatial gaps in available water sample data and made extensive reference to previous work in the basin by Orr and Myers (1986) that utilized surface-based electrical resistivity profiling techniques to help map and infer groundwater quality distributions (Newton and Land, 2016).

In Utah, the Utah Geological Survey (UGS) is primarily involved in the assessment of groundwater resources and groundwater quality. Groundwater quality is classified by the Utah Water Quality Board primarily by the amount of TDS in the water (UGS, 2018). Several basin-scale hydrogeologic studies have been conducted throughout the state, primarily utilizing water use and recharge maps, as well as well water sampling and testing for TDS and various other contaminants. These studies apparently did not rely on log data for informing groundwater quality or aquifer characteristics, although drillers' logs were used for determining lithology (Lowe et al., 2002, 2003, 2004; Bishop, 2008).

In Nevada and Colorado, several hydrogeologic studies have been conducted on basin-scale areas. Studies involving the use of geophysics for assessing groundwater salinity, however, are very sparse (Ball, 2015; Bedinger and Harrill, 2012). In Ball et al. (2015), airborne electromagnetic (AEM) surveys were used to map salinity within alluvial basin infill. Bedinger and Harrill (2012) only briefly mentioned the use of geophysical surveys for mapping basin infill. Similar studies with an emphasis on the use of AEM were also performed in Arizona, Nebraska, and California (Abraham et al., 2012; Bedrosian et al., 2014; Rittgers, 2018).

In a 2018 telephone conversation, Mathew Sares, Colorado Division of Water Resources (CO-DWR), expressed unawareness of any programs or research focused on the use of geophysical well logging explicitly for brackish groundwater characterization or salinity/TDS mapping purposes. Sares could recall only one project, the Windy Hill Project near Fort Morgan, where "higher TDS water is being developed for potential frack-water use by the oil and gas industry. Other than that, it's all fresh water," (Mathew Sares, personal communication, 2018).

One study, however, in Colorado's Denver Basin area, made note of the use of geophysical well logs (SP) and short and long-normal resistivity logs) for helping to constrain lithologic units at depth and enable cross-well correlation efforts. In this study, Denver Basin Group hydrogeologic unit geometries were interpreted based on rock outcrop mapping data and correlations observed across multiple geophysical logs (Barkmann et al., 2011, 2015).

3. Use of Geophysical Well Logs to Characterize Brackish Groundwater

3.1 Federal Efforts

The only Federal efforts specific to interpretation of well logs are those currently being undertaken by Reclamation in collaboration with TWDB. This chapter provides details about this collaborative effort.

3.2 State Efforts

Only a select few State studies have specifically utilized geophysical well logging techniques as a significant component for analyzing and characterizing brackish groundwater quality throughout larger study areas.

3.2.1 Arizona

In Arizona, numerous water quality studies have been implemented. One state-wide AZGS study, which made an effort to map and assess the salinity of deep groundwater across the state, was presented in an AZGS 2012 Open-File Report OFR-12-26 (Gootee et al., 2012). In this study, water samples were predominantly utilized to map the distributions of TDS at depth, and data obtained from the AZGS Oil and Gas Conservation Commission (AZ OGCC) were used to locate wells in the Colorado Plateau that had driller logs, geophysical logs, and mud-logs associated with them. According to Gootee et al. (2012), "reported salinity data were extracted," and these values were then added to the [AZGS] salinity database. While the gathering of geophysical well logs was reported, no details were provided to explain how the log data were utilized to estimate TDS values.

On April 26, 2018, Reclamation and Arizona Water Science Center (AZWSC) engaged in a conference call to discuss the group's previous work and future opportunities for interagency collaborative research efforts focused on well log analysis for groundwater characterization. While the group has not yet employed borehole geophysics to a great extent, a high level of interest was expressed in such future collaborative research efforts.

In addition, information was also obtained through correspondence with Alissa Coes and Jamie Macy, AZWSC (Coes and Macy, personal communication, 2018). It states:

> "The Arizona Water Science Center does not have any current projects using GP well log analysis to characterize brackish groundwater. However, groundwater is a challenge in Arizona, and we do have several

> people here with vast expertise in geophysics, including down-hole methods. This is an area, therefore, that we'd be very interested in pursuing. We have used ground-based methods (TEM) to characterize areas with brackish groundwater and have written proposals to map brackish groundwater using Airborne EM. I [Alissa] have expertise in water-quality and Jamie Macy has expertise in geophysics."

This potential Federal-State interagency partnership offers the opportunity to further research, develop, and adopt new advanced geophysical well log analysis techniques for brackish groundwater characterization.

3.2.2 Arkansas

In Arkansas, there are state-level efforts underway to provide groundwater characterization and management strategies based on use needs and groundwater resources within 16 aquifers that span the state (defined by unique hydrogeologic and geochemical settings). According to a recent USGS study, these 16 aquifers are further grouped into two major "physiographic regions of the State: (1) the Coastal Plain Province (referred to as Coastal Plain) of eastern and southern Arkansas, which includes 11 of the 16 aquifers; and (2) the Interior Highlands Division (referred to as Interior Highlands) of western Arkansas, which includes the remaining 5 aquifers (Kresse et al., 2014).

One of the components of this larger assessment effort includes the Mississippi Embayment Regional Aquifer Study (MERAS), which covered the extent of the Mississippi embayment, including eastern Arkansas. According to Kresse et al., 2014, "A numerical groundwater-flow model was developed to explore the effects of human activities and climate variability on groundwater levels, changes in aquifer storage, and flow between groundwater and surface-water bodies." Kresse et al. (2014) also describes previous efforts by Hart and Clark (2008) and Hart et al. (2008) involving the use of analysis tools and databases integral to the MERAS model construction, which included a database of over 2,600 geophysical logs used in the construction of the hydrogeologic framework. Clark and Hart (2009) utilized geophysical logs to assess the spatial extents and thicknesses of various hydrogeologic units within the MERAS model, as well as to estimate the percentage of clean sand throughout the Mississippi Embayment Aquifer.

In addition, a groundwater study related to the MERAS effort was conducted within the Ozarks Plateaus Aquifer system as part of the USGS Regional Aquifer Systems Analysis (RASA) program. This study used several various data types, as well as geophysical log data, to help develop hydrogeologic and hydraulic parameters of the system (Kesse et al., 2014). No specific information was located, however, to explain how the log data were used to produce various system model parameters. In each case, Kesse et al. (2014) describe the use of extensive water sample analysis for sake of identifying geochemical quantities and distributions within the various aquifers throughout the state.

USGS performed another recent study in Arkansas (USGS SIR 2014-5068) aimed at characterizing one of the main brackish groundwater aquifers using various data types, including geophysical well logs, to estimate aquifer thickness and TDS distributions (Gillip, 2014). Note that this aquifer extends approximately 5,000 feet below ground (below shallower and fresher aquifers), making this one of the deeper brackish groundwater characterization studies identified in this review.

According to Gillip (2014), the Nacatoch Sand and Tokio Formations are Upper Cretatceous aged units within the Mississippi Embayment that extend across much of southeastern and southern Arkansas. These formations contain rich groundwater resources, but large portions of the aquifers have high concentrations of dissolved solids. In the Gillip (2014) study, historical geophysical logs were used to estimate the concentration of dissolved solids, interpret characteristics of lithological contacts, identify the thickness of the stratigraphic layers and altitude, and measure the thickness of clean sand percentage for future groundwater development. A database of over 22,600 wells was queried to locate logs in the Nacatoch Sand and Tokio Formation. Those well logs were comprised of the following geophysical methods:

1. Gamma
2. Spontaneous potential (SP)
3. Resistivity

All three borehole log types were used in lithological interpretations and were considered when additional logs were selected from previous investigations. Additionally, the distribution of percentage clean sand was qualitatively estimated using primarily SP logs to help estimate volumetric quantities. The top of the Nacatoch Sand was determined from 635 geophysical boreholes, and the bottom was determined from 417 logs, giving a thickness range of 0-550 feet. The Tokio Formation used 437 geophysical borehole logs for the top, and 232 for the bottom, giving a thickness range of 0-400 feet. The estimated thickness and structure were in close agreement to previous published investigations, with the difference in thickness attributable to less data available in previous work.

Water quality (e.g., R_w) calculations used the temperature compensated resistivity ratio method, otherwise known as the “quick-look method,” in the oil and gas industry because of the use of historical log data. For compensation, the temperature at sample depths was interpolated by taking the average annual air temperature (60.4 degrees Fahrenheit [°F]) and the reported bottom hole temperature from the log. Where no temperature was reported, the geothermal gradient from a nearby well with a recorded temperature was used. In the Gillip

(2014) study, "the temperature compensated R_w was calculated using the methods described in Jorgensen (1990, 1996), and R_w was then related to specific conductance (SC) and dissolved solids using the methods described by Jorgensen (1996) and Hem (1985).

3.2.3 California

In California, recent research efforts related to the GAMA program have been conducted by the California Oil, Gas and Groundwater (COGG) Program in cooperation with the California State Water Resources Control Board and various regional water quality control boards. COGG's efforts include more relevant uses of geophysical well logging data for groundwater quality mapping in California. Gillespie et al. (2016 and 2017) implemented water sampling in conjunction with geophysical well logging data to help address data gaps (spatial sparsity of water sample data) to map the three-dimensional (3D) distribution of TDS in and around oil and gas field within the San Joaquin Valley and published the general results. Several additional publications related to this San Joaquin Valley study provide a greater focus on specific methods used to integrate water quality sample data and geophysical log data (Shimabukuro and Ducart, 2016; Shimabukuro et al., 2016, 2018).

According to CAWSC's COGG program website, "Determining where protected groundwater resources are in relation to oil and gas resources and production activities is a key step in answering the question *What lies between oil and gas operations and protected water?*" (CAWSC, 2018b). Here, analysts explain how they are "mining information from existing oil and water well records." Specifically, they are using several different approaches to address spatial gaps, including:

- Compiling water-quality sampling data from existing records and plotting them in three dimensions
- Expanding spatial coverage by using borehole measurements made when oil and water wells are drilled to calculate salinity
- Expanding spatial coverage beyond drilled wells and oil fields using ground-based and aerial measurements (CAWSC, 2018b)

COGG and partners emphasize the usefulness of existing geophysical well logs made available from oil and gas wells for brackish groundwater characterization. Specifically, "borehole geophysical log data from oil wells commonly span the depth intervals between where water and oil well casings are perforated and can be used to estimate salinity in these gaps" (CAWSC, 2018a). Figure 6 depicts the depth coverage data available from both shallow water samples and deeper well logs. Here, "several different methods using a combination of produced water geochemistry and borehole geophysics have been used to understand deep groundwater TDS, where various data types can be extrapolated into three dimensions using geostatistical methods, such as kriging, that allow spatial heterogeneity to be better represented" (Shimabukuro et al., 2018).

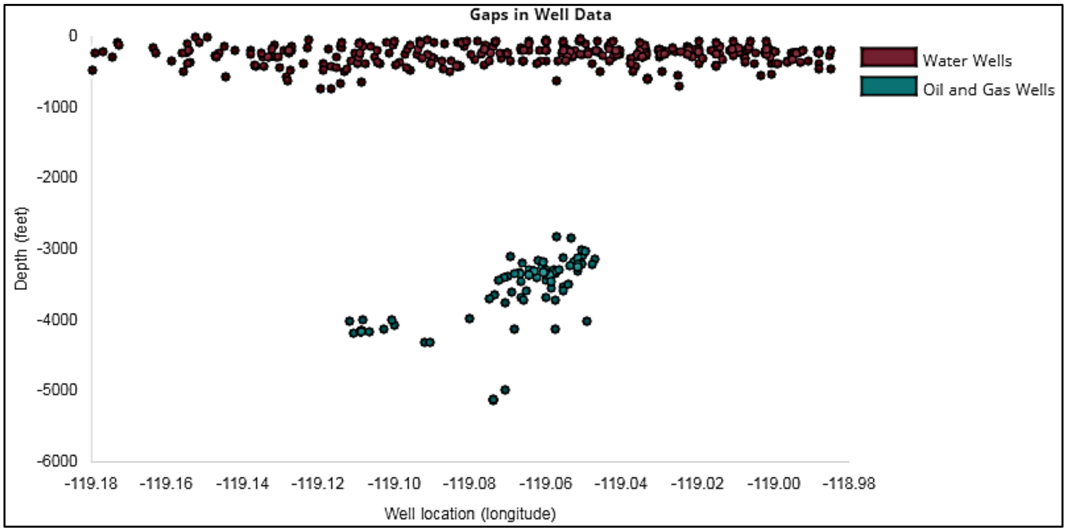


Figure 6. Graph depicting the gap in data below water wells and above the top of the oil producing interval. (Source: CAWSC, 2018b)

According to CAWSC (2018a), the COGG program utilizes geophysical log analysis techniques provided in Shimabukuro and Ducart (2016) and Shimabukuro et al. (2016) to calculate salinity along the depth profile of an individual well. The process is generally described by CAWSC (2018a) as using the following steps:

1. Trace the resistivity lines on the scanned image (resistivity log) to create a numerical record

2. Select depth intervals on the resistivity line that reflect the right conditions for applying salinity equations

3. Apply Archie's equation for estimating salinity, and

4. Convert to TDS based on salinity equations and various geospatial statistical analysis methods (e.g., inverse methods of data fitting using Kriging and nearby water quality data).

In addition to the borehole geophysical log data, AEM was employed to help further address data gaps (e.g., to fill in the vertical data gap in depth ranges between water samples and underlying oil and gas well logs, as seen in figure 6) and to laterally extend the TDS estimations to areas between and beyond wells

(CAWSC, 2018b). Here, CAWSC explains that available TDS data do not provide "adequate coverage to clearly define the distribution of underground sources of drinking water near the oil fields. Therefore, [existing] geophysical logs from 50 oil and gas wells were evaluated to fill spatial gaps." CAWSC further explains that Archie's equation was implemented in conjunction with kriging interpolation and iterative regression analysis to predict TDS values throughout the study area. This analysis approach involved the use of resistivity, porosity, and temperature log data from the 50 existing wells to parameterize Archie's equation, and the iterative regression analysis was employed to best-fit modeled values with all available TDS data throughout the study area (CAWSC , 2018b).

Analysts involved in the San Juaquin Valley groundwater study explain the implemented analysis process as involving manual digitization of scanned resistivity well logs to create a digital dataset for each available paper well log, identifying clean sandy intervals that are suitable for applying salinity equations, and, finally, performing 3D interpolation of estimated salinity values throughout the study area (Shimabukuro and Ducart, 2016; Shimabukuro et al., 2016). The COGG program website also explains that the "basic procedure for digitizing scanned images is labor-intensive and finding more efficient techniques is important" (CAWSC , 2018b; Gillespie et al., 2016). This point is one of the identified potential future research topics listed in Chapter 7, "Conclusions and Recommendations," of this report).

Several related publications that describe a similar significant use of geophysical well log data analysis for addressing water sample data gaps were recently produced for a study conducted in the vicinity of the Fruitvale and Rosedale Ranch oil fields near Bakersfield, California. These include Stephens et al. (2018a, 2018b) and Wright et al. (2018).

3.2.4 Indiana and Ohio

In Indiana and Ohio, one notable groundwater characterization study was carried out in 1995 that involved the detailed use of geophysical well log analysis for brackish groundwater characterization (Schnoebelen et al., 1995). According to Schnoebelen, the Midwestern Basins and Arches Regional Aquifer System Analysis study was initiated in 1988 as part of the USGS RASA program. "The objectives of the Midwestern Basins and Arches-RASA project are to define the geology, hydrology, geochemistry, and regional groundwater-flow system in glacial and Silurian and Devonian carbonate-bedrock aquifers" (Bugliosi, 1990). This study encompasses most of central Indiana and western Ohio, an area of approximately 43,000 square miles (111,370 square kilometers) (Schnoebelen et al., 1995).

In the Schnoebelen et al. (1995) study, analysis of geophysical logs obtained in 157 hydrocarbon exploration boreholes was carried out to the estimate TDS boundary of <10,000 mg/L in Devonian and Silurian carbonates where groundwater data was sparse. For this effort, three methods were used to calculate the R_w values in determining TDS:

1. Static-spontaneous potential (SSP); otherwise called the SP Method

2. Mud filtrate-resistivity (Quick-Look); otherwise called the Resistivity Ratio Method

3. Resistivity porosity method; otherwise called Archie's equation

For the resistivity-porosity method (Archie's equation), the cementation exponent and porosity values were estimated using tests on 19 core log samples from 7 counties that measured grain density, permeability, and porosity to be incorporated into the geophysical calculations for greater accuracy.

One of the more unique aspects of the Schnoebelen et al. (1995) study is that the TDS concentrations derived from the geophysical log data were compared to chemical analysis of groundwater from previous studies. Previous work on the saltwater characterization occurred in 1959, when 185 samples of groundwater were chemically classified in 20 stratigraphic units in Indiana and bordering Illinois and Kentucky. A 1983 study compiled 247 additional chemical analyses for 10 stratigraphic units. In addition, a 1984 study examined TDS in 12 counties. Most of these previous studies described by Schnoebelen et al. (1995) focused on the southwestern part of the state, where the greatest oil and gas production took place.

Of the three methods mentioned above, statistical analysis comparing the estimated TDS from the geophysical methods to the chemical analysis indicated that the resistivity porosity method (Archie) had the best correlation. The SP method had the next best statistical correlation, but it was inconsistent across the samples. Resistivity ratio method did not correlate very well at all.

3.2.5 Nebraska

Nebraska has been very active in groundwater exploration and hydrogeologic framework characterization efforts over the last decade. Many studies have included extensive airborne electromagnetics geophysical mapping surveys in conjunction with geophysical well log data interpretation and water quality testing to enhance understanding of groundwater resources and groundwater-surface water interactions. Specifically, the Eastern Nebraska Water Resources Assessment (ENWRA) project aims to better understand groundwater conditions throughout several counties and groundwater management districts.

As an example, part of the ENWRA project was conducted by the USGS within the North and South Platte Natural Resources Districts, as part of the Cooperative Hydrology Study (COHYST), which is a hydrogeologic study of surface water and groundwater resources in the Platte River Basin of Nebraska (Abraham et al., 2012). In this particular study, ground-based geophysical data, borehole lithology, and geophysical logs were used to help constrain the interpreted lower boundary of the local aquifer. No extensive use of borehole geophysical well log data or analysis methods were reported for estimating salinity or TDS. Reports for other surveyed areas of the ENWRA project show similar workflows, where geophysical well log data are mainly used to help constrain and validate lithologic interpretations based on airborne geophysical survey results (ENWRA, 2019).

One USGS study, unrelated to the ENWRA project, focused on the use of borehole geophysical log data for mapping lithology (Anderson et al., 2009). As part of this investigation, a comprehensive set of geophysical logs was collected from six test holes at three sites and analyzed to delineate the penetrated stratigraphic units within the Ogallala Formation (depths to approximately 500 feet) and characterize their lithology and physical properties. The integrated analysis of the geophysical logs showed the value of these methods for detailed characterization of the hydrostratigraphy of the High Plains aquifer. While well log data are presented in the Anderson et al. (2009) report, few details are provided regarding the specifics of log analysis workflows for mapping the hydrostratigraphy of the aquifer. Furthermore, this study did not report the use of well log data analysis specifically for estimating water quality.

3.2.6 New Mexico

NMBGMR has been involved in the Aquifer Mapping Program (AMP), an effort that characterizes groundwater resources and groundwater quality throughout the State of New Mexico. According to its website, NMBGMR has been

> "…engaged in hydrogeologic studies of New Mexico's aquifers in cooperation with partners at the New Mexico Office of the State Engineer, the New Mexico Environment Department, the U.S. Geological Survey Water Resources Program, and other federal, state, and local agencies. Beginning with geologic mapping and aquifer analysis in the Albuquerque Basin and a hydrogeology study in Placitas, NMBGMR developed an Aquifer Mapping Program to apply a combination of geologic, geophysical, hydrologic, and geochemical information to develop descriptive models of groundwater flow in important aquifers around the state." (NMBGMR, 2018)

For this effort, geophysical logs were obtained from the New Mexico Oil Conservation Division (NM-OCD) oil and gas well data repositories. Specifically, the NM-OCD's Imaging System provides public access to "view and download over 4 million documents including: Well files, Well logs, Administrative and Environmental Orders, Hearing Orders and Case Files" (NM-OCD, 2019).

In a related NMBGMR Open File Report 583, state-wide water quality data were compiled from various sources, including newly digitized historic regional water quality reports, more recent NMBGMR water chemistry data from the Aquifer Mapping Program, and data from the USGS, in order to extend the assessment of brackish groundwater supplies on a state-wide basis. Among the data utilized, geophysical surveys, regional investigations of deep aquifer systems, water chemistry from deeply sourced artesian springs and deep exploratory wells "suggest that more saline groundwater probably does exist at greater depths in some areas of New Mexico, and possibly in large quantities" (Land, 2016). These assessments of brackish groundwater distributions are similar to those presented by Kelley et al. (2014), where a strong correlation is observed between depth and salinity in brackish aquifers. An opposite relationship, however, was observed in southern Arizona, near Yuma and the South Gila Valleys, suggesting this depth-salinity relationship is not universal and likely varies laterally on a basin or sub-basin scale (Rittgers, 2018).

In a "Future Work" section of Land's 2016 report, several references are made to the use and value of borehole geophysical logs for calculating groundwater salinity in the assessment of groundwater resources in the San Juan Basin. Here, Land (2016) refers to the prior work of Kelley et al. (2014), which used the standard method of calculating pore fluid salinity for wells that had spontaneous potential logs (methodology and analysis workflow is summarized by Kelley et al., 2014; SP method details are presented in Asquith and Krygowski, 2004). In this same section of the NMBGMR report, Land states that "[surface and airborne] geophysical investigations that supplement our existing water chemistry data probably have the most potential to more precisely evaluate brackish water resources in individual basins in New Mexico" (Land, 2016).

Note that NMBGMR is a promising source of geophysical well log data, geologic logs, and water quality data for use in future collaborative research efforts. Specifically, the New Mexico Subsurface Data, Core & Cuttings Libraries contain more than 20,000 boxes of New Mexico core (oil and gas core and mining core), cuttings from more than 16,000 wells in New Mexico, [geophysical] logs from 50,000 New Mexico wells, maps of frontier and the lesser productive counties showing locations of oil and gas exploratory wells, and other useful subsurface geologic data. An additional related potential source of data for future research collaborations is the USGS National Geological and Geophysical Data Preservation Program (NGGDPP).

One study that is particularly relevant to the use of geophysical well logging analysis for groundwater quality assessment is USGS Water Resources

Investigations Report 95-4300 (Hudson, 1996). As summarized in that report, the effort was conducted and prepared in cooperation with the City of Albuquerque. It describes methods that can be used to estimate groundwater quality and aquifer permeability through the use of geophysical logs made in freshwater wells. The employed methods were developed using data collected from water wells completed in basin-fill deposits in the Rio Grande Rift from near Santa Fe to the southern boundary of New Mexico (figure 7).

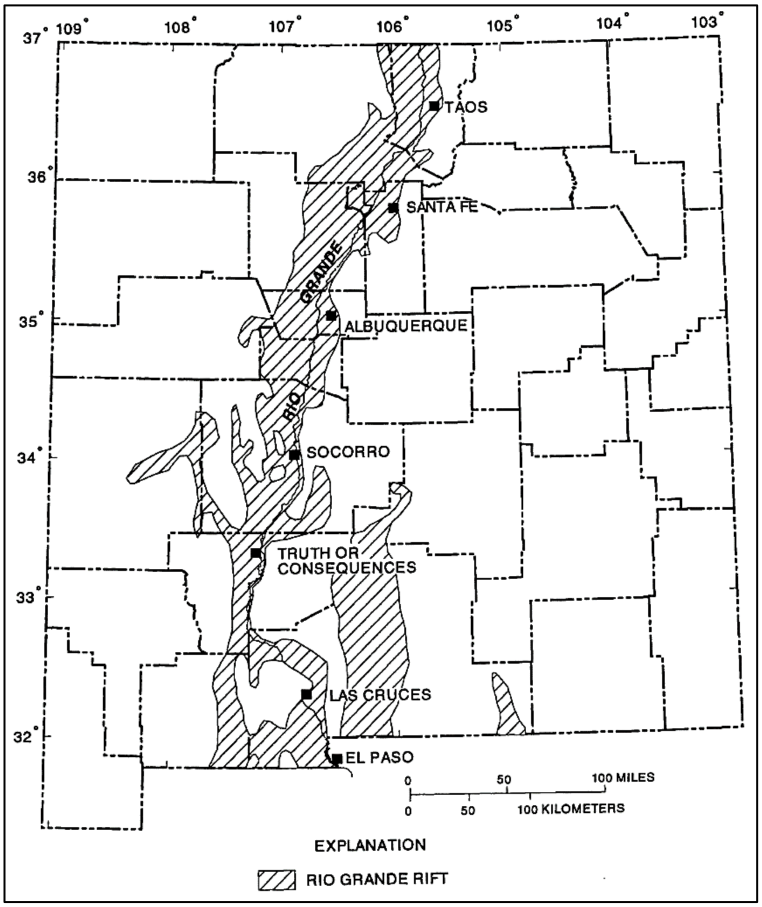


Figure 7. Location of the Rio Grande Rift in New Mexico.

The Hudson (1996) report also presents a relevant summary of previous research conducted to better account for hydrogeologic factors that influence the formation factor, and negatively affect standard approaches to inferring water quality from normal resistivity logs. Here, an ongoing challenge is to separate out the influences of the matrix (host aquifer material) from the electrolyte (groundwater) influences of upmost interest on measured resistivity logging data.

In Hudson's work, gamma ray, neutron density, and short and long-normal resistivity logs are used to correlate geophysical-log responses to known characteristics of freshwater aquifers and sedimentary units. This approach is quite similar to various studies that utilize water samples to ground-truth or calibrate and interpolate water quality values and lithology from cuttings samples throughout a larger study area. Hudson extended previous efforts by utilizing neutron logs to estimate the correction value for surface or matrix conduction, assuming that decreases in grain size result in increases in surface conduction and that clay has small grain size that results in increases in total porosity. This method was effective in improving groundwater resistivity (R_w) values in various sedimentary units of varying quality and, hence, surface conductivity.

Additional recent work in New Mexico that utilized geophysical data includes a hydrogeologic investigation of the Southern Taos Valley (Johnson et al., 2016). This investigation describes the extensive use of results from geophysical surveys to help construct a hydrogeologic framework. According to the final report,

> "A number of existing and new geophysical studies in the area were incorporated into this investigation. Each of these geophysical techniques can be used alone to provide useful constraints on the subsurface geology, but the real value of these techniques is that when they are interpreted collectively by a geophysicist, they can provide immensely valuable, detailed information on the subsurface geology" (Johnson et al., 2016).

Specifically, it was reported that airborne magnetic and gravity surveys were utilized in conjunction with borehole data to help build a detailed geologic model of the basin. According to Johnson et al. (2016), "[several prior studies] have provided updated interpretations of regional geophysical studies of the southern San Luis Basin." Each of these prior studies referenced by Johnson (2016) report the use of airborne and borehole geophysical surveys to establish geologic cross sections and basin-scale hydrogeologic models (Grauch and Keller, 2004; Bankey et al., 2006; Grauch et al., 2004, 2004b, 2009, 2015).

Finally, a recent hydrogeologic study that used a significant amount of geophysical data was performed in New Mexico (Teeple, 2017). This study made use of new surface-based geophysical and geochemical surveying coupled with previously published geophysical studies in Doña Ana County, New Mexico, and El Paso County, Texas. Here, 3D data from previously published airborne frequency-domain electromagnetic surveys and one-dimensional direct-current electrical resistivity soundings were combined with newly collected time-domain electromagnetic soundings to perform a combined inverse modeling approach to mutually interpret all data types simultaneously. The results of the combined 3D electrical conductivity model were then combined with various ionic tracer studies to infer groundwater recharge zones and water quality distributions throughout the study area (Teeple, 2017).

3.2.7 Oklahoma

The OWRB recently received new statutory authority to permit water wells from 5,000-10,000 ppm TDS, prompting OWRB to develop rules and construction standards. In 2018, the OWRB organized a Marginal Quality Water Mapping Brackish Groundwater work group comprised of federal, state, and non-governmental organizations with vast amounts of technical and regulatory experience in brackish water. OWRB has a vision that these marginal waters could be used as source water. The goal is to develop a statewide brackish groundwater map contouring different zones of brackish water. A pilot project is currently under consideration. Opportunities have been identified that include hydraulic fracturing of source water, managed aquifer recovery, active storage and recovery, and guidance on which areas should not be drilled for fresh water.

3.2.8 Texas

In Texas, there has been interest in state-wide brackish groundwater quality and quantity studies that have been conducted for several decades. A program to evaluate geophysical logs for groundwater salinity began in 1950 to provide recommendations on setting and cementing surface casing for oil and gas wells. The objective was to protect groundwater aquifers with a salinity of 3,000 mg/L or less. The program was transferred from the Railroad Commission of Texas to the Texas Board of Water Engineers in September 1955 and migrated to a number of water agencies until 2002. The program was transferred back to the Railroad Commission of Texas in 2002, along with staff, a paper geophysical well log library of over 300,000 logs (known as Q-logs), and a set of linen property ownership maps with water data spanning 1955-1999. John Estepp documented the log analysis techniques in two unpublished reports (Estepp, 1998; 2010) that are the basis of log analysis used by the TWDB Brackish Resources Aquifer Characterization System program (BRACS) program.

In 1956, USGS studied the saline water resources of Texas (Winslow and Kister, 1956). This study led to the development of the salinity classification system which is still in use. In 1972, TWDB contracted with Core Laboratories to evaluate the subsurface saline water resources compiled in an eight-volume report (Core Laboratories, 1972). TWDB contracted with LBG-Guyton Associates in 2003 to evaluate the brackish water resources of the 30 major and minor designated aquifers in Texas (LBG-Guyton, 2003). This study formed the basis for the 2.7 billion acre-feet of brackish groundwater estimate often cited in Texas studies. The Texas Legislature provided funding in 2009 for brackish groundwater characterization once the magnitude of the brackish resource was understood. This funding led to the development the BRACS program in 2009 to map and delineate brackish groundwater and promote desalination projects in Texas.

In a 2015 effort led by the USGS, in cooperation with the San Antonio Water System, the brackish water movement and potential lateral brackish water intrusion on adjacent water supply wells was assessed within the Edwards Aquifer, San Antonio, Texas (Brakefield et al., 2015). According to the report, several prior surveys had been conducted to better characterize the fresh-brackish groundwater transition zone by using water-level measurements, lithologic logs, temperature logs, and various geophysical logs that were obtained in wells that "traverse the transition zone (transect wells)" (Brakefield et al., 2015). These prior studies were conducted by Lambert et al. (2009), Lambert et al. (2010), and Thomas et al. (2012). In these prior studies, the brackish-fresh groundwater interface was studied using both indirect and direct salinity methods. Lambert et al. (2009) utilized resistivity logs to infer salinity, and Thomas et al. (2012) used direct formation fluid conductivity and flowmeter data to identify salinity values and infer the transition zone(s).

According to the Brakefield et al. (2015) report, all available geophysical well logs within the study area were searched, and 120 well logs were identified that provided the necessary data to estimate formation water salinities along the corresponding borehole paths. These estimated values were then combined with all directly measured conductivity values to produce a 3D model of salinity distributions throughout the study area. Geophysical logs for this study were obtained from the Railroad Commission of Texas Oil and Gas Well Logs database (Railroad Commission of Texas, 2012).

The Brakefield et al. (2015) report also describes the use of kriging of salinity values and difficulties encountered in this final step of the analysis process due to spatial data gaps and a lack of spatial coherence in the salinity values (Isaaks and Srivastava, 1989; Oliver et al., 2008). Difficulties encountered while attempting 3D kriging were apparently overcome by implementing a series of two-dimensional (2D) horizontal kriging interpolations across eight assigned elevation intervals (e.g., layers). The implied lack of vertical coherence in salinity values could be due to inaccurate corrections applied for formation factor influences on the measured bulk resistivities and subsequently inferred salinity distributions along borehole paths. 2D interpolations across each of the eight layers were performed using "ppk2fac" and "fac2real" utilities that were developed by a cross-industry research and development consortium titled Model-Independent Parameter Estimation & Uncertainty Analysis (PEST) (Doherty, 2003, 2005, 2011, 2015; Doherty et al., 2010a, 2010b; Doherty and Hunt, 2010; Doherty and Welter, 2010).

The Brakefield (2015) report also provides a review of the Archie and SP methods used in analysis, and "where possible, the Archie and SP methods were used to estimate dissolved-solids concentrations, and an average of the two dissolved-solids concentrations was computed. Three-dimensional grids were created from dissolved-solids estimates and reviewed for outliers, which were removed from the dataset" (Brakefield et al., 2015). These methods and considerations are discussed in more detail in Chapter 6, “Addressing Data Gaps Associated with Well Log Interpretation.”

Today, the TWDB is considered to be on the forefront of specifically utilizing geophysical well logging data for characterizing brackish aquifers in the state of Texas. TWDB provides regional water planning, water use surveys, groundwater availability models, data collection, and technical assistance services. The TWDB has designated 31 major and minor aquifers in Texas (George et al., 2011) and has constructed a water well database and document collection for over 139,000 wells used to describe aquifer conditions. The mapped extent of the major and minor aquifers includes fresh to slightly saline water for all but one aquifer. Information is extremely limited for sections of aquifers with a salinity greater than 3,000 mg/L, and this mapping is occurring in the BRACS program.

Furthermore, passage of House Bill 30 (84th Texas Legislature) in 2015 directed the TWDB to map brackish groundwater production zones, recommend groundwater monitoring, and estimate zone production over a 30- and 50-year period. Eight aquifer studies were contracted: Blaine, Blossom, Carrizo-Wilcox, Gulf Coast, Nacatoch, Rustler, Queen City and Sparta, and the Trinity. Of the several log analysis techniques used in these studies, the Rustler Aquifer study by Lupton et al. (2016) was the most comprehensive.

The BRACS projects have identified geophysical well logs and data that can help map the geologic structure of aquifers and estimate groundwater salinity. The BRACS projects have also compiled a bibliography of reports, articles, and graduate research papers that focus on Texas geologic formations containing brackish groundwater and their potential for extraction and desalination (TWDB, 2016). The TWDB sponsored reports for the Pecos Valley Aquifer in West Texas (Meyer et al., 2012), Queen City and Sparta Aquifers in Atascosa and McCullen Counties (Wise, 2014), and the Gulf Coast Aquifer in the Lower Rio Grande Valley (Meyer et al., 2014). These reports all identified a lack of detailed information on brackish aquifers.

The following subsections summarize the research purpose, methods, key findings, benefits, and future improvements for three representative TWDB efforts carried out in the State of Texas: the Pecos Valley Aquifer, the Queen City and Sparta Aquifers, and the Gulf Coast Aquifer.

3.2.8.1 Pecos Valley Aquifer, West Texas: Structure and Brackish Groundwater (Meyer et al., 2012)

3.2.8.1.1 Purpose of Research. The Pecos Valley Aquifer in western Texas was chosen for a pilot study as part of the BRACS program because brackish groundwater in the aquifer is the major water supply for this area. The report

(Meyer et al., 2012) compiled thousands of well logs to map the geologic formation profiles and analyzed aquifer test data to characterize brackish groundwater in the Pecos Valley aquifer. The objective was to enhance techniques of aquifer data analysis and develop a database management system for future projects and studies. The report also produced a new database, built Geographic Information System (GIS) datasets, and assembled raw well records.

3.2.8.1.2 Methods Used. The SP and Alger-Harrison geophysical well log methods were used in this pilot study and were applied to interpret concentration of TDS. Table 1 summarizes the parameters for these and other common well log interpretation techniques that were discussed but not implemented in the Pecos Valley Aquifer study.

3.2.8.1.3 Key Findings. It was estimated that the Pecos Valley aquifer stores about 15 million acre-feet of fresh water, 85 million acre-feet of brackish groundwater, and 1 million acre-feet of very saline water. Table 2 summarizes these results.

At the onset of this Meyer et al. (2012) study, the intention was to implement, compare, and evaluate several previously introduced TDS analysis techniques (Estepp, 1988 and 2010, as cited in Meyer et al., 2012) using both SP and resistivity well logs throughout the study area. Specifically, these analysis techniques included the SP, Alger-Harrison, resistivity water apparent (R_{wa}) Minimum, Estepp, and Mean R_o methods. Unfortunately, geophysical logs were scarce throughout the Pecos Valley study area, and most logs had inappropriate depth-coverage and other data quality/applicability issues. It was therefore not feasible to use resistivity logs for analysis techniques, so the SP and Alger-Harrison methods were used. Meyer et al. (2012) concluded: “The lack of appropriate geophysical well logs at shallow depths within the study area precluded a thorough assessment of the geophysical well log techniques to interpret the total dissolved solids concentration in groundwater.” Meyer et al. (2012) analyzed two sample geophysical well logs that did have SP and resistivity analysis for TDS and determined:

> “The interpretation of total dissolved solids using the spontaneous potential tool in the Pecos Valley Aquifer study area appears promising, despite the limited number of logs available. Additional work will need to be done to incorporate a cation-correction process for this method. Interested users should continue to look for shallow geophysical well logs that may be available in other collections.” (Meyer et al., 2012)

Table 1. Parameters and Correction Factors Required for Geophysical Well Log Interpretation of TDS Concentrations (Meyer et al., 2012)

Parameter			TDS methods (for calculating R_w)				
Name	**Symbol**	**Units**	**Spon-taneous Potential**	**Alger-Harrison**	**R_{wa} Minimum**	**Estepp**	**Mean Ro**
Depth of well	Dt	feet	Yes	Yes	Yes	Yes	Yes
Depth of formation	Df	feet	Yes	Yes	Yes	Yes	Yes
Temperature at surface	Ts	°F	Yes	Yes	Yes	NA	NA
Temperature at bottom of hole	Tbh	°F	Yes	Yes	Yes	NA	NA
Resistivity of mud filtrate	R_{mf}	ohm-meter	Yes	Yes	NA	NA	NA
R_{mf} temperature	none	°F	Yes	Yes	NA	NA	NA
Spontaneous potential	SP	+/- millivolts	Yes	NA	NA	NA	NA
Deep resistivity	R_o	ohm-meter	NA	Yes	Yes	Yes	Yes
Shallow resistivity	R_{xo}	ohm-meter	NA	Yes	NA	Yes	NA
Porosity	none	percent	NA	NA	Yes	NA	Yes
Correction Factors							
TDS and specific conductivity	ct	none	Yes	Yes	Yes	NA	NA
High anions: R_{we} to R_w	R_{we} to R_w	none	Yes	Yes	Yes	NA	NA
Resistivity: invasion zone	none	none	NA	Yes	NA	NA	NA
Cementation factor	m	none	NA	NA	Yes	Yes	NA
High anions: m correction	m cor	none	NA	NA	NA	Yes	NA
High anions: mean R_o	none	none	NA	NA	NA	NA	Yes
Mean R_o nomograph	none	none	NA	NA	NA	NA	Yes

Notes: NA = not applicable, R_w = water resistivity in the formation, R_{we} = water resistivity equivalent in the formation.

Table 2. Pecos Valley Aquifer Brackish Water Volumes (Meyer et al., 2012)

Water classification (mg/L of TDS)	Volume of aquifer matrix (million cubic feet)	Volume of groundwater (thousand acre-feet)
Fresh water (0-999)	5,345,270	14,725
Brackish water: (1,000-2,999) (3,000-9,999) Total: (1,000-9,999)	 16,784,642 14,151,901 30,936,543	 46,239 38,986 85,225
Very saline water (> 10,000)	331,737	914
Total volume Pecos Valley Aquifer (saturated thickness)	36,613,551	100,864

3.2.8.1.4 Benefits. The computer program for this pilot study was coded to automate the computations of the two techniques, minimize the time required for the analysis, and minimize errors within the BRACS database. The Meyer et al. (2012) pilot study provides the foundation for future BRACS projects by developing a database management system and GIS datasets based on raw geophysical well log records. Once the computer program code and database table design are tested, a user's manual with the methodology and data entry process can be written.

3.2.8.1.5 Future Improvements Identified in this Report. The Meyer et al. (2012) study addressed the lack of detailed information for using geophysical well log analysis to estimate the salinity of brackish aquifers. Future studies should include more techniques to use geophysical well log analysis to evaluate TDS concentrations. The integrated BRACS database, detailed GIS maps, and partnerships with other experts and stakeholders will be key components to the success of the BRACS program to evaluate brackish aquifer resources for desalination. Meyer et al. (2012) further identified the need to identify and access consultant reports, and other reports, and noted challenges in doing so, especially with reports that are several decades old.

3.2.8.2 Queen City and Sparta Aquifers, Atascosa and McCullen Counties, Texas: Structure and Brackish Groundwater

3.2.8.2.1 Purpose of Research. While the Queen City and Sparta Aquifers that were studied only account for a small amount of the total groundwater use in the project area, projected oil and gas activity in the region was forecasted to possibly lead to greater use (Meyer et al., 2014). The primary goals of the project focused on the two formations and included mapping the top and bottom depths and thicknesses, mapping sand content, mapping the distribution of key chemical parameters of interest to desalination, estimating the volume of brackish water, and providing publicly available project data and information. One of the primary objectives of the project was to gather available well-control data from existing water well report, geophysical well logs, water chemistry samples, and aquifer tests to augment existing well information in the TWDB's Groundwater Database.

3.2.8.2.2 Methods Used. Three geophysical well logs methods were used for this study: spontaneous potential, gamma ray, and resistivity. In addition, water well data and water quality data from several different sources were used to map and characterize the two formations.

3.2.8.2.3 Key Findings. The entire project area has about 8,880,000 acre-feet of brackish groundwater in storage within the Sparta Aquifer and approximately 49,380,000 acre-feet of brackish groundwater in storage within the Queen City Aquifer, resulting in an estimated total amount of 58,260,000 acre-feet.

3.2.8.2.4 Benefits. One important study objective was met: making the gathered information and datasets for the project readily available to the public.

3.2.8.2.5 Future Improvements Identified in this Report. Collecting additional Queen City and Sparta water well data and geophysical well logs in the project area will help future studies improve the accuracy of groundwater quality and quantity assessments.

3.2.8.3 Gulf Coast Aquifer, Lower Rio Grande Valley, Texas Brackish Groundwater Characterization

3.2.8.3.1 Purpose of Research. The Gulf Coast Aquifer in the Lower Rio Grande Valley was selected as a brackish study area because of future municipal water demand due to the population growth, and because most of the groundwater in the region does not meet drinking water quality standards. Moreover, this study area has 7 existing and 23 recommended desalination plants to treat brackish groundwater. The main purpose of the Meyer et al. (2014) study was to develop a GIS layer, enhance the BRACS database, and collect geophysical well log data for future projects and studies.

3.2.8.3.2 Methods Used. Thousands of water well and geophysical well log data points were obtained to characterize groundwater of the Gulf Coast Aquifer in the Lower Rio Grande Valley. The geophysical well log data was used to interpret the TDS concentrations in the Meyer et al. (2014) study area. Existing groundwater quality data was used to calibrate the interpretation of salinity at shallow depths.

The R_{wa} Minimum method was used to calculate groundwater TDS concentrations in geologic formation using geophysical well logs were used in the Meyer et al. (2014) study. Meyer et al. (2014) standardized the equations used to estimate interpreted TDS for each parameter, and then coded in Visual Basic within the BRACS database for automated calculation. Salinity zones were mapped in three dimensions.

3.2.8.3.3 Key Findings. The study or Gulf Coast Aquifer in the Lower Rio Grande Valley (Meyer et al., 2014) identified 275 million acre-feet of brackish groundwater in the Lower Rio Grande Valley — a potentially important water supply in Texas. The Meyer et al. (2014) study indicates that the Gulf Coast Aquifer can serve as a potential water resource. The aquifer contains a significant volume of brackish groundwater including:

1. Slightly saline (approximately 1,000 - 3,000 mg/L TDS): > 40 million acre-feet

2. Moderately saline (approximately 3,000 - 10,000 mg/L TDS): 112 million acre-feet

3. Very saline (approximately 10,000 - 35,000 mg/L TDS):
   123 million acre-feet

The deep brine zone (> 35,000 mg/L) that underlies this aquifer was not evaluated.

The Meyer et al. (2014) study also indicates that the R_{wa} Minimum method yields results that are reasonably well based on the available data and assumptions. The R_{wa} Minimum method is based on Archie's equation (1942) and requires several input parameters to interpret TDS concentrations in the aquifer. The input parameters for the R_{wa} Minimum method are summarized in table 3.

Table 3. Input Parameters for the Rwa Minimum Method (Meyer et al., 2014)

Parameter	Symbol	Units
Total depth[1]	D_t	Feet
Depth formation[2]	D_f	Feet
Temperature at surface[3]	T_s	Degrees Fahrenheit
Temperature at bottom hole[4]	T_{bh}	Degrees Fahrenheit
Deep resistivity[5]	R_o	Ohm-meter
Porosity[6]	Φ	Percent
Conversion factor[7]	ct	Dimensionless
Cementation factor[8]	m	Dimensionless
Water quality correction factor[9]	R_{we}, R_w, cor	Dimensionless

[1] Total depth: required to calculate the temperature of the geologic formation at the depth of investigation.
[2] Depth formation: required to calculate the geologic formation temperature.
[3] Temperature surface: used a surface temperature value of 73 °F in this study.
[4] Temperature bottom hole: calculated using the well's surface temperature and well depth.
[5] Deep resistivity: determined from a deep investigation logging tool (e.g., induction logging and deep normal resistivity logging tools).
[6] Porosity: a significant factor for interpreting TDS concentration (e.g., 30% used for all shale formation and 25% used at depths more than 1,000 feet below ground surface).
[7] Conversion factor: represented TDS concentrations divided by specific conductance, determined empirically from water quality samples, and used to convert conductivity to TDS concentrations.
[8] Cementation factor: dimensionless parameter that can be determined empirically.
[9] Water quality correction factor: all water quality samples were grouped by the Gulf Coast Aquifer geologic formation, and each chemical constituent was averaged within defined ranges of TDS concentration.

The steps to perform the R_{wa} Minimum method for interpreting the TDS concentrations are:

1. Determine the temperature of the formation.
2. Determine resistivity of water equivalent.

3. Correct resistivity water based on groundwater type correction factor.
4. Convert resistivity water at formation temperature to 75 °F.
5. Convert resistivity water at 75 °F to conductivity water at 75 °F.
6. Calculate interpreted TDS.

3.2.8.3.4 Benefits. The technique utilizes commonly available well log data types, so it is often an option for analysts in most study areas that have limited geophysical well logs.

3.2.8.3.5 Future Improvements Identified in this Report. It is complicated to interpret TDS concentrations in geologic formations because the geologic environment is complex, and some parameters were not available in the Meyer et al. (2014) study area. Another limitation is the lack of quantitative information about TDS and salinity distributions for many geologic formations. This lack of information poses challenges for plans to desalinate or otherwise treat this water. TDS concentrations were represented by only a few samples. In addition, some results may not occur in the same geologic formation. Difficulties were also encountered in analyzing water quality samples with elevated salinity in the laboratory, and water quality data had insufficient well screen information. Due to the lack of data and other difficulties, Meyer et al. (2014) estimated some parameters based on areas with similar geologic conditions.

Due to insufficient data, the TWDB is interested in obtaining aquifer test data in brackish groundwater of the Gulf Coast Aquifer. Groundwater modeling may be a good tool to simulate impact among fresh, brackish, and saline water sources according to the long-term development of the brackish groundwater in the aquifer. Modeling may be a good tool to map salinity zones in the study area.

3.2.9 Utah

In Utah, recent hydrogeologic studies, including Wallace et al. (2017), have been conducted using both borehole geophysical logging and ground-based geophysical data to help infer regional water salinity distributions. This study utilized shallow geophysical profiling methods (e.g., resistivity tomography) to assess shallow aquifer properties and shallow water salinity distributions. TDEM soundings to infer electrical resistivity versus depth at various test locations. Additionally, deeper geophysical logs were obtained from oil and gas wells to help constrain geologic structure within the study area. Generally, two low resistivity zones were identified in the geophysical data: one spatially confined shallow zone interpreted as an elevated salinity recharge area, and a deeper continuous feature interpreted as a shaly stratigraphic interval. Groundwater salinity was predominantly assessed using water sample data. Other similar studies did not mention use of geophysical data (Wallace et al., 2010; Wallace 2012).

3.3 Academic and Industry-Based Research on Geophysical Well Logging for Interpretation of Brackish Groundwater

Especially since the early 1990s, many focused academic and industry-based research efforts have analyzed subsurface data, including geophysical well logs, to research and develop means for accurately estimating or otherwise measuring the groundwater quality distributions and corresponding quantities across large areas (McConnell, 1983; Jorgensen, 1990; Keys, 1990; de Lima, 1993; Nativ and Fligelman, 1994; Csókás, 1995; and Huang et al., 2014). Many of these and similar studies focus on using borehole measurements of the bulk electrical resistivity (resistivity) of the subsurface to infer groundwater quality. This can be characterized by its own separate resistivity value, which has a primary influence on the measured bulk resistivity value. Research into the effective porosity of the host rock or sediment can help indicate the potential quantity of recoverable groundwater.

The use of short- and long-normal resistivity logging for groundwater exploration and quality assessment has been a major focus of research for many years (Biella et al., 1983; Kwader, 1985; Jorgensen, 1988; Alger and Harrison, 1989; Hearst et al., 2000; Hudson, 1996; Deltomb and Schepers, 2004; and Kobr et al., 1996, 2005). These studies mainly focus on the use of additional logging data types, such as neutron density and full waveform sonic logs, to infer physical and hydrologic properties of the host rock that influence the formation factor ($F=R_o/R_w$), and to correct for the influence of the host rock on measured bulk electrical resistivity (i.e., data fluctuations related to facies properties and unrelated to the saturating water's salinity/TDS of interest).

Additionally, various studies have utilized geophysical logging specifically to address localized environmental contamination and transport fate modeling within shallow to intermediate-depth aquifers. Specifically, logging is often used to infer lithologic units by means of data correlation to core and drilling samples (i.e., 3D geologic or stratigraphic mapping) to infer the distribution of hazardous compounds and potential flow-directions aquicludes within shallow contaminated aquifers (Jorgensen, 1991; Karous et al., 1993; Keys, 1997; and Sloto, 2002).

Finally, focused research efforts have usually involved incorporating borehole logging methods with surface-based and airborne geophysical surveys (e.g., ground-based vertical electrical soundings and electromagnetic soundings, and airborne electromagnetic mapping) and with water samples used for ground-truthing and calibration of modeled or otherwise inferred salinity/TDS values (Marconi, 2007; Ley-Cooper and Tweed, 2008; Goes et al., 2009; Abraham et al., 2012; Ball et al., 2015; and Rittgers, 2018). Opportunities to research and apply combined ground-based and airborne geophysical techniques with well logging data and water samples to better characterize groundwater aquifers three-dimensionally is discussed in more detail in the appendices to this report.

4. Essential Data for Optimal Characterization of Brackish Groundwater Using Well Logs

Parameters needed to calculate or otherwise estimate water quality and quantity include: water quality testing results from extracted water samples (ground-truthing and calibration data), formation permeability, porosity, water saturation, clay content, cementation factor, and correction factors. These various parameters are either acquired through testing of extracted samples or are calculated by using well log data analysis.

Table 4 incorporates many of the parameters and correction factors found in a similar table in Meyer et al. (2012). It lists specific target parameters identified by other publications that address geophysical well log interpretation efforts (e.g., Moore et al., 2011; Land 2016). The priority is based on what each method requires and how much the parameter affects the final result. For instance, the final results of interpretation will have more validity if deep resistivity and porosity are available. In contrast, if deep resistivity and porosity are assumed, the validity of the results would be far less if only SP and clay volume are available. Deep resistivity is the most important parameter, followed by porosity and spontaneous potential.

Data for most of these parameters can be obtained by any logistically and physically accessible well in the area by collecting additional well log data, including decommissioned, inactive, or otherwise abandoned oil and gas (hydrocarbon) wells, domestic wells, municipal wells, and industrial wells. State engineers should be able to identify most well locations and available existing log data in the area.

Table 4. Geophysical Well Log Analysis for TDS Calculations: Required Parameters for Each Method Used to Estimate TDS Concentrations

Parameter (In Order of Priority)			Methods for Calculating R_w *			
Name	**Symbol**	**Units**	**Archie's Equation Using R_{wa} Minimum**	**Spontaneous Potential**	**Resistivity Ratio**	**Connectivity Equation**
Deep resistivity	R_o	Ohm-meter	Yes	NA	Yes	Yes
Porosity	none	Percent	Yes	NA	NA	Yes
Spontaneous potential	SP	+ / - millivolts	NA	Yes	NA	
Clay volume	none	Percent	NA	NA	Yes	Yes
Shallow resistivity	R_{xo}	Ohm-meter	NA	NA	Yes	Yes
Resistivity of mud filtrate	R_{mf}	Ohm-meter	NA	Yes	Yes	NA
Water resistivity equivalent	R_{we}	Ohm-meter	Yes	Yes	NA	NA
Information from Header and Logging						
Depth of well	Dt	Feet	Yes	Yes	Yes	Yes
Depth of formation	Df	Feet	Yes	Yes	Yes	Yes
R_{mf} temperature	none	°F	NA	Yes	NA	NA
Temperature at surface	Ts	°F	Yes	Yes	NA	NA
Temperature at bottom of hole	Tbh	°F	Yes	Yes	NA	NA
Correction factors						
TDS and specific conductivity	ct	None	Yes	Yes	Yes	Yes
Tortuosity factor	a	None	Yes	NA	NA	NA
Cementation factor	m	None	Yes	NA	NA	Yes
Saturation exponent	n	None	Yes	NA	NA	Yes
Connectivity exponent	μ	None	NA	NA	NA	Yes
Water connectivity index	χw	None	NA	NA	NA	Yes
Static SP	SSP	NA	NA	Yes	NA	NA

* See Section 6, "Addressing Data Gaps Associated with Well Log Interpretation," in this report.
NA = not applicable, R_w = water resistivity in the formation, R_{we} = water resistivity equivalent in the formation

5. Data Gaps and Challenges

Previous applications and research involving well log analysis have identified key data gaps often found in available well log and water sampling data. Various analysts and stakeholders express many of the same challenges that occur during brackish aquifer characterization, and future needs exist for improving analysis workflows.

A common theme throughout brackish aquifer characterization research is the lack of adequate local water samples in aquifers related to the following:

1. A lack of water samples taken at and representative of discrete depths within a given well (e.g., vertical sparsity, or large screen intervals that result in mixing of water produced from all screened depth intervals).

2. Sparsity of water wells for taking water samples (e.g., horizontal sparsity).

3. Limited or biased depths of water samples (e.g., shallow water wells are predominantly used for water sampling, resulting in a lack of information at greater depths).

Similarly, another common theme throughout brackish aquifer characterization research is the lack of adequate geophysical well log data attributed to the following:

1. A lack of co-located log data types or limited vertical overlap of required log data types for certain log analysis techniques.

2. Sparsity of wells with log data available (e.g., horizontal sparsity).

3. Limited or biased depth coverage of log data; typically, only within relatively shallow water wells and far below brackish aquifer depths of interest (e.g., oil and gas exploration well data, where shallow depths are typically cased and not logged during well development).

Several publications developed during COGG program efforts discussed addressing water sample data gaps at certain depth intervals with the use of geophysical logs collected near oil and gas well installations (Stephens et al., 2018a and 2018b; Wright et al., 2018; Shimabukuro et al., 2018; CAWSC, 2018a; Gillespie et al., 2016, 2017; and Kelley et al., 2014). Related approaches to using geophysical data were discussed by Land (2016) and Rittgers (2018).

The California DWR has also detailed existing data gaps. DWR separated the geophysical data gaps into two categories: (1) data collection and analysis, and

(2) basin assessments. This includes information such as annual estimates to groundwater depth changes and region-wide depth-to-groundwater information (DWR, 2015).

The NMBGMR makes a concerted effort to collect as many water samples as possible; however, the "knowledge of the distribution of brackish groundwater in many aquifers in New Mexico is still poorly constrained" (Land, 2016). Land discusses the typical data gap of lateral sparsity of water samples (e.g., sparsity of available wells for sample extraction). Both DWR (2015) and Land (2016) discuss how water sample data gaps could be filled in by using geophysical logs and other data types to inform data correlation techniques.

Hudson (1996) also discusses the use of geophysical well log analysis to fill in between water samples, addressing the data gap of vertical sparsity of water samples within a given well. This vertical and lateral sparsity of water sampling is a universal challenge in the characterization of brackish aquifers. Similar issues are also faced by oil and gas reservoir analysts. Using well logging data, which has essentially a continuous data coverage versus depth, can help address water sample sparsity in a given well, but it cannot necessarily help with lateral sparsity of wells.

TWDB's recent work highlighted many data gaps. One of TWDB's recent reports, completed by INTERA Inc., discussed a sensitivity analysis that was performed, which "…illustrated the importance of collecting site specific information to reduce the uncertainty in calculated total dissolved solids concentrations" (Young, 2016). This sensitivity analysis is similar to the probabilistic modeling introduced in Chapter 6.5, "Combining All Well Log Interpretive Techniques," of this report.

Additional data gaps in reports that have not been discussed include the following:

1. Water quality (ground-truth) data. This data gap was also encountered in various other brackish groundwater characterization efforts (Rittgers, 2018). Without water samples, estimates of TDS concentrations and available groundwater quantity and quality calculations can be underrepresented and poorly constrained. A fundamental lack of water quality data can lead to incorrect assumptions in log analysis. These incorrect assumptions can then lead to erroneous estimations in different geologic units, or even in the same geologic formation where mineralogical and groundwater ion constituents can vary widely. This data gap is very noticeable within the moderately to very saline aquifers.

2. Relationships between TDS concentrations and conductivity in non-sandstone aquifers (Lee, 2011). The presence of water in shales and clays can create inaccurate resistivity calculations if unaccounted for because most TDS calculations assume that the formation matrix is mostly sand.

3. Relationships between TDS concentrations and conductivity in non-sodium chloride brackish aquifers (Al Dahaan et al., 2016).

4. Relationships between temperature and conductivity in non-sodium chloride waters in slightly to moderately brackish groundwater.

5. Well construction data, leading to insufficient well screen information. Uncertainties include the depths at which these water samples were obtained and the depths and aquifer layers that water quality lab results represent.

6. Aerial and surficial geophysical data types to enhance the interpretation of the existing geophysical well log data (Binley et al., 2015).

Moreover, interpretation options are limited based on a paucity of geophysical well logs, as discussed also in Chapter 6, "Addressing Data Gaps Associated with Well Log Interpretation." Relying on limited data sources and techniques introduces uncertainties into the analysis. Using multiple analyses with varying estimates or parameters can increase confidence in the analysis results.

The two most critical data gaps that pose fundamental challenges to stakeholders' ongoing efforts are: (1) the lack of geophysical well log data in a usable format (i.e., a numeric database of values that can be queried and are readily accessible for use in calculations and other data analytics steps); and (2) the lack of discrete water quality data for calibration and analysis ground-truthing purposes (e.g., water quality data with known absolute XYZ coordinates), taken at discrete depths or from wells with relatively short screen intervals within specific lithologic units/beds.

The data gaps, challenges, and analysis limitations discussed in this chapter shed light on the shortcomings that result from relying on existing well log data alone. Well log data points are dense in the Z-axis (vertical at depth in the subsurface), but then become relatively sparse in the X- and Y-axis. When brackish aquifer characterization is performed, the changes in the X- and Y-axis are just as important as the changes in depth. A natural data gap occurs between each well location where no wells are present. To properly interpolate between X and Y locations, a variety of interpolation and inversion techniques will need to be explored. The greater the distance a well is located from neighboring wells, the higher the potential for error exists when using a "straight line" technique from well to well (or any other interpolation technique). This is the main reason that ground-based and airborne geophysics surveys have become a key data type for guiding hydrologic investigations.

Increasing the breadth of the data lowers the amount of "blind interpolation" required, which increases the validity of the inferred or interpolated properties.

Our research identified several stakeholders who have encountered these numerous data gaps and challenges while working on various aspects of groundwater resources characterization. These stakeholders are shown in table 6, which appears later in this report.

6. Addressing Data Gaps Associated with Well Log Interpretation

This chapter identifies various opportunities for brackish groundwater stakeholders to improve the applicability of identified state-of-the-art geophysical well log interpretation techniques. Here, we discuss in greater detail the aforementioned standard well log interpretation techniques commonly used in previous studies to characterize brackish groundwater quality from existing geophysical well log data.

Most of the standard approaches to calculating water resistivity have been driven by the oil and gas industry, since water resistivity and saturation are important when calculating the amount of hydrocarbons present in the ground. Analytical approaches to brackish groundwater exploration and quality assessment are generally considered ideal, depending on all currently available data as inputs to the analysis. However, analytic results of these interpretive techniques are by no means 100-percent accurate. It should be understood that these results are only estimates. These estimates can then be used to guide future efforts to help fill in missing lithology and water quality data through further testing of wells, gathering more existing data, and determining target depth intervals for relatively better quality groundwater during well screen design/testing efforts.

As discussed in Chapter 2, "General Efforts to Characterize Brackish Groundwater," researchers have historically implemented various geophysical well log analysis techniques in conjunction with spatially sparse water quality datasets. Use of these methods can help users gain confidence in the validity of existing water quality data. Some of these geophysical well log analysis methods include: Archie's equation, SP, resistivity ratios, and the connectivity equation, which are discussed in greater detail in the following subsections of this report.

Most initial well log interpretation attempts involve using Archie's equation independently from any other method. Each method, however, provides an estimate of R_w (formation water electrical resistivity), and the R_{wa} Minimum Method is then used to convert from R_w values (ohm-meters) to estimate TDS (ppm). (See the "Texas" discussion under Section 3.2, "State Efforts.")

If a single method is selected for use in calculating R_w and corresponding TDS, it is not feasible to cross validate by comparing the results of other well log analysis methods to water quality samples. The TWDB BRACS program addressed this issue by experimenting with using multiple approaches and comparing results. The different log analysis techniques, however, use different logging tools, assumptions, and/or input parameters (some are estimated). Comparing the results is often ambiguous, and averaging the results also may not result in a correct answer. To date, therefore, TWDB typically selects one approach that correlates best with available water quality data.

There is a possibility, however, that unifying multiple methods into stochastic approaches to minimizing data errors (e.g., the difference or error between measured and predicted water quality data) could provide a more comprehensive approach to analyzing all existing datasets, where probabilistic modeling could be applied to the results of these multiple methods to assess different levels of confidence in different parts of the data. Furthermore, these integrated approaches may enable better estimates of input parameters that may introduce errors in the outputs of various methods. Using multiple analysis methods and interpretation techniques to determine water quality by calculating water resistivity (R_w) could be an effective way to address the data gaps and limitations of existing well logs.

6.1 Archie's Equation

Archie's law is named after Gus Archie (1907-1978), who developed an empirical quantitative relationship between porosity, electrical conductivity, and brine saturation of rocks. Archie's law laid the foundation for modern well log interpretation as it relates borehole electrical conductivity measurements to hydrocarbon saturations.

Archie's law can be used to approximate the relationships between deep-penetration resistivity measurements and the groundwater quality distributions. The resistivity of water can be found based on the porosity and saturation of the formation by separating the contribution of water from deep-penetration resistivity (a combination of formation matrix and groundwater resistivities). The estimated resistivity of water has a direct relationship with the water quality and can be converted to TDS. Lithology data can be used to help parameterize the variables of Archie's law, and comparing estimated electrical conductivity (EC) values to known EC data can be used to help iteratively improve the estimates.

It is important to understand and recognize the data gaps and limitations when working with existing well log data when examining the industry standards for calculating Archie's parameters and water resistivity (R_w).

The typical well log profile includes data gathered from geophysical borehole techniques: SP, gamma ray, resistivity (can be single log or logs at shallow, medium, and deep depths), neutron porosity, density, and sonic. Specific circumstances may necessitate the use of only one geophysical borehole technique.

When the main goal of well log analysis is to calculate water resistivity (R_w) and TDS conductivity, of all six techniques, the "sonic" technique is the least important. If all of these logs are available, and a sandstone aquifer is present or can be assumed, R_w is most often calculated using Archie's equation, which can be written as Equation 1:

$$S_w = \left[\frac{a * R_w}{\Phi^m * R_t}\right]^{\frac{1}{n}} = \left[\frac{R_w}{R_{wa}}\right]^{\frac{1}{n}} \tag{1}$$

Where:

- S_w = water saturation, which equals 1 in aquifers
- Φ = porosity, from porosity log
- R_w = formation water resistivity
- R_{wa} = apparent formation water resistivity
- R_t = bulk resistivity, from resistivity log
- a = tortuosity factor, usually 1
- m = cementation factor, varies around 2
- n = saturation exponent, generally 2

The goal for brackish aquifer characterization is water resistivity in the formation (R_w). Archie's equation can be solved for R_w, when S_w is set equal to 1, as in Equation 2:

$$R_w = \left[\frac{\Phi^m * R_t}{a}\right] \tag{2}$$

Two variables in Equation 2 (Φ and R_t) are found from well logs, and two variables (a and m) need to be either measured from core samples, be calculated, or be otherwise assumed.

At this juncture, analysts sometimes utilize a simplified version of Archie's equation (sometimes referred to as the R_{wa} method) in "clean" water bearing sand units (depth intervals with little to no shale volume). To use this simplified use of Archie's equation, assume 100% water saturation (S_w in equation 1 is set equal to 1), and that the minimum value of all R_{wa} values observed within all nearby similar or otherwise representative "clean" sand units is equal to the true formation water resistivity R_w. This simplified R_{wa} method assumes that there is no influence from the formation material on the minimum value of measured bulk resistivity (R_t) within these "clean" formations. Although this assumption could be incorrect in the presence of even a small amount of clay or shale within a given depth interval, it prevents the need to continue with Archie's method by calculating or otherwise assuming the other required parameters with the use of Pickett plots, which are discussed below.

The most common way to calculate a and m is by using a Pickett plot construction. A Pickett plot enables the comparison of water saturations of different parts of a reservoir in one or many wells. The Pickett plot is a visual representation of the Archie equation and, therefore, is a powerful graphic technique for estimating *a* and *m* in an aquifer. All that is needed to make a Pickett plot is a set of porosities and corresponding resistivities taken from well logs.

Figure 8 shows the first step of plotting data points that correspond to the R_t and porosity measured at the same depth. Once the data points are plotted, an estimated R_w value is plotted at 100-percent porosity, as shown in figure 9. This data point is plotted at 100 percent because R_w contains only water in the formation, and zero percent of the formation matrix. The R_w data point becomes the anchor point for calculating *m*. The slope of the line extending from R_w is equal to -*m*. Therefore, the line begins with a slope of -2 since $m = 2$ is an assumption made at the beginning of processing. Figure 10 shows this process with an example data set. To find a value for *m* that is better suited for the dataset, the slope of the line can change to best fit the data set. Using the best fit for a particular data set helps improve the accuracy of the results.

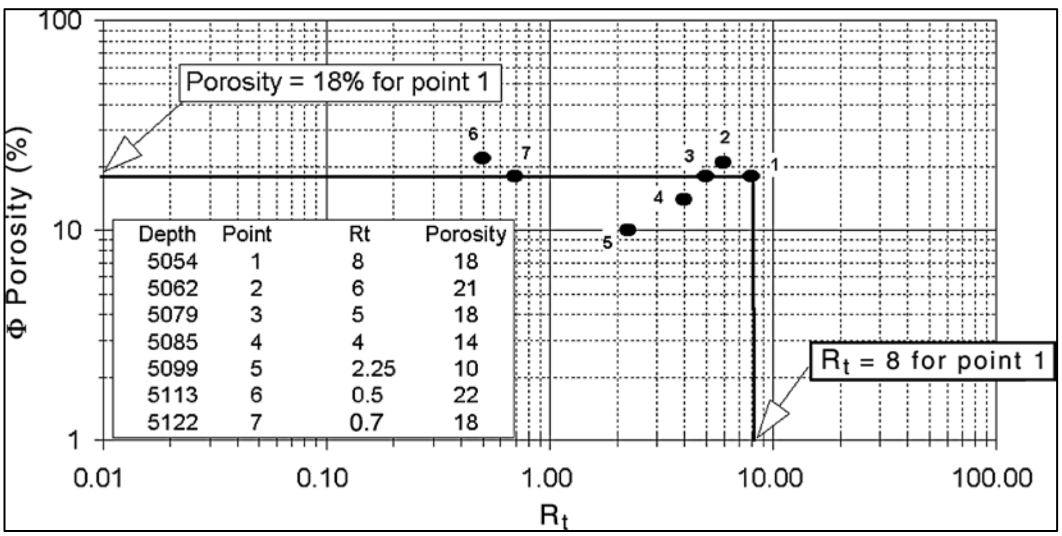


Figure 8. Plot points of matching porosity and formation resistivity (R_t) values obtained from well logs. (Source: American Association of Petroleum Geologists [AAPG], 2017c)

Using the prescribed methods shown in figures 8-10 will generally produce the best well log analysis results for R_w and Archie's parameters; however, analysts often have a limited number of wells associated with data from a typical full well log suite (i.e., a well logged with porosity, density, resistivity, gamma ray, sonic, and SP), which creates significant limitations to the analysis methods prescribed above. Figure 11 shows an example of limited well log data most commonly available to analysts. These limited well log profiles are a sharp contrast to the industry standard.

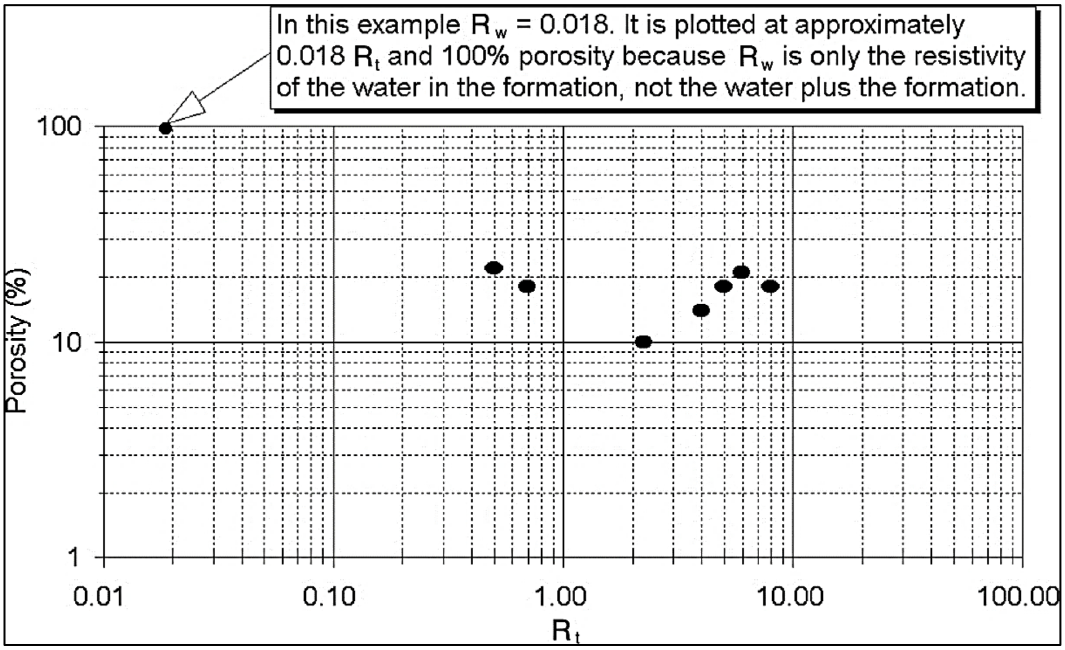


Figure 9. Example of plotting an estimated *R_w* value (which can be an assumed value or one calculated from SP analysis) by plotting the *R_w* point along the *Rt* scale on the x-axis at the top of the graph grid where porosity is 100%. (Source: AAPG, 2017b)

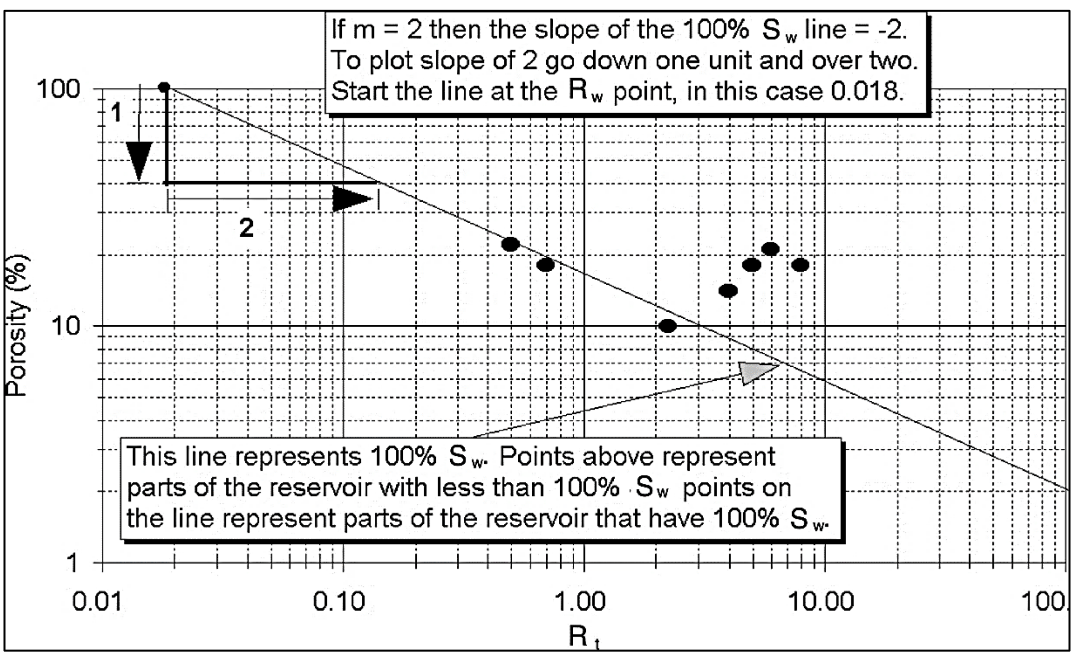


Figure 10. Example of plotting *m*. (Source: AAPG, 2017a)

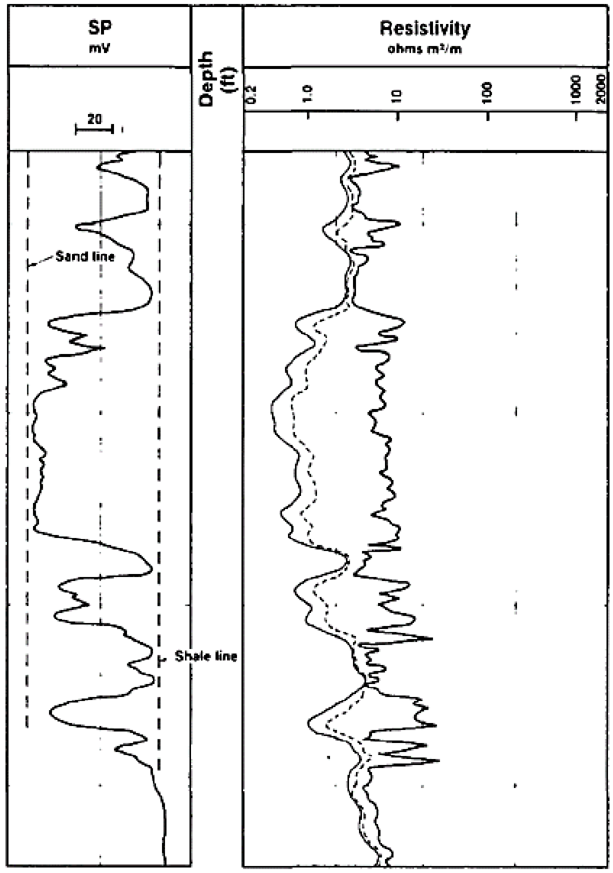


Figure 11. A typical well log profile provided to TWDB. (Source: TWDB, 2019)

There are many different tools available for geophysical borehole techniques, as discussed in Appendix A, "Additional Data Types and Complementary Well Log Interpretative Techniques for Brackish Groundwater Characterization." Some of these tools include gamma ray, porosity and density logs, and sonic logs. Resistivity and SP logs, however, are the two main tools available for most existing well logs. Fewer tools used in the field means that fewer physical parameters can be quantified. Without lab tests or field measurements, analyzing the data requires a significant amount of assumptions. These assumptions create more uncertainty during processing.

Porosity is a vital physical parameter used when conducting aquifer calculations. The lack of porosity and density logs is one of the most significant data gaps that exist with old well logs. Nearly every comprehensive well log analysis used porosity as an important variable in calculating the quality and quantity of water in an aquifer. As stated previously, multiple well log analysis methods and equations must be used to lower the level of uncertainty in the data set.

6.2 Spontaneous Potential Method

Most well log databases contain a SP measurement for almost every well. The availability of this dataset makes the SP method valuable for well log interpretation. The first step in the interpretation of the SP log is the establishment of sand and shale lines, as shown in figure 12**.**

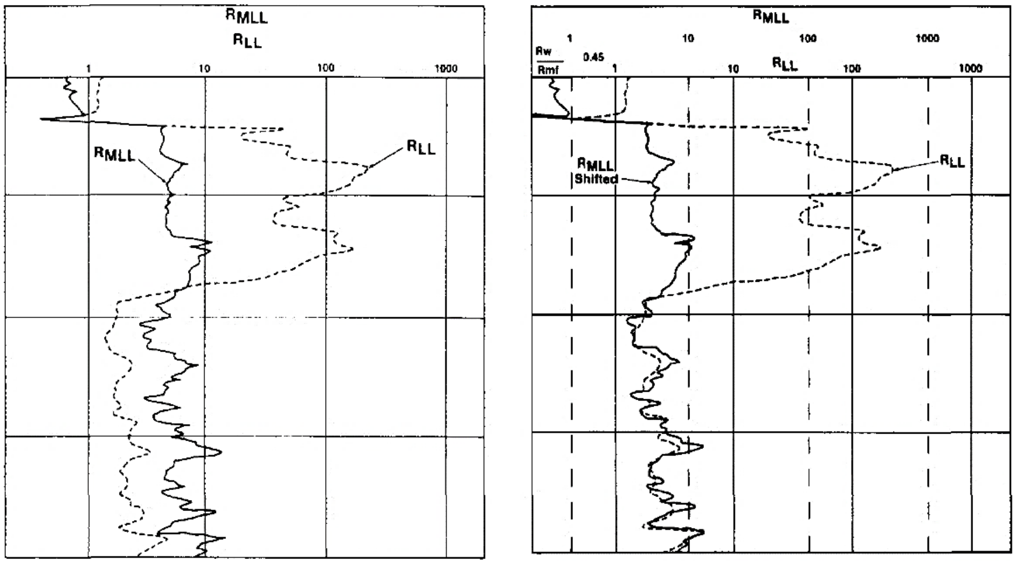


Figure 12. Example showing the type of components needed in a resistivity log for the resistivity ratio method. (Source: Andrews, 2013).

Sand and shale lines are arbitrary limits, with the sand lines normally representing the maximum deflection to the left and shale lines representing the maximum deflection to the right. The static SP (SSP) is the magnitude of deflection from the shale base line to the maximum deflection that develops in a thick, clean, water-bearing sand. Knowing the SSP is essential to derive the R_w, which is required to calculate water saturation in the uninvaded zone. Equation 3 relates the SSP to measurable quantities; namely, water resistivity (R_w) and the resistivity of mud filtrate (R_{mf}), and it introduces values that are linearly related to their respective chemical activities. These values are referred to as equivalent resistivities and are denoted by R_{we} and R_{mfe}. Thus, the standard equation that relates the SSP to the mud filtrate and uninvaded formation water resistivities can be created. Equation 3 gives the SSP equation in relation to resistivities:

$$SSP = -K * log(\frac{R_{mfe}}{R_{we}}) \quad (3)$$

Here, $K = 61 + 0.113 * T_f$, where T_f is the formation's temperature (°F).

This relationship between SSP and resistivity allows for the SSP value picked from the log to be used in quantitative interpretation of R_w from the SP log. The data required include the SP log, the invaded zone resistivity, the formation temperature, and the mud and mud filtrate resistivities at the given formation temperature. Charts for SSP calculations are located at the end of this section. The steps to determine R_w from the SP are:

1. Select the log data for the zone in which water resistivity (R_w) will be determined.

2. Establish the formation temperature using the Gen-6 chart in figure 13 and correct the values of mud and mud filtrate resistivity using the Gen-9 chart in figure 14.

3. Establish the shale and sand lines, determine the bed boundaries on the SP curve, and read the maximum SP inflection (SSP) for that permeable bed off the log.

4. If the bed is thinner than 20 feet, it is too thin for the SP to develop fully, so apply the appropriate correction from the SP-3 chart shown in figure 15.

5. Use the SP-1 chart in figure 16 to determine R_{mfe}/R_{we} from the SP log and, from that, R_{we}.

6. Use the SP-2 chart in figure 17 to derive the true value of R_w from its equivalent R_{we} value. This value of R_w is at the formation temperature and can be converted back to 75 °F for a surface level value using the Gen-9 chart shown in figure 14.

Limitations: It is assumed that all salts in solution in the fluids are sodium chloride (NaCl) or equivalent and that the aquifer is essentially clay free. This method does not work for oil-based muds.

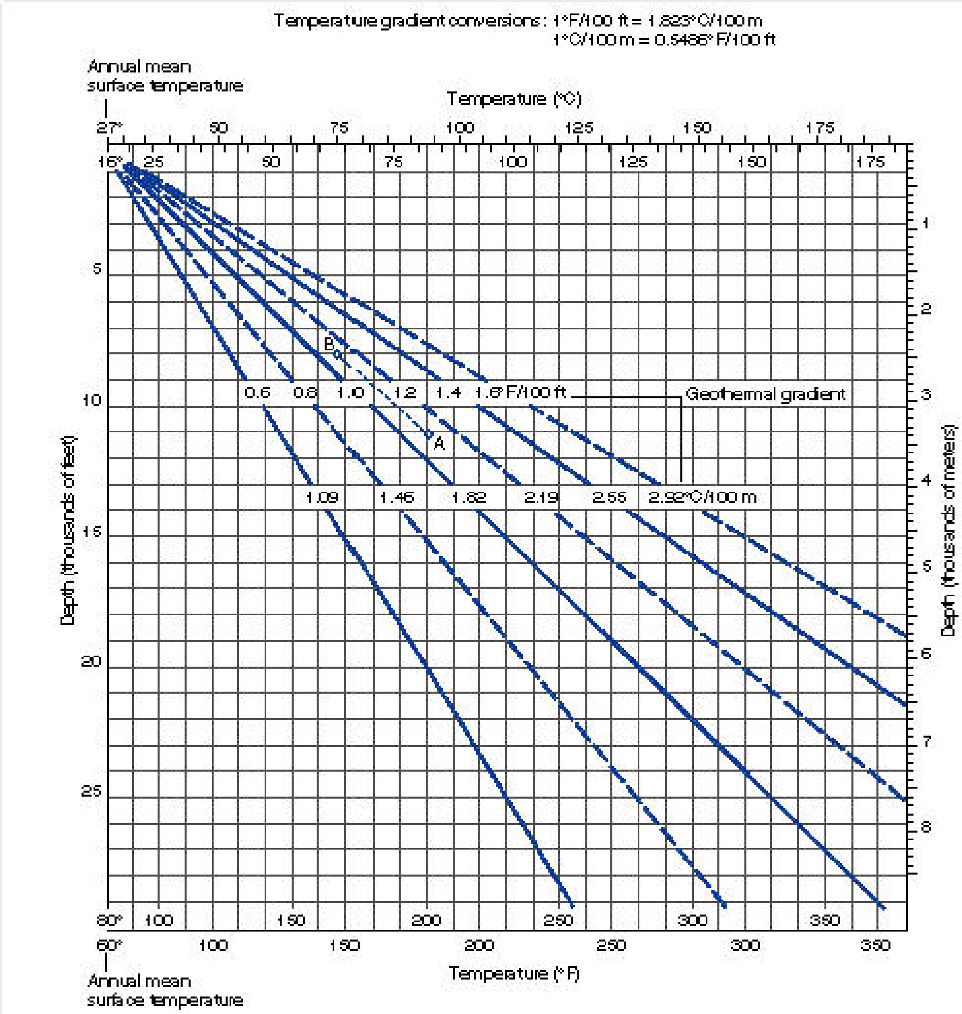
Basic Material

Estimation of Formation Temperature

Linear gradient assumed

Gen-6

Gen



* Schlumberger

Example: **Bottomhole temperature (BHT) at 11,000 ft = 200°F (Point A)**

Temperature at 8000 ft = 167°F (Point B)

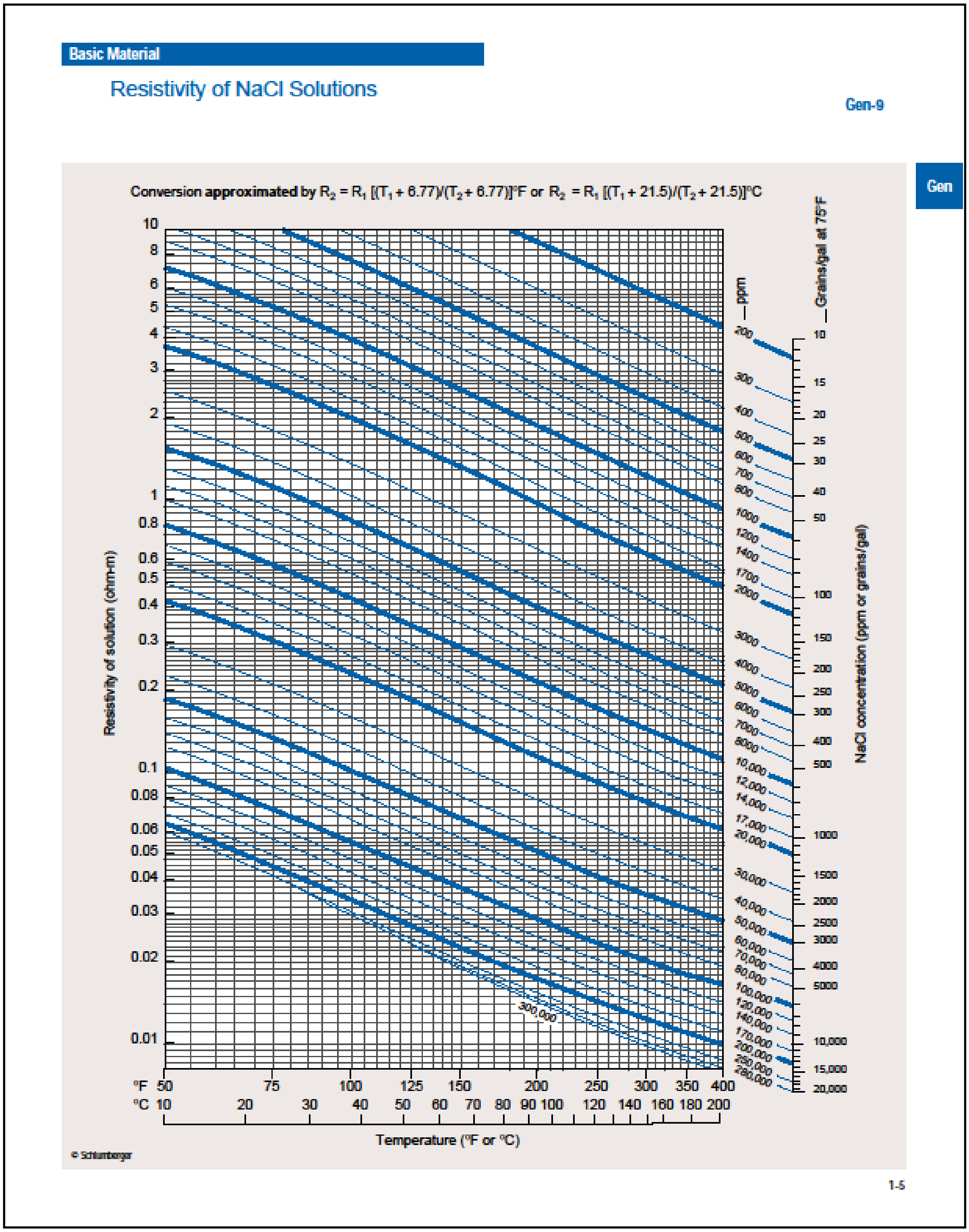
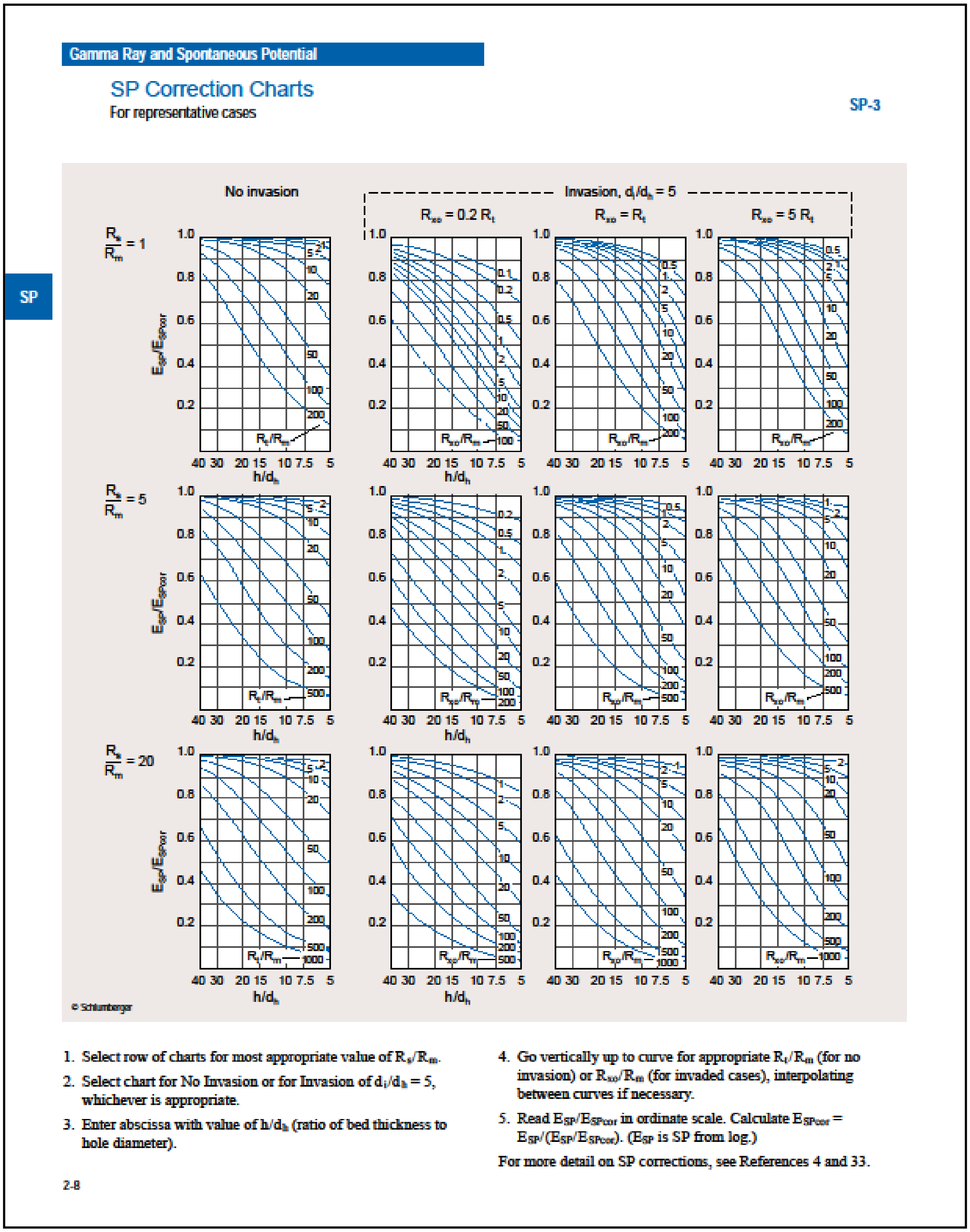


Figure 14. Gen-9 chart to convert resistivities to different temperatures or ppm value (Source: Schlumberger, 2013).


Gamma Ray and Spontaneous Potential

SP Correction Charts

For representative cases

SP-3

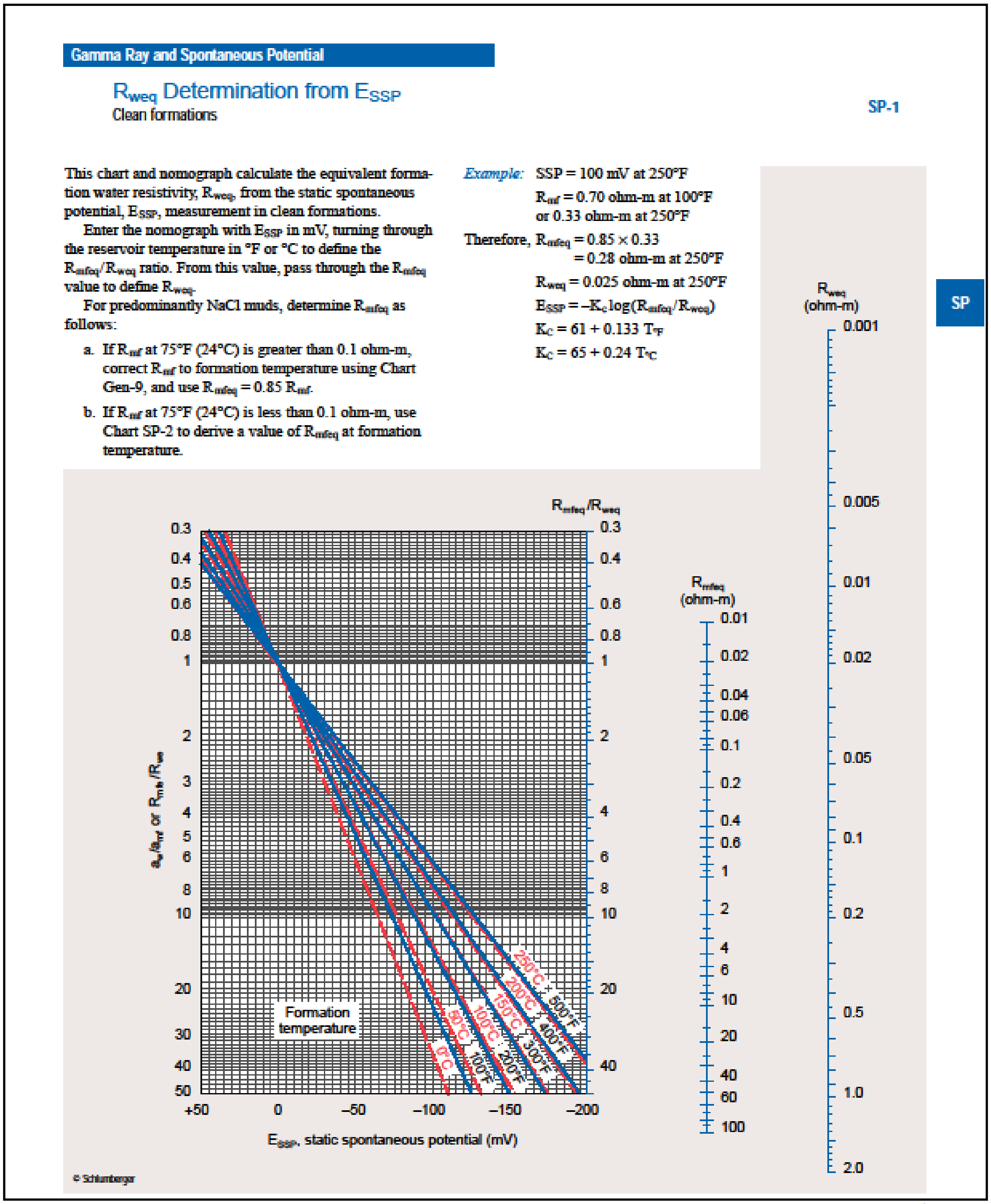
SP

1. Select row of charts for most appropriate value of R_s/R_m.
2. Select chart for No Invasion or for Invasion of d_i/d_h = 5, whichever is appropriate.
3. Enter abscissa with value of h/d_h (ratio of bed thickness to hole diameter).
4. Go vertically up to curve for appropriate R_t/R_m (for no invasion) or R_{xo}/R_m (for invaded cases), interpolating between curves if necessary.
5. Read E_{SP}/E_{SPcor} in ordinate scale. Calculate E_{SPcor} = $E_{SP}/(E_{SP}/E_{SPcor})$. ($E_{SP}$ is SP from log.)

For more detail on SP corrections, see References 4 and 33.

2-8

Figure 15. SP-3 chart for SP corrections, if needed (usually if beds are thinner than 20 feet). (Source: Schlumberger, 2013).



Gamma Ray and Spontaneous Potential

R_{weq} Determination from E_{SSP}

Clean formations

SP-1

This chart and nomograph calculate the equivalent formation water resistivity, R_{weq}, from the static spontaneous potential, E_{SSP}, measurement in clean formations.

Enter the nomograph with E_{SSP} in mV, turning through the reservoir temperature in °F or °C to define the R_{mfeq}/R_{weq} ratio. From this value, pass through the R_{mfeq} value to define R_{weq}.

For predominantly NaCl muds, determine R_{mfeq} as follows:

a. If R_{mf} at 75°F (24°C) is greater than 0.1 ohm-m, correct R_{mf} to formation temperature using Chart Gen-9, and use $R_{mfeq} = 0.85\ R_{mf}$.

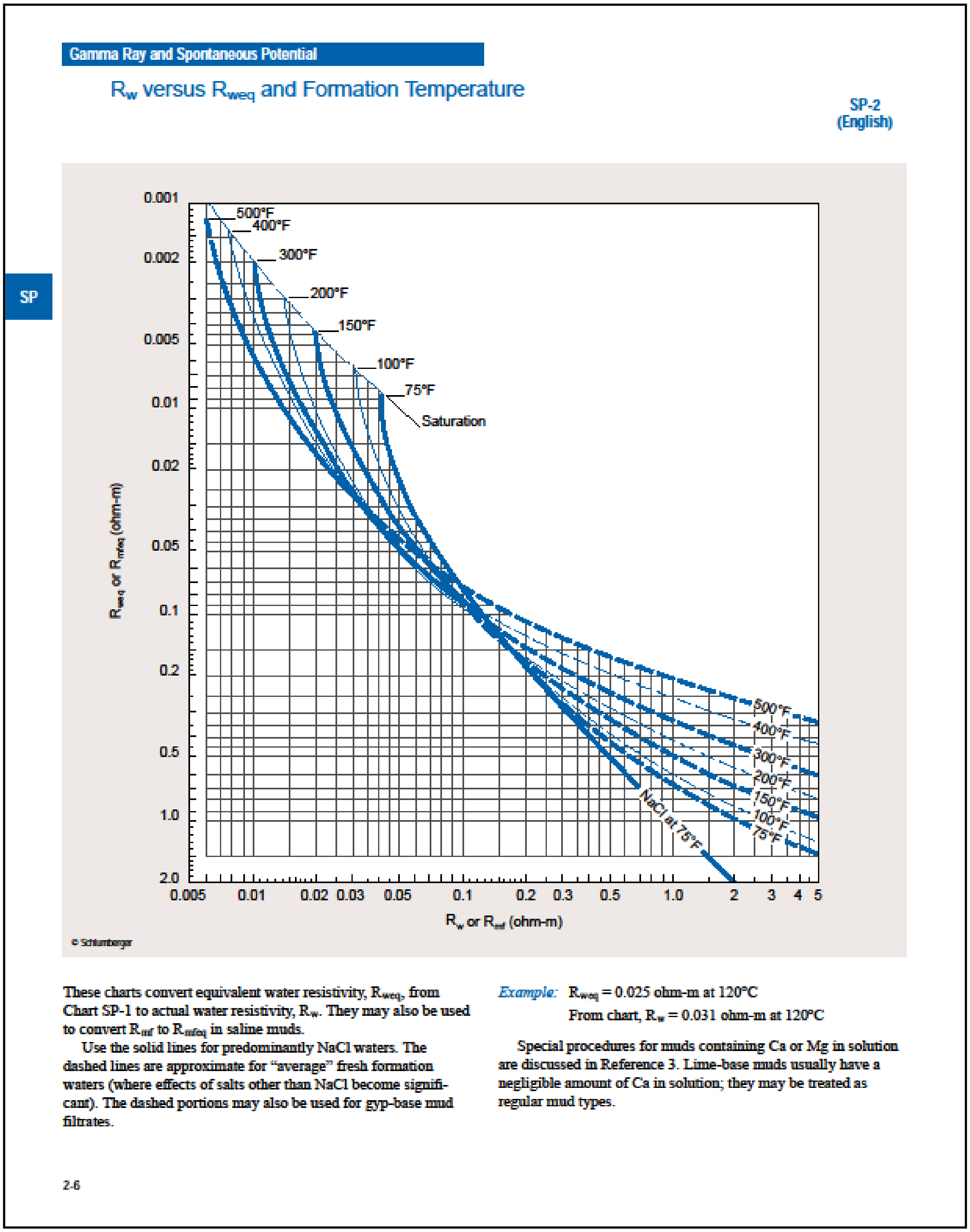
b. If R_{mf} at 75°F (24°C) is less than 0.1 ohm-m, use Chart SP-2 to derive a value of R_{mfeq} at formation temperature.

Example: SSP = 100 mV at 250°F
$R_{mf} = 0.70$ ohm-m at 100°F
or 0.33 ohm-m at 250°F

Therefore, $R_{mfeq} = 0.85 \times 0.33$
$= 0.28$ ohm-m at 250°F
$R_{weq} = 0.025$ ohm-m at 250°F
$E_{SSP} = -K_c \log(R_{mfeq}/R_{weq})$
$K_C = 61 + 0.133\ T_{°F}$
$K_C = 65 + 0.24\ T_{°C}$

2-5

SSP value. Note that R_{weq} is the same as R_{we} (water resistivity formation equivalent). (Source: Schlumberger, 2013)


Gamma Ray and Spontaneous Potential

R_w versus R_{weq} and Formation Temperature

SP-2
(English)

SP

© Schlumberger

These charts convert equivalent water resistivity, R_{weq}, from Chart SP-1 to actual water resistivity, R_w. They may also be used to convert R_{mf} to R_{mfeq} in saline muds.

Use the solid lines for predominantly NaCl waters. The dashed lines are approximate for "average" fresh formation waters (where effects of salts other than NaCl become significant). The dashed portions may also be used for gyp-base mud filtrates.

Example: R_{weq} = 0.025 ohm-m at 120°C
From chart, R_w = 0.031 ohm-m at 120°C

Special procedures for muds containing Ca or Mg in solution are discussed in Reference 3. Lime-base muds usually have a negligible amount of Ca in solution; they may be treated as regular mud types.

2-6

Figure 17. SP-2 chart to convert R_{weq} to R_w. (Source: Schlumberger, 2013).

6.3 Resistivity Ratio Method

In the resistivity ratio method, it is assumed that a formation is divided into two distinct regions: a flushed zone and a non-invaded zone. Both zones have the same $\frac{a}{\Phi^m}$ value, but each zone contains water of a distinct resistivity (mud filtrate resistivity [R_{mf}] in the invaded zone and water resistivity [R_w] in the non-invaded zone). The resistivities of the two zones must be measurable or derivable from logs, and methods for determining the resistivity of the water in each zone must be available.

The assumptions needed for these calculations create limitations for the resistivity-ratio method, but when no porosity or formation factor data are available, using these calculations is sometimes the only choice. The principal limitation arises from the inability of any resistivity device to measure either R_x or R totally independent of the other. Simply put, invasion must be deep enough to allow a shallow investigating resistivity device to measure resistivity of the flushed zone (R_{xo}), but not so deep that a deep-resistivity device cannot measure true resistivity (R_t). Figure 12 shows the different measurements acquired from a dual laterolog resistivity tool that can measure into the formation at different lengths from the borehole.

In a clean, water-bearing zone, the following relationships can be obtained from application of the Archie equation in the uninvaded and invaded zones in Equations 4 and 5:

$$R_t = \frac{a * R_w}{\Phi^m * S_w^n} \tag{4}$$

$$R_{xo} = \frac{a * R_{mf}}{\Phi^m * S_{xo}^n} \tag{5}$$

Where S_{xo} = flushed zone saturation. It is a fair assumption that in most aquifers, we can set $S_w = S_{xo} = 1$, and a and ϕ are the same in both the flushed and uninvaded zones. We can therefore simplify these equations by dividing Equation 4 by Equation 5, as shown by Equation 6:

$$\frac{R_t}{R_{xo}} = \frac{R_w}{R_{mf}} \Rightarrow R_w = \frac{R_t}{R_{xo}} * R_{mf} \tag{6}$$

The procedure for determining R_w from the resistivity ratio method is listed below. The data that are required include R_{mf}, T_f, R_t from deep resistivity measurements (usually denoted on log as ILd or LLd), and R_{xo} from shallow resistivity measurements.

1. `Correlate logs for depth mismatch.

2. Locate a clean, water-bearing zone. If using an induction log, the minimum thickness should be 15 feet. For a laterolog (resistivity tool that measures at 3 different distances), the minimum thickness should be 4 feet.

3. Read R_t and R_{xo} from the logs.

4. Correct R_{mf} to the appropriate formation temperature (T_f) value (see Gen-9 chart in figure 14.).

5. Calculate R_w by using Equation 6.

Limitations: This method is unreliable in reservoirs that are fractured or vuggy (i.e., formations with a porosity commonly found in carbonates). The method requires a reliable measurement of R_{xo}. Results can be questionable if the mud resistivity properties have varied significantly after the zone to be analyzed is drilled.

6.4 Connectivity Equation and Shaly-Sand Correction for Resistivity

All methods discussed in this section require primarily clean sandstone aquifers. This requirement is necessary because Archie's equation assumes that the material is sandstone. This condition will most commonly be met because most stakeholders prefer sandstone aquifers due to sandstone's generally greater permeability compared with other aquifer rock types. Stakeholders, however, may encounter shaly sandstone aquifers, which require an additional analysis to correct for the conductivity of shale present in bulk conductivity.

Lee (2011) derives a shaly-sand correction using the theories of Archie's equation, Waxman-Smit equation, and Bernard Montaron's Connectivity approach. The Waxman-Smits equation, shown in Equation 7, is a semi-empirical extension of the Archie's equation, considering the additional conductivity caused by shale. The Waxman-Smits equation is mostly used for dispersed shaly sandstones:

$$\frac{1}{R_t} = \Phi^m * S_w^n \left(\frac{1}{R_w} + \frac{B * Q_v}{S_w}\right) \tag{7}$$

Where:

B = equivalent conductance per cation, which can be calculated using a function of water resistivity and temperature

Q_v = cation exchange capacity, which is the number of positive ions attracted to the clay surface that depends on the amount and type of clay

Most of the variables are carried over from Archie's equation, except B and Q_v. The Waxman-Smits equation, in some instances, is adequate enough to correct for shaly sands; however, the variable Q_v presents a new data gap for stakeholders, because this approach requires additional information such as the resistivity of clay or cation exchange capacity. Most Q_v values are found through lab testing. If no information is available for the electrical properties of shale, the connectivity equation can be used to model the resistivity of the sediments. Equation 8 shows Montaron's connectivity equation:

$$R_t = \frac{R_w}{(S_w * \Phi - \chi_w)^{\mu}} \tag{8}$$

Where:

M = the connectivity exponent, equivalent to Archie's equation, when $n = m$

χ_w = the water connectivity correction index, which is a small number typically ranging from –0.02 to 0.02

For most analyses, it must first be assumed that $\mu = 2$ will be best suited because other information is lacking. Because χ_w is small, the effect of χ_w in the denominator of Equation 7 can generally be ignored. However, in freshwater with high conductivity, due to the presence of shale, χ_w could be large and should be retained in Equation 7. Lee (2011) alters Montaron's overall approach and applies some probabilistic modeling to test out these results. To calculate resistivity, Lee simplifies the approach to two steps:

1. For a given μ, calculate χ_w according to Equation 9, which can be simplified in aquifers since a and S_w both equal 1. C_v is equal to the amount of clay present in the soils:

$$\chi_w = a * C_v * \Phi^{\mu} * S_w \Rightarrow \chi_w = C_v * \Phi^{\mu} \tag{9}$$

2. Calculate the resistivity of water-saturated sediments using Equation 8, and compare it with the measured resistivity. Scaling may be needed to match calculated and measured resistivities. In this case, an adjustable parameter, α, may be used. The parameter α can be estimated by trial and error by fitting total resistivity calculated from the connectivity equation to the total measured resistivity.

Interpreters would then solve for R_w in Equation 8 with the new calculated resistivity curve as R_t. This produces values that calculated R_w while eliminating the effect that shales and clays have on resistivity. Figure 18(a) shows an example of results from this approach. As seen, quantifying the effect of shales/clays on resistivity has a large impact on this example data set. Lee (2011) also suggests testing multiple μ values if *m* and *n* are not equal. In figure 18(b), the dataset used $m = 1.6$ and $n = 2$. Figure 18(b) then shows both of those values used for μ and plotted against measured resistivity. It is important to compare the results of different values for variables to test the accuracy of calculations (which will be explained in detail in next section). Using this method for shaly-sand correction is efficient for well log analysis because the proposed connectivity equation is simple and requires no additional unmeasured parameters or assumptions.

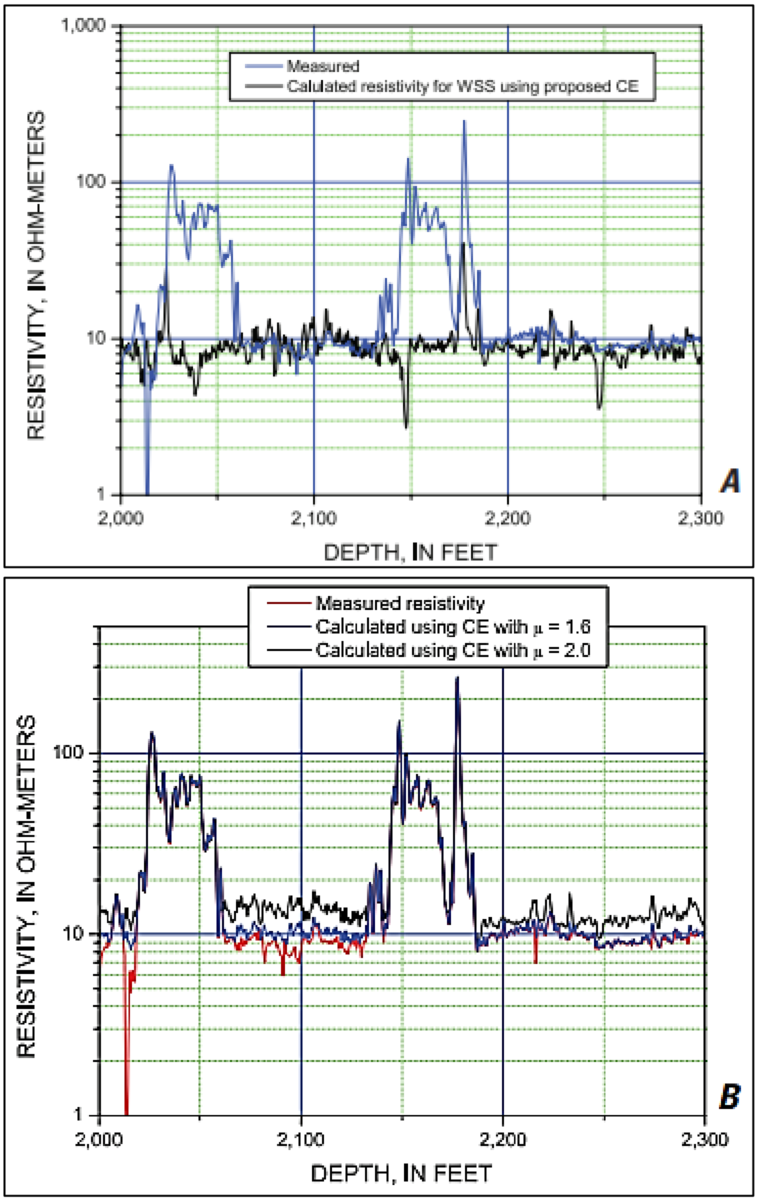


Figure 18. (a) Plot of connectivity equation results. Measured resistivity versus calculated resistivity; (b) Plot of measured resistivity versus different values of *μ*. (Source: Lee, 2011)

6.5 Combining All Well Log Interpretative Techniques

It is an arduous task to estimate hydrogeologic parameters, such as R_w, with limited geophysical well log data and without lab tests. Additional input parameters need to be estimated or otherwise measured to improve a given analysis technique's outcome. As a possible alternative, a more comprehensive result could be achieved by using all analysis methods described above, in conjunction with probabilistic modeling and iterative inverse modeling.

Figure 19 is an example well log that calculates a formation physical property. S_W represents water saturation, which is plotted using three different calculation methods. Note that although the overall shape of the plots is similar, the values vary. This example shows how different well log interpretative techniques can produce similar, yet different, results, which can lead to ambiguities in subsequent interpretations.

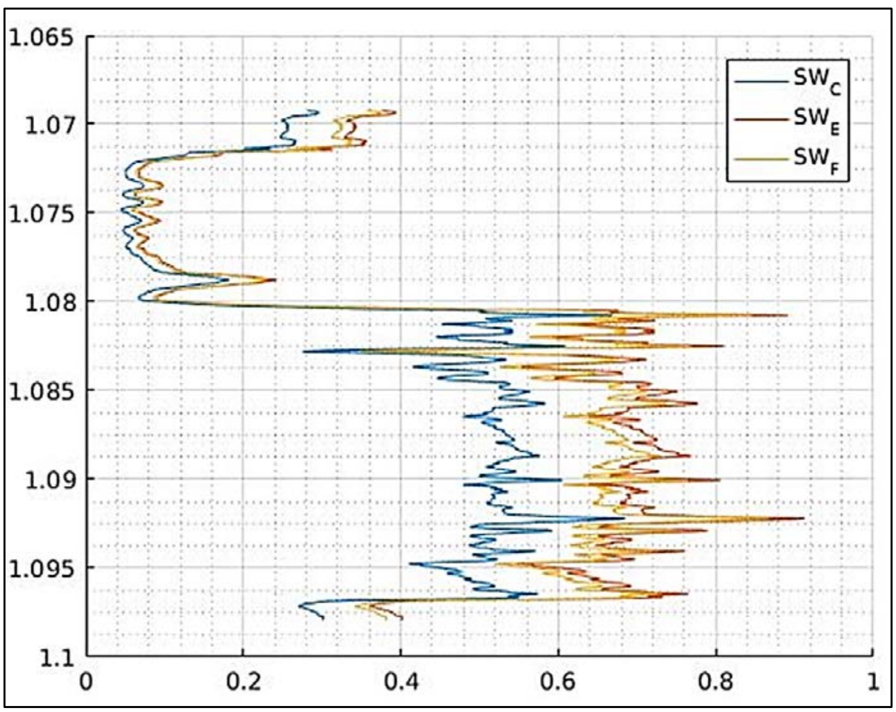


Figure 19. Example of a well log comparing three different methods to calculate a formation physical property.

Extending this concept to estimation of R_w values, one simple approach when combining results from the various analysis methods is to simply average the R_w values, once analysts are satisfied with the assumptions and parameters chosen. Results may be satisfactory if the R_w value can match some water samples, or if the average number is similar to previous analysis. If not satisfied by the assumed values of *a*, *m*, and porosity, various levels of confidence can be assessed by comparing and contrasting the results of each method. This approach, however, is vulnerable to human error and bias of estimated input parameters, and it does not lead to a more comprehensive understanding of possible estimates of R_w values.

Alternatively, a probabilistic approach, such as Monte Carlo techniques, could help assess the various levels of confidence in each method's results. Monte Carlo methods are a broad class of computational algorithms that rely on repeated random sampling to obtain numerical results. The main benefit of using the Monte Carlo technique or similar statistical approaches (e.g., probabilistic or Stochastic analyses) is that these types of analyses test several combinations of input parameters (sometimes thousands or even millions) to estimate a dependent variable (e.g., water quality at point XYZ). The results of these probabilistic modeling (e.g., parameter estimation) techniques inherently produce probabilities associated with each model, including the "best-fit answer." A suite of equivalent models and results are also generated. Figure 20 shows a 95-percent confidence interval plotted for impedance.

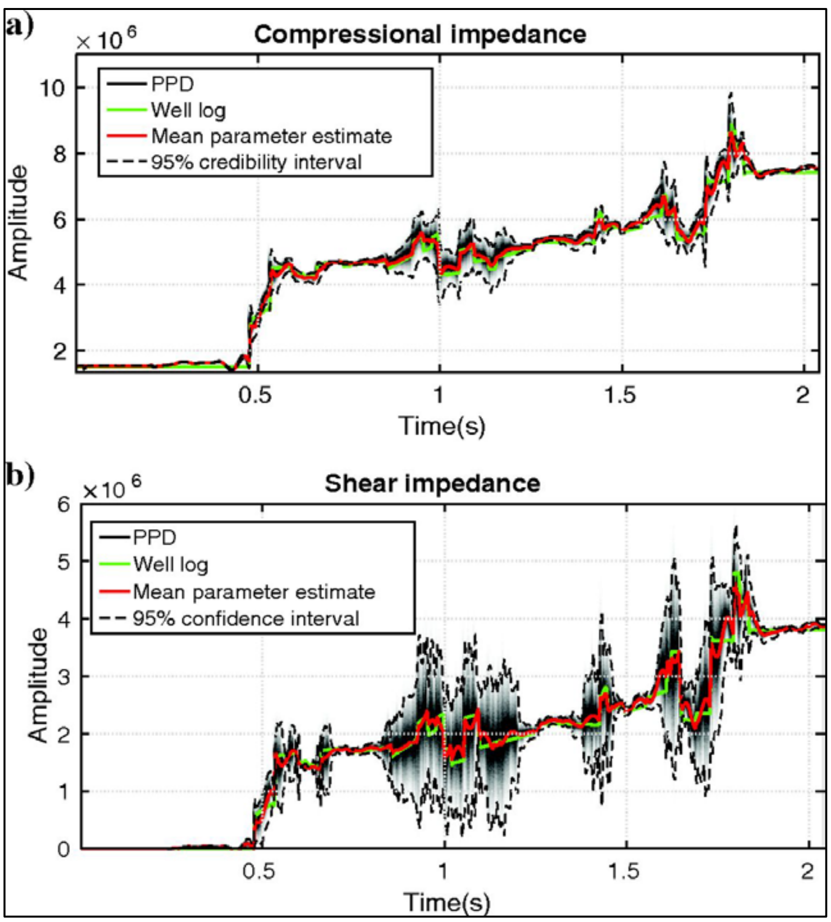


Figure 20. Example of the Monte Carlo technique used in geophysics. The red line represents the "best fit" model chosen for analysis. (Source: Mrinal and Reetam, 2017)

As shown in figure 20, the Monte Carlo technique (and similar probabilistic-modeling approaches) generate a “suite” of models that “fit the observed data” equally well (plotted here as a grey “cloud” of models surrounding the red line). Then, the highest probability model (usually somewhere near the moving-mean of all equivalent models) is selected as the best-fit model for analysis. This suite of equivalent model results enhances confidence in, or serves as a potential error-bar, for the final outcome model parameters. These probabilistic approaches also offer insight into highly sensitive, yet underdetermined, independent variables (e.g., poorly constrained input variables), input log data, and correction factors that can be updated to readily improve the results and decrease the “spread” in equivalence models. These aspects of probabilistic modeling techniques contrast with deterministic analysis techniques, which make assumptions of independent variables input into some equation or model to calculate a single result that best fits or matches existing ground-truth data.

Example of Monte Carlo approach:

1. Calculate R_w using all four methods and different values of *a, m*, and porosity best suited for sandstone aquifers.

2. Plot all of the results on same graph.

3. Select the R_w line that represents the “best fit” or alter the parameters until the highest level of confidence in the results can be achieved. Confidence in the parameters or R_w value can be derived from observing consistency and reliability in the results.

The Monte Carlo approach is explained in detail in two publications: *Uncertainty Analysis in Well Log and Petrophysical Interpretations* (Moore et al., 2011) and *Quantitative Log Interpretation and Uncertainty Propagation of Petrophysical Properties and Facies Classification from Rock-Physics Modeling and Formation Evaluation Analysis* (Grana et al, 2012). Both reports provide similar workflows as described above and utilize the following input variables within the probabilistic schemes:

a = tortuosity factor
m = cementation factor
n = saturation exponent
R_{mf} = resistivity of mud filtrate
R_{mfe} = resistivity of mud filtrate equivalent
R_t = bulk or true resistivity
R_w = water resistivity in the formation
R_{we} = water resistivity in the formation equivalent

R_{xo} = resistivity of flushed zone
SSP = static SP
S_w = water saturation
S_{xo} = flushed zone saturation
T_f = formation temperature
Φ = porosity

6.6 Advantages and Disadvantages of Each Approach for Addressing Data Gaps

Table 5 below summarizes the advantages and disadvantages of geophysical well log analysis methods discussed in this section.

Table 5. Advantages and Disadvantages of Existing Brackish Water Well Log Interpretation Methods

Method	Advantages	Disadvantages
Archie's method	Useful in sandstone aquifers Variety of methods to fine-tune Archie's parameters	Shale content in the lithology causes a breakdown in the empirical equation Without water samples and necessary well logs (resistivity, gamma ray, SP, neutron porosity, and density), the amount of assumptions can greatly increase the error margin when calculating TDS
SP	Only requires SP log Allows quick interpretation	Assumes all dissolved solids are NaCl Aquifer must be clay free Not applicable in oil-based muds
Resistivity ratio	Only requires shallow and deep resistivity logs Allows quick interpretation	Not applicable in vuggy fractured layers Shallow log can be unreliable if hole changed conditions after drilling
Connectivity equation	Can be used in shales and clays to correct for shale effect on measured resistivity	Relies on the same assumptions as Archie's method

7. Conclusions and Recommendations

This research project involved an expanded literature and technology review to examine available geophysical well logs to determine the types of data, analysis techniques, and processes that are applicable to brackish aquifer characterization. The project also defined specific research areas required to support geophysical well log data with borehole physical properties. In addition, this project reviewed various methods to address data gaps and challenges to the use of existing analysis techniques. (For detailed information on techniques, sources, and contacts used in this research project, please consult the appendices provided at the end of this report.) Recommendations made as a result of this research project are identified and discussed below:

7.1 Well Log Interpretation Techniques

As previously stated, one of the biggest challenges in using existing well log interpretation techniques is the lack of organization and digitization of all available well log data into a numeric database that can be queried (i.e., digitized well logs in the form of XYZ data value) and that can support advanced 3D mathematical operations, data analytics, and modeling. Subsequently building on this successful foundation can expand the applicability of research and can develop programmatic strategies to take advantage of the research tools and techniques identified in this report and in Appendix A, "Additional Data Types and Complementary Well Log Interpretative Techniques for Brackish Groundwater Characterization."

Stakeholders can further analyze their existing data using techniques discussed in the Section 7.2, "Future Research Opportunities." Additionally, stakeholders have the opportunity to address current data gaps by implementing existing data analytics techniques and advanced spatial interpolation techniques for both addressing missing log data, and for correction factor calibration and tuning.

Estimations of water quality obtained from log analysis efforts can be adequately fit to water quality ground truthing data using semi-automated regression analysis workflows. This best-fit approach to known data will offer the opportunity to tune and better constrain input parameters that are also of interest to interpreters (e.g., automatic tuning of inferred porosity or permeability values used in R_w estimation workflows).

Probabilistic modeling can be used to perform a more comprehensive analysis, offering the opportunity to estimate levels of uncertainty and associated levels of confidence in the results. In contrast to simple deterministic modeling approaches that simply provide a single answer without indication of uncertainty, probabilistic approaches offer the opportunity to perform more synergistic analysis workflows, allowing analysts to identify and correct for biased or contaminated input data, to also identify where data gaps exist, and to prioritize where and when to acquire additional data.

All of the existing calculation methods rely on analytic and modeling techniques that produce results that approximate reality but are never completely accurate. These well log analysis results can be made more accurate and robust by applying continuous updates as additional water sample ground-truthing becomes available, or when additional information and data types become available, such as from the implementation of geophysical methods discussed in appendix A.

Integrating ground-based and airborne geophysical mapping and imaging technologies can help inform current sparse well log data and address specific data gaps and challenges most typically within relatively shallow to intermediate depths (e.g., up to approximately 1,000 feet deep or more in some instances or implementations of survey designs to help maximize depths of investigations). Using these additional data types would provide stakeholders with a means to better characterize brackish groundwater resources across large areas.

Collecting additional data or conducting cross-validation analysis (where a data point is left out and the analyses are compared) will help characterize the validity and accuracy of the analysis results. Stakeholders can investigate the utility and site-specific applicability of the recent advancements in “see-through-casing” wireline data collection and analysis and interpretation techniques to collect data in the existing oil and gas wells. These specific advancements are discussed in appendix A. TSC has conducted several types of geophysical surveys applied to groundwater salinity characterization and mapping, that have proven invaluable in better understanding various complex hydro-geologic situations.

Stakeholders can perform nuclear logging throughout the State and can correlate this data with other open-hole well logs to provide the background structure image, although more data collection may be required.

Results from various geophysical borehole techniques are key elements in identifying and characterizing brackish groundwater resources; however, no one technique or technology is going to be applicable in all conditions and may potentially only be suitable for a limited range of conditions.

This literature and technology review has led to the general conclusion that the most promising approaches to addressing the challenges currently faced by log analysists and stakeholders are invariably going to be hybrid techniques that use a variety of complementary technologies, data types, and multiple analysis techniques to assess and characterize the brackish groundwater resources. This general conclusion is based on the bulk of approaches, cited successes, and added value of information obtained by implementing various hybrid approaches, as discussed in the literature reviewed for this research report. The main additional advantage of hybrid analysis approaches is the ability for analysts to overcome significantly problematic data gaps (both spatial sparsity and a fundamental lack of necessary well log data types in certain studies). Additional data types and approaches to collecting these additional data should be:

- Cost effective
- Adequately sensitive to physical and chemical properties, and processes of interest
- Accurate and robust enough for repeated or even routine assessments
- Useable without impacting the resources themselves

7.2 Future Research Opportunities

Potential future research directions and topics could benefit all Reclamation regions by improving the use of groundwater to address water supply challenges in the Western United States. Research should enhance geophysical techniques and investigate other fields to gain insight into data processing and analytics, which can improve efficiency in using existing data and acquiring additional data, as well as optimize data analysis methods.

7.2.1 Efficient Digitizing of Existing Well Log Data

Data logs are old, recorded on paper, and may be handwritten. While text detection is straightforward, hand-drawn logs are not to scale and can be wrapped across the horizontal scale in varying manners, depending on who developed the log and the range of the data values. Pattern recognition and data analytic techniques may help address some of the challenges involved in the laborious process of digitizing data logs.

7.2.2 Collecting Additional Data within Existing Cased Wells

The thousands of exploration wells throughout the United States could provide a massive opportunity for future research into techniques for data collection within existing and accessible steel-cased exploration wells. Analysists could collect new logging data from oil and gas exploration wells within the uppermost several hundred feet of the subsurface. See-through-casing well logging technologies could prove indispensable in mapping lithology and helping to infer groundwater conditions outside of these cased wells within these shallow-to-intermediate depth intervals. These logging techniques are often useful for identifying stratigraphy and physical and hydrologic properties of surrounding materials behind steel-cased and grouted exploration wells. Appendix A discusses techniques that can be used to obtain data from existing and accessible cased wells.

Future research and technical development strategies and priorities will benefit from including new wireline technologies that can be used to characterize aquifer properties through steel casing and grouted annulus, enabling the use of any accessible exploration wells to collect key data types within relatively shallow brackish aquifers. These tools provide the opportunity to correlate cased hole logs with other nearby water quality and uncased log data, and also to collect data directly on porosity and bulk resistivity estimates—both key parameters for use in groundwater quality and brackish aquifer characterization analyses.

7.2.3 Advanced and Interdisciplinary Data Analysis Techniques

Future research and technical development strategies and priorities will benefit from including advanced and interdisciplinary data analysis techniques that can make the best use of existing log data and help bridge current data gaps and analysis challenges. These techniques include data analysis tools and cross-discipline areas of research such as advanced interpolation techniques, computer vision, machine learning, deep learning, neural network theory, and multivariate regression analysis. These relatively advanced areas of computer science research alone could help drastically increase the accuracy and detail of basin-scale aquifer characterization efforts using existing well logging data throughout arid regions, where brackish groundwater is becoming an increasingly important resource.

Use of advanced image guided interpolation could further refine cross-validation results to more accurately interpret existing data. In addition to helping infer input parameters for brackish aquifer characterization analysis techniques, these same data analysis tools could be used to help guide correction factor calibration functions in challenging high-salinity environments, such as more precisely predicting groundwater conditions far away from existing well data or water quality samples. As additional water quality data becomes available, predictions could be improved by updating 3D calibration functions.

7.2.4 Explore Additional Techniques to Acquire New Data

Techniques to acquire data are summarized in appendices at the end of this report. These tools can be further refined, and research can adapt industry methods to brackish aquifer characterization. For example, beyond the nuclear logging techniques, several companies have developed electrical resistivity and sonic logging tools and processing techniques that claim to reveal the surrounding formation’s resistivity and seismic p- and s-wave velocities, even when data are collected in steel-cased and grouted holes.

While many claims have been made about the capabilities of these data analysis tools for "seeing through steel casing and cement annulus," a lot of testing and research must still take place to help validate and improve these types of tools. Specifically, research could focus on both cased-hole seismic (sonic) logging and resistivity logging instruments to determine their applicability in brackish aquifer characterization. For example, one area of research could include exploration of capacitive coupling with steel casing to obtain resistivity measurements using capacitively induced displacement currents through the casing wall (similar to land-based capacitive resistivity profiling systems).

7.2.5 Partner with Interested Entities

Further research will benefit from partnerships with government, industry, and academia experts. Partnerships with academic institutions are usually very effective because existing state-of-the-art techniques are available for organizing and digitizing existing data. In addition, partnerships with academic institutions frequently provide access to cutting-edge fundamental and applied research and emerging knowledge. Partnerships with interested entities are also beneficial because they incorporate various data analytics and interpolation techniques to fill existing data gaps more effectively to better support standard well log interpretation techniques.

Chapter 8, "Researchers, Companies, and Contact Information," presents interested academic researchers and various governmental and commercial entities in the United States that specialize in data analysis, inverse modeling, computer science, groundwater exploration, and brackish aquifer characterization. Stakeholders could work with these and similar experts to help identify, develop, and apply new techniques to analyze existing data and incorporate any available new data. Reclamation can function as a liaison between stakeholders and academic and industry partners to help compare results and determine cost-effective approaches for future efforts.

Table 6 lists primary contacts for entities within Reclamation's jurisdiction (17 Western States) that were identified in this research and are involved in relevant efforts. Additional researchers involved in similar or related research and project work are listed in table 7.

Table 6. Entities Identified in this Research Project that are within Reclamation's Jurisdiction (17 Western States) and Involved in Relevant Efforts

(Contacts in Reclamation's Jurisdiction [17 Western States])				
State	**Organization**	**Website**	**Contacts**	**Email or Phone #**
Arizona	Arizona Department of Water Resources	http://www.azwater.gov/azdwr/	Frank Corkhill, Chief Hydrologist	efcorkhill@azwater.gov, (602) 771-4566
	Arizona Water Science Center, USGS	http://az.water.usgs.gov/	Alissa Coes	alcoes@usgs.gov, (520) 670-3321
			Jamie Macy	jpmacy@usgs.gov, (928) 556-7276
			Christopher Magirl	magirl@usgs.gov, (520) 670-3315
			Jesse Dickinson	jdickins@usgs.gov, (520) 670-3323
California	California Department of Water Resources	https://www.water.ca.gov/	Tom Lutterman	Thomas.Lutterman@water.ca.gov, (916) 651-9263
	California Water Science Center, USGS	https://ca.water.usgs.gov/	Jeffrey Hansen	jahansen@usgs.gov, (916) 278-3076
			Matthew Landon	landon@usgs.gov, (619) 225-6109
	California State University - Bakersfield	https://www.csub.edu/~jgillespie/	Janice Gillespie	jgillespie@csub.edu, (661) 654-3040
	University of Stanford	https://profiles.stanford.edu/rosemary-knight	Rosemary Knight	rknight@stanford.edu, (650) 736-1487
	California State University - Sacramento	https://www.csus.edu/geology/faculty/shimabukuro.html	David Shimabukuro	dhs@csus.edu, (916) 278-6382
Colorado	Colorado Geologic Survey	http://coloradogeologicalsurvey.org	Peter Barkmann	barkmann@mines.edu, (303) 384-2642
	USGS: Geology, Geophysics, and Geochemistry Science Center		Lindsay Ball	lbball@usgs.gov, (303) 236-0133
	Colorado School of Mines	www.mines.edu/	Kamini Singha, Professor of hydrology	ksingha@mines.edu, (303) 273-3822
			Brandon Dugan, Professor of geophysics	dugan@mines.edu, 303-273-3512
Idaho	Idaho Water Science Center	http://id.water.usgs.gov/	Kyle Blasch, Director	kblasch@usgs.gov, (208) 387-1321
Nevada	Nevada Water Science Center, Division of Hydrologic Sciences	http://nevada.usgs.gov/water/groundwater/groundwater.htm	David Berger, Director	dlberger@usgs.gov, (775) 887-7658
	Desert Research Institute	http://www.dri.edu/	Kumud Acharya, Director	Kumud.Acharya@dri.edu, (702) 862-5371
New Mexico	University of New Mexico and New Mexico Energy, Minerals, and Natural Resources Department	http://cwe.unm.edu/	Jeri Sullivan Graham, Chief Research Scientist	ejsgraham@unm.edu, (505) 412-1092
	Bureau of Geology & Mineral Resources	https://geoinfo.nmt.edu/resources/water/home.html	Shari Kelley	shari.Kelley@nmt.edu, (575) 835-5306
			Alex J. Rinehart	Alex.Rinehart@nmt.edu, (575) 835-5067
	Petroleum Recovery Research Center	http://www.prrc.nmt.edu/	Martha Cather	martha@prrc.nmt.edu, (575) 835-5685
	Sandia National Laboratories	http://www.sandia.gov/	Vince Tidwell	vctidwe@sandia.gov
Oklahoma	Oklahoma Water Resources Board	https://www.owrb.ok.gov	Owen Mills	Owen.Mills@owrb.ok.gov, (405) 530-8800
Oregon	Oregon Water Science Center	http://or.water.usgs.gov	Nicholas Corson-Dosch	ncorson-dosch@usgs.gov, 503-251-3269
Texas	Texas Water Development Board, Water Science & Conservation	https://www.twdb.texas.gov/	Erika Mancha	Erika.mancha@twdb.texas.gov, (512) 463-7932
			John Meyer	John.Meyer@twdb.texas.gov, (512) 463-8010
Utah	Utah Water Science Center	https://www.usgs.gov/centers/ut-water	Mike Hess	mhess@usgs.gov, (801) 908-5047
	Utah Geologic Survey	https://geology.utah.gov/	Janae Wallace	janaewallace@utah.gov, (801) 537-3387
Washington	Washington Water Science Center	http://wa.water.usgs.gov/	Scott W Anderson	swanderson@usgs.gov, (253) 552-1633
Reclamation	Research and Development Office	https://www.usbr.gov/research/dwpr/index.html	Yuliana Porras-Mendoza, Advanced Water Treatment Coordinator	yporrasmendoza@usbr.gov

Table 7. Other Researchers with Relevant Research and Project Work

Researchers	Institution	E-mail	Phone Number
Ayi Syaeful Bahri	Sepuluh Nopember Institute of Technology	syaeful_b@geofisika.its.ac.id	+62-31-5994251
Antoine M. Collin	EPHE in France	antoine.collin@ephe.sorbonne.fr	+02-9946-1072
E. Ross Crain	Crain's Petrophysical Handbook	ross@spec2000.net	+01-(403) 845-2527
Gualbert H. P. O. Essink	Utrecht University	G.H.P.OudeEssink@uu.nl	+31-63-055-0408
Nader Fathianpour	Isfahan University of Technology	fathian@cc.iut.ac.ir	+98-311-3915130
Scott Hamlin	Bureau of Economic Geology @ UT-Austin	scott.hamlin@beg.utexas.edu	+01-(512) 475-6527
Benard Ofosu	Building and Road Research Institute of Ghana	bennofosu@gmail.com	+233-032-206-0064
Joel E. Podgorski	Swiss Federal Institute of Aquatic Science and Technology	joel.podgorski@eawag.ch	+41-58-765-5760

8. Researchers, Companies, and Contact Information

During this literature and technology review, several USGS researchers were contacted at the California Geophysics and Geochemistry Science Center and California Water Sciences Center . These researchers included: Jesse Dickinson, Matthew Landon, Justin Kulongoski, Peter McMahon, and Lyndsay Ball. Follow-up correspondence with Lyndsay Ball provided the following recommended contacts at the USGS Texas office: Jon Thomas, Andy Teeple, and Greg Stanton. Jonathan Thomas made references to two recent efforts using geophysical logs to evaluate brackish groundwater conditions in Texas, including a saline zone study near San Antonio and surface geophysical data (no log data) used near El Paso. The El Paso study utilized ground-based transient electromagnetic (TEM) data and groundwater samples.

Other regional USGS Water Science Centers were contacted, including the Arizona Water Science Center, where Alissa Coes stated that the AWSC does not have any current projects using GP well log analysis to characterize brackish groundwater, but that brackish groundwater is a challenge in Arizona. According to Ms. Coes, the AZWSC does have several people with vast expertise in geophysics, including down-hole methods, so this is an area that they would be very interested in pursuing. A conference call was held on April 26, 2018, to discuss the group's previous work, and opportunities for future collaborative research, and the group expressed a high level of interest in future collaborations.

Jared Abraham of HydroGeoFrameworks Inc. (a former USGS researcher involved in many groundwater studies), and John Fleming (a former AZGS hydrologist, now working for Reclamation in the Yuma Area Office) were also contacted and voiced interest in future research collaborations. Numerous additional industry-based well logging service providers were contacted throughout this literature and technology review, including COLOG Inc.; Southwest Exploration Services; Pacific Surveys, LLC; Enviroprobe Service, Inc., etc. However, none of the contacted service providers responded or offered specific information about their current state of practice for applying geophysical well logging to groundwater quality and salinity assessments.

When canvasing and contacting Federal and State-level government-based researchers, Dr. John Lane and Dr. Fredrick Day Lewis of the USGS Hydrogeophysics Branch in Storrs Mansfield, Connecticut, were mentioned as researchers in the area of groundwater. Dr. Lane supervises Branch applied research, technical support, and technology transfer programs utilizing borehole, surface, and airborne geophysical methods, including emerging applications of small unmanned aircraft systems. Dr. Lane's applied research focuses on the development of quantitative geophysical methods in fractured rock and porous media, geophysical assessment of hydrologic processes, and application of hydrogeophysical methods for water resource and contamination assessment studies. A key component of Dr. Lane's work is development and implementation of geophysical training and support for diverse audiences. He has developed and supervised national, international, regional, and local instruction for USGS scientists and other cooperating agency personnel on the use of geophysics for groundwater exploration, water-resource assessment, and addressing groundwater contamination and environmental engineering problems. Dr. Fredrick Day Lewis has extensive experience and publications on the use of surface and airborne geophysical techniques for groundwater exploration. While neither Dr. Lane nor Dr. Lewis were corresponded with directly, both could serve as resources for future partnerships. This assessment is based both on referrals received and reviews of their biographies and lists of publications available on https://www.usgs.gov.

When canvasing and contacting researchers, the following academic professors were repeatedly recommended by others as leading researchers in academia pertaining to brackish aquifer characterization. When contacted directly, each of these academic professors expressed interest in partnering for future research endeavors, and they have graduate students available to perform some of the research, particularly processing the existing data. Both professors at Colorado School of Mines met with Reclamation's TSC on campus during the year to discuss the project. Dr. Brandon Dugan echoed the need for multiple well log analysis techniques to overcome the lack of physical parameters measured. Dr. Kamini Singha leads research in applied hydrogeophysics at School of Mines. As the Associate Director of the Hydrologic Science & Engineering Program, Dr. Kamini Singha is using many of the techniques described above to tackle the hydrogeophysical problems of the future. She has an entire program of graduate students that would be interested in partnering on future well log analysis and brackish groundwater characterization research:

Dr. Kamini Singha
Colorado School of Mines
Phone: (303) 273-3822
E-mail: ksingha@mines.edu

Dr. Rosemary Knight
Stanford University
Phone: (650) 736-1487
E-mail: rknight@stanford.edu

Dr. Brandon Dugan
Colorado School of Mines
Phone: (303)-273-3512
E-mail: dugan@mines.edu

9. Data Sources

Water Data Interactive website for water well and geophysical well log research and data download:

https://www2.twdb.texas.gov/apps/waterdatainteractive/groundwaterdataviewer

The TWDB data, in addition to the associated interactive groundwater viewer, is available at:

Groundwater database:
https://www.twdb.texas.gov/groundwater/data/gwdbrpt.asp

BRACS database:
https://www.twdb.texas.gov/innovativewater/bracs/database.asp

BRACS study data:
https://www.twdb.texas.gov/innovativewater/bracs/studies.asp

Groundwater reports:
https://www.twdb.texas.gov/publications/reports/numbered_reports/index.asp

Groundwater models:
https://www.twdb.texas.gov/groundwater/models/gam/index.asp

Yuma Area Office's data, models, and correspondence for this S&T Research Project are located on the TSC's network drives and available on request. TSC has also been involved in other AEM studies, and these models are also located on the TSC network drive.

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Appendix A

Additional Data Types and Complementary Well Log Interpretative Techniques for Brackish Groundwater Characterization

Acronyms and Abbreviations

1D	one-dimensional
2D	two-dimensional
3D	three-dimensional
4D	four-dimensional
AEM	airborne electromagnetics
AVO	amplitude variation with offset
BCR	both cross receivers
C/O	carbon/oxygen
CCL	casing collar log
CGR	uranium corrected gamma ray
CHFD	cased hole formation density
CHFP	cased hole formation porosity
CHFR	cased hole formation resistivity
CNL	compensated neutron logs
EC	electroconductivity
EM	electromagnetic
FDEM	frequency domain electromagnetic
HI	hydrogen index
LWD	logging while drilling
MWD	measure while drilling
NMR	nuclear magnetic resonance
OTV	optical televiewer
PDF	portable document format
RST	reservoir saturation log
SGR	standard gamma ray
SNL	spectral noise logging
TDS	total dissolved solids
TDT	pulsed thermal-neutron decay time
TDEM	time domain electromagnetic
TEM	transient electromagnetic
TSC	Technical Service Center
TWDB	Texas Water Development Board
UXO	undetonated explosive ordinance

Appendix A

Additional Data Types and Complementary Well Log Interpretative Techniques for Brackish Groundwater Characterization

A.1 Data Correlation and Advanced Spatial Interpolation of Missing and Sparse Data

Data gaps are often the limiting factor in groundwater characterization and mapping. Sometimes, specific key data types are missing from certain wells, making standard well log analysis challenging at best. This appendix describes techniques for gathering additional data, which can lessen uncertainty and provide more information about aquifer characteristics. This, in term, will enable more effective planning and use. This appendix presents case studies showing how additional data can be used along with existing well log data to provide a better picture of groundwater conditions.

The Hamlin and De La Rocha (2014) case study is a good example of correlating various types of available data from wells within south Texas' Carrizo-Wilcox aquifer to create an accurate, two-dimensional (2D) geologic structural model, where background seismic reflection or other types of 3D geophysical images are not available. As depicted in figure A-1, researchers created isopach maps (e.g., stratigraphic unit thicknesses) by correlating and interpolating lithology and groundwater sample salinity measurements between wells with continuous stratigraphic units (Hamlin and De La Rocha, 2014).

This type of data correlation can produce 2D or three-dimensional (3D) structure maps that can be used to help guide interpolations of other sparse data types (e.g., to interpolate a specific log data type to a well that lacks this piece of information, which, in turn, prevents log analysis efforts from being conducted to predict groundwater quality). This approach to help fill in missing data at and between existing wells is most likely a valid approach within a given geologic setting or sedimentary depositional environment where petrophysical relationships (e.g., relationship or trend observed between resistivity and seismic velocity) are relatively constant across a given study area. These petrophysical relationships between various physical and chemical properties are often constant enough across a local study area. These relationships, however, are usually site specific and not universally applicable to other regions or geologic units.

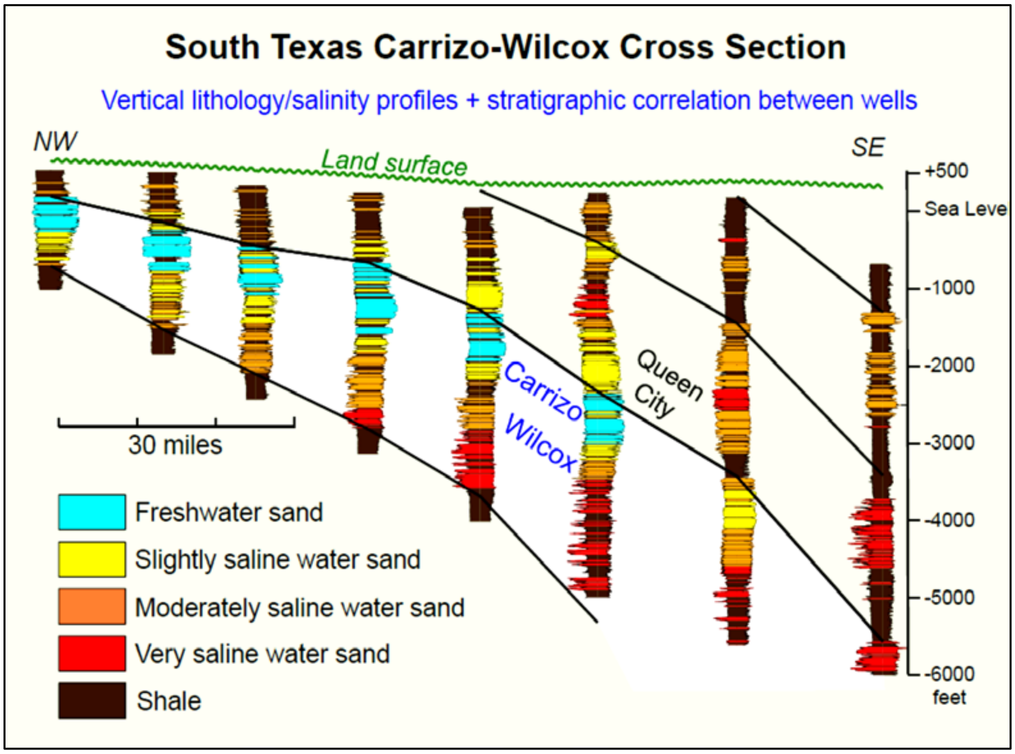


Figure A-1. South Texas' Carrizo-Wilcox aquifer chemical and stratigraphic correlation interpretations using straight lines between wells with continuous stratigraphic units, shown in a 2D cross-sectional view.

Moreover, sometimes well logs do not correlate very well, as stratigraphic discontinuities occur between wells. In this same example, Hamlin and De La Rocha (2014) found lateral stratigraphic discontinuities that created laterally confined aquifer layers with different water qualities. These discontinuities can vary drastically in both the vertical and horizontal directions (figure A-2). This is a very common issue with stratigraphic correlation efforts, as discontinuities occur at some unknown location between wells. These "blind" structural features can cause issues for interpolating and interpreting hydrogeologic parameters and are a good example of where surface or airborne-based geophysical imaging techniques can add valuable information.

Spatial interpolation of existing well log data is a key step in characterizing brackish aquifers quantitatively. There are several underlying challenges that this single step of the analysis process faces, fundamentally including the question, "Which approach or technique is the best for interpolating extremely sparse well log data over large lateral distances?" This is a significant challenge because using an inappropriate approach could lead to false aquifer characterization results.

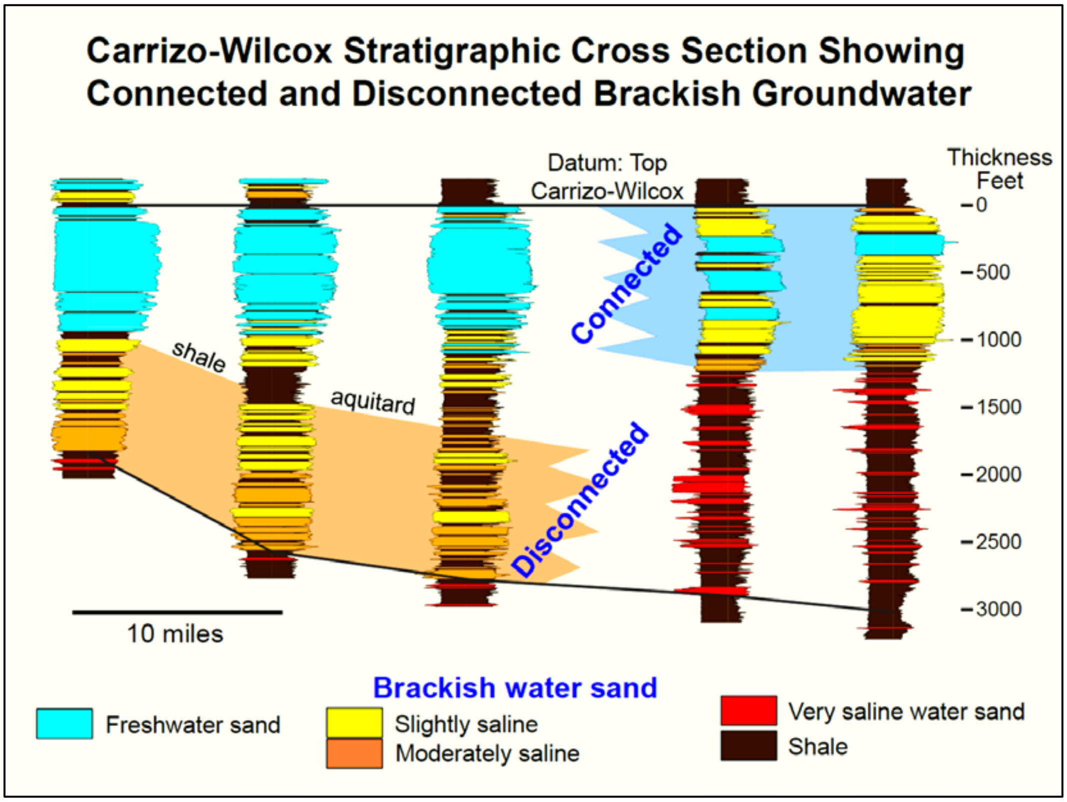
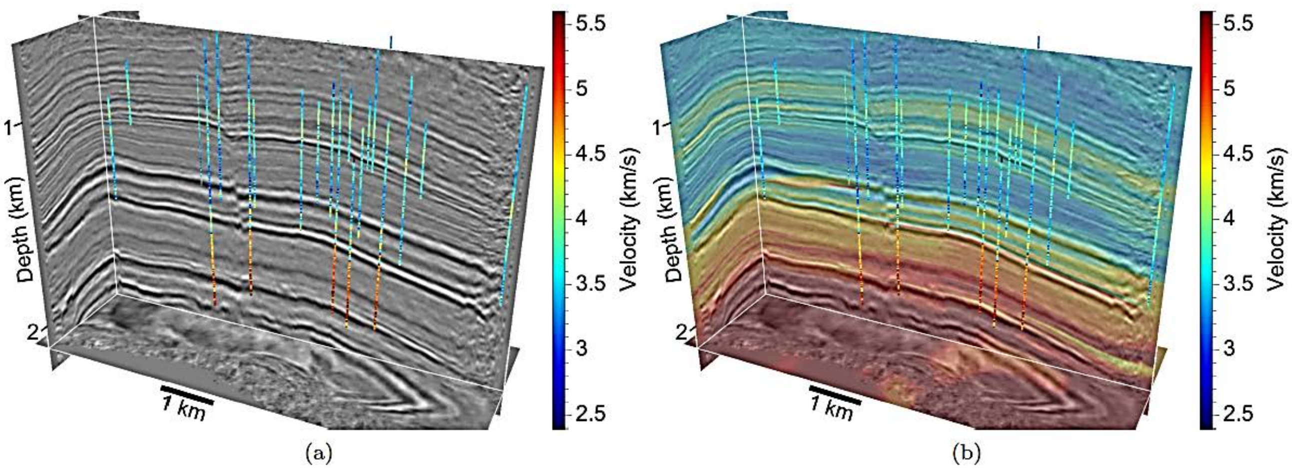


Figure A-2. South Texas' Carrizo-Wilcox aquifer chemical and stratigraphic correlation interpretations using straight lines between wells with discontinuous stratigraphic units, shown in a 2D cross-sectional view.

Using correlation methods discussed above, as well as other methods such as recent advances in image-guided interpolation, can help to make the best use of existing sparse geospatial information (Hale, 2009a; 2009b; 2010a; 2010b; and 2011). Figures A-3 and A-4 show examples of Hale's analysis using a background seismic reflection image to help guide the interpolation of very sparse well log data that are key to lithologic unit identification and aquifer characterization (e.g., density, porosity, and gamma ray log data). These interpolated values honor background structural images (seismic reflection image in figure A-5), and interpolated values (e.g., porosity) can be used in subsequent well log analysis efforts to estimate groundwater conductivity at wells where data was originally missing. The interpolated values follow the "structure" (i.e., layers) captured within the 3D reflection image. The final distribution of interpolated values are much more geologically reasonable, as we expect each layer to have unique hydrogeological characteristics that change relatively slowly in the lateral directions along known layers and material types, and we expect that these characteristics will change relatively abruptly across layer interfaces.



Slices of a 3D seismic image (a) with P-wave velocities measured in boreholes and an image-guided 3D interpolation (b) of those measured velocities.

Figure A-3. Image-guided 3D interpolation of sparse seismic velocity well logging data using a 3D seismic reflection image.

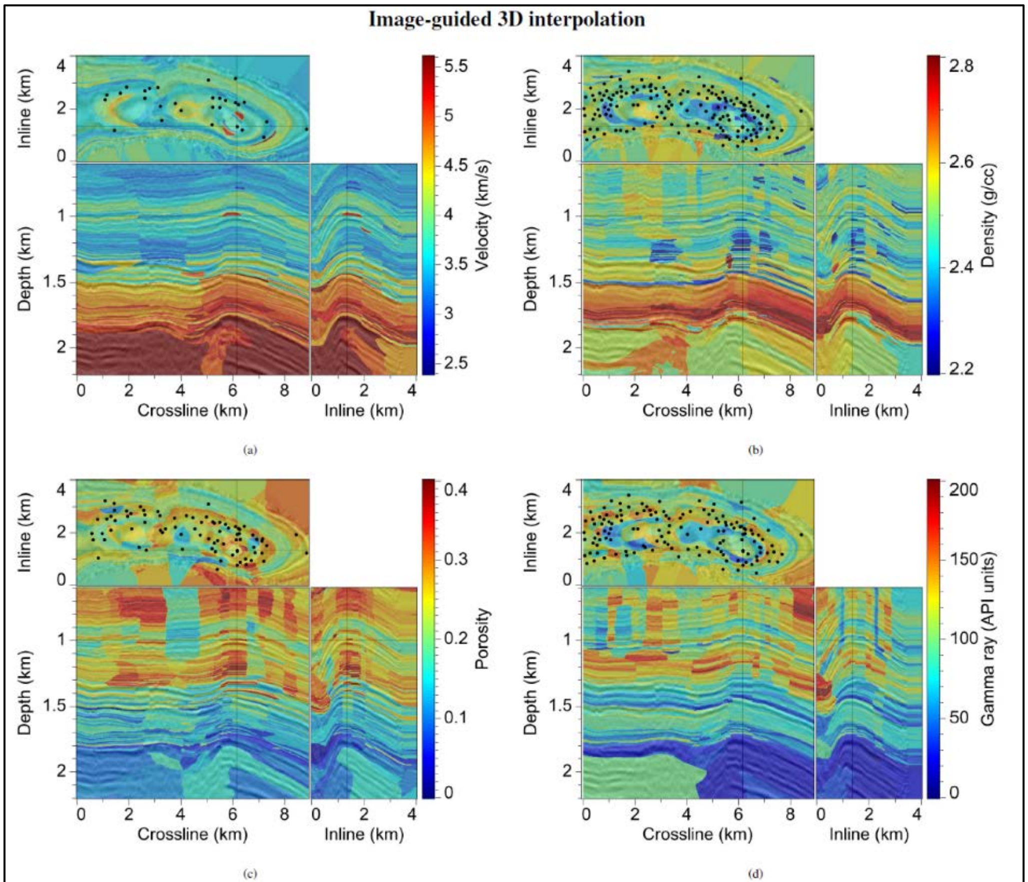


Image-guided nearest neighbor interpolation of velocity (a), density (b), porosity (c) and gamma ray (d) logs.

Figure A-4. Image-guided 3D interpolation of seismic velocity (a), density (b), porosity (c), and gamma ray (d) log data.

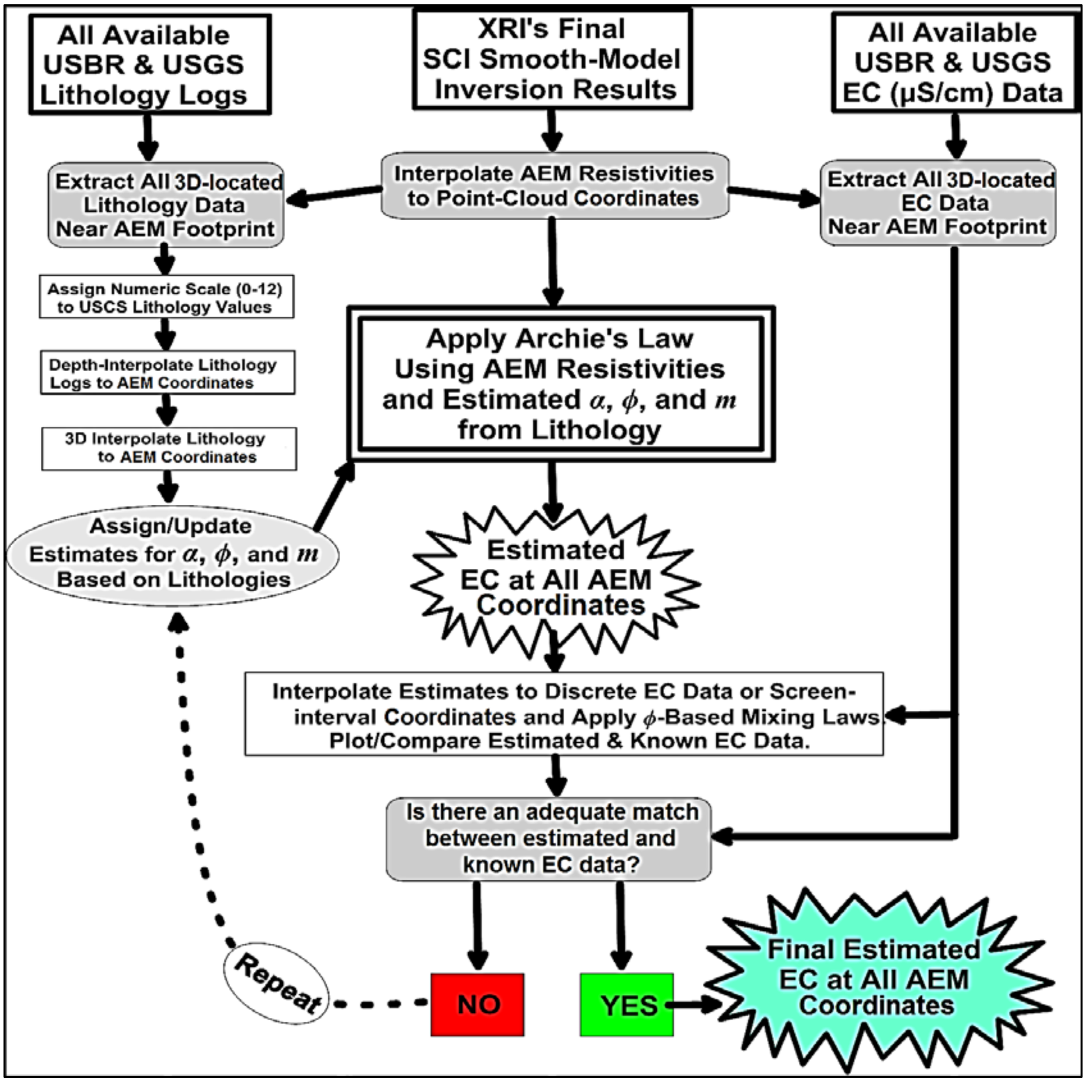


Figure A-5. Flowchart representing the general workflow carried out for estimating groundwater electrical conductivity (EC) using Archie's law informed by airborne electromagnetics (AEM)-derived resistivity values and lithology data.

In many cases, a background seismic reflection image or similar stratigraphic information is not available for guiding the structural nature of the interpolations. While a best guess of the geologic or stratigraphic structures near and in between existing well logs from all available data can be made, this guess may not include a consideration of stratigraphic discontinuities or other unknowns, as discussed above. "Best guess" geologic structure images/models, however, have been successfully used to help guide data interpolation and have been shown to improve interpolation results beyond more standard unguided approaches (Hale, 2009a).

A.2 Airborne-Based Geophysics

A.2.1 Description

Airborne geophysical surveys involve the collection of geophysical data with systems that are mounted or slung below an airplane, helicopter, or other aircraft. This category of geophysics most commonly involves electromagnetic (EM) surveys, magnetic surveys, gravity surveys, various remote sensing surveys (e.g., visual-band or thermal infrared imaging of the immediate ground surface), and, occasionally, airborne ground-penetrating radar surveys (e.g., for mapping thickness of oceanic ice sheets and glaciers). These types of surveys are most commonly used for natural resource exploration or for mapping large-scale geologic structures or other natural features of interest (e.g., regional patterns in Earth's magnetic field).

Airborne electromagnetics (AEM) is a very common airborne geophysical survey technique applicable to groundwater studies. These AEM surveys can be further subcategorized as either frequency domain electromagnetic (FDEM) or time domain electromagnetic (TDEM) surveying techniques and are typically performed using a helicopter or fixed-wing aircraft that carries the EM system as it navigates parallel flight lines over the area of interest. The EM system is usually suspended below the aircraft as it flies relatively low over the ground surface. The basis for AEM is essentially the same as for surface methods. The system uses a transmitter coil, which generates a time-varying EM signal to induce eddy currents in the subsurface materials. These eddy currents then interact with a receiver coil in the EM system to generate a voltage, which is translated to a resistivity reading.

A.2.2 Application

The airborne geophysical survey technique most applicable to groundwater studies is AEM. This technique measures and maps variations in electrical resistivity of subsurface materials anywhere from just below the ground surface down to depths of thousands of feet. AEM methods produce resistivity images that can be used to help inform geologic mapping (e.g., mapping faults or depth to bedrock and bedrock topography), and for groundwater exploration and aquifer characterization and management (e.g., monitoring and controlling groundwater-surface water interactions in agricultural areas).

A.2.3 Advantages and Disadvantages

AEM surveys are often used for geologic mapping and hydrogeologic investigations over large areas where ground-based methods are not time or cost efficient. These airborne techniques can collect a vast amount of data over large areas very quickly, providing more comprehensive images of basin-scale geology and subsurface structures of interest, including mineral deposits, groundwater aquifers, and oil and gas reservoirs. The primary advantage of airborne geophysical surveying techniques is the resulting broad spatial data coverage. Relative to groundwater exploration, AEM surveys are particularly useful, in that they provide images of electrical resistivity, a key parameter often missing for use in well log analysis techniques.

While airborne geophysical data is extremely inexpensive, relative to the expected cost of similar data coverage obtained with ground-based surveys or drilling-based exploration efforts, there is generally a high initial cost to perform one of these surveys (e.g., contractors typically have minimum costs or survey fees to cover expensive equipment and crew mobilization costs). Another limitation of these survey types is airspace access. The surveys often require low-altitude flight, which precludes the system from being flown over human activity or residential/municipal areas.

AEM mapping technologies have enabled region-scale interpretation of groundwater quality and quantity, dramatically increasing knowledge of aquifer conditions beyond what is contained in well log or water sample data alone. To more effectively address project needs and goals, several types of AEM surveys and systems can be customized and site-specifically tailored for optimal system performance, depth of investigation, and lateral and vertical resolutions.

A perfect example of the successful implementation of AEM for brackish groundwater exploration, mapping, and characterization, and for informing longer-term groundwater management planning over a large area, is a recent brackish groundwater study conducted in the Yuma, Arizona area. Here, four separate areas were surveyed with AEM, and inverse modeling was performed on the resulting data to provide a series of models that reveal the 3D distributions of resistivity within the subsurface down to depths of approximately 800 feet below ground surface. About 2,000 line-kilometers (the total length of data collection along flight lines) were flown in approximately 5 days. Reclamation's Technical Service Center (TSC) then analyzed the AEM results to estimate groundwater distributions and delineate areas of greater or lesser groundwater quality (e.g., estimating EC and total dissolved solids [TDS]). This project primarily involved integrating all available lithology well logs, water quality samples, and airborne geophysics products to help quantify and guide future groundwater resource production and management efforts (Rittgers, 2018).

For this groundwater study, Archie's law was utilized to estimate water conductivity (e.g., R_w) values (figure A-6) from the AEM-derived bulk resistivity values (figure A-7). Only lithology logs and very limited water quality data from tested well samples were available, and there was no porosity data. This data gap was overcome by first performing a series of advanced 3D interpolation techniques to obtain an estimated lithology type wherever there was an AEM resistivity value (figure A-8), and then by estimating appropriate porosities based on published values. TSC staff interpolated the existing lithology logs to the AEM model footprint. This provided bulk resistivity values and lithology values at common points throughout the 3D footprint of the AEM model. At this point, interpolated lithology values were first used to identify regions of the subsurface that corresponded to Archie-type materials (i.e., lithologic material with minimal clay content). Next, these interpolated lithology values were used to help guide parameterization of Archie parameters, including porosity, tortuosity, cementation exponents, and water saturation. Finally, estimated porosity values were iteratively updated and tuned to minimize the difference between the predicted EC values and measured EC values at known water sample locations, as shown in the analysis flowchart in figure A-5 (Rittgers, 2018).

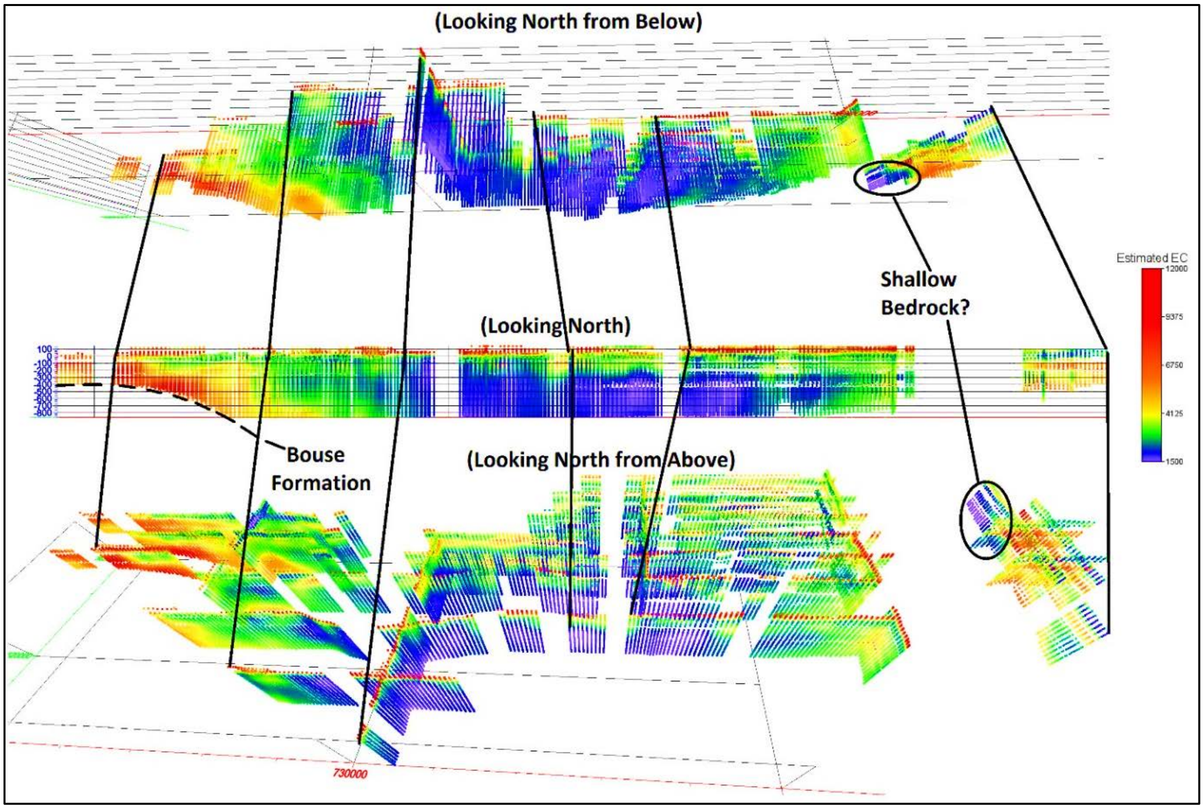


Figure A-6. Yuma Groundwater Study results showing the Archie's law estimated EC values based on AEM modeled resistivity values and assumed porosities. The dataset shows the South Gila Valley area, where the main flight lines are spaced approximately 1,200 feet apart, and the depth of investigation is approximately 800 feet. There is a 3.28X vertical exaggeration applied to the data.

This particular project encountered the same types of key data gaps that most well log analysts face, including the daunting task of digitizing all available relevant data (e.g., portable document format [PDF] scans of lithology logs, and water quality sample data within and near the project study area) into a single database of 3D point data (i.e., XYZ values) with all known 3D coordinate locations (e.g., latitude, longitude, and elevation above mean sea level). This was the single most challenging portion of the project, where all the pertinent data was in nonusable graphic formats and needed to be entered into a useable database format for performing calculations.

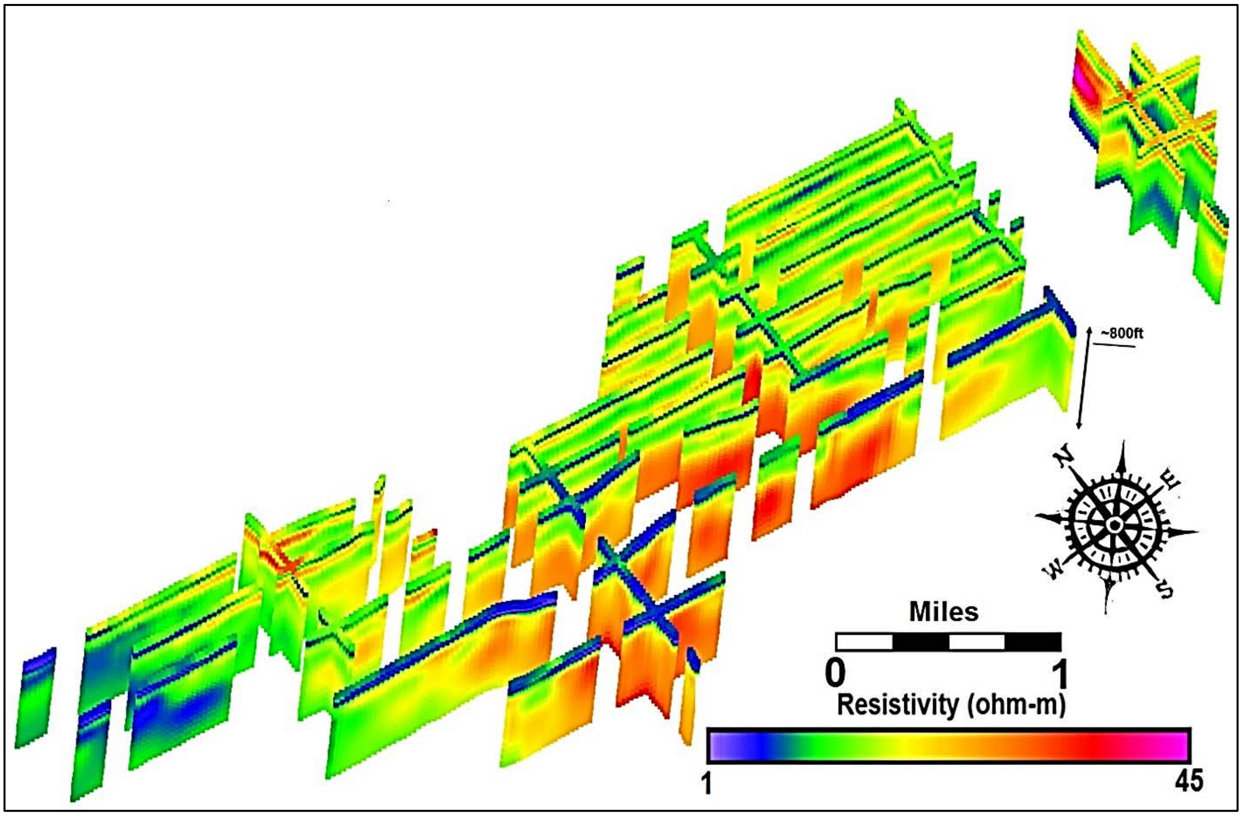


Figure A-7. Yuma Groundwater Study: AEM modeled resistivity values for the South Gila Valley area. The main survey lines are approximately 400 meters apart, and the depth of investigation is approximately 800 feet below ground surface.

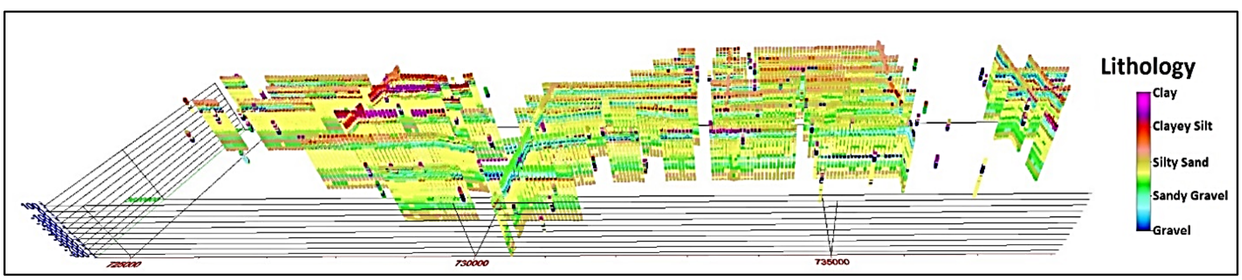


Figure A-8. Yuma Groundwater Study: 3D plot of lithology well logs and the 3D interpolated lithology values throughout the South Gila Valley. Lithology values have been interpolated to the XYZ locations of resistivity model parameters derived from the AEM survey results.

The nature of the water quality data posed another challenge because most of the water quality data was gathered from samples taken in wells that have very large screen intervals. In many cases, the well screen intervals were several hundreds of feet tall, so water samples were effectively an average of all water produced from this depth range. Very little discrete water sample data was available, so mixing laws were incorporated into the analysis to estimate what the mixed groundwater EC values would be when they were compared to real data. This and many other subtle aspects of the data analysis workflow for the Yuma Groundwater Study are good examples showing where future research and technology development efforts can be focused to help improve brackish aquifer characterization workflows.

AEM is a cost-effective method for charactering brackish groundwater resources across large areas (e.g., basin-scale studies) compared to physically drilling wells or conducting more focused ground-based geophysical surveys at discrete locations. Well drilling costs can range from tens to hundreds of thousands of dollars for one well. In contrast, for the same cost as several wells, AEM can provide greater spatial coverage and information that has greater value to the analysis of groundwater quantity and quality. Results of AEM surveys can provide guidance for subsequent drilling operations, such as targeting confined pockets of relatively fresh (e.g., low EC/low salinity) groundwater.

A.3 Surface-Based Geophysics Data

Incorporating information other than geophysical well log data will dramatically improve and further guide future brackish aquifer characterization and management efforts. This will most likely involve acquiring additional surface-based and perhaps airborne geophysical data, as well as collecting additional geophysical well logging data within accessible yet steel-cased exploration wells. The following sections provide overviews of various geophysical techniques that could be implemented to help inform and guide future groundwater characterization efforts.

Many recent groundwater studies have used some combination of ground-based and airborne geophysics surveying to complement existing, yet sparse, well data (e.g., well logs, pump tests, water sample data). Various geophysical techniques can be used to map the one-dimensional [1D], 2D, 3D, or even four-dimensional [4D] distribution of physical and chemical properties and processes, including key parameters such as resistivity. Ground-based geophysical mapping and imaging techniques are similar and complementary to Spontaneous Potential (SP) or resistivity and induction logging, where the main difference is the spatial breadth of data coverage (e.g., 2D or 3D tomographic images instead of 1D logs).

A.3.1 Resistivity Methods

A.3.1.1 Description

Electrical resistivity is a measure of a material's ability to impede the flow of an electrical current. Resistivity is the inverse of conductivity, which is a measure of how well a material can conduct electricity. Water content and salinity are the primary factors that determine a geologic unit's resistivity. While a dry porous rock is a poor conductor of electricity, a porous rock that is saturated with water will conduct electricity much better, giving it a lower resistivity value. Salt content increases the EC of water. In a saturated porous rock, the greater the salinity of the formation's water, the lower the resistivity. This is the basis for performing resistivity surveys in characterizing brackish aquifers.

Resistivity surveys use current electrodes, potential electrodes, a power source, and a voltmeter. The basic theory is to apply a direct or low frequency alternating current to the ground surface using current electrodes and then to measure the potential difference between various potential electrode pairs. Many different resistivity survey designs and electrode configurations use three common electrode configurations for either 1D soundings or 2D and 3D imaging:

1. *Wenner array:* The Wenner array has the simplest geometric electrode configuration. The array consists of four electrodes (a quadrapolar measurement) that are aligned equidistant to one another in a straight line. Two current electrodes on the outside of the array are connected to a power source so that a current flows between them. Two interior electrodes are potential electrodes that are connected to a voltmeter. The electric potential is measured between these two electrodes and then translated into a resistivity value. Several readings may be needed to survey an area of interest, and the entire array must be moved together.

2. *Schlumberger array:* Similar to the Wenner array, the Schlumberger array uses the same four electrodes in a straight-line configuration. In the Schlumberger array, however, the two potential electrodes start closer together. Once a resistivity reading is taken, the potential electrodes can be moved to increase the spacing between them before taking another reading. The process can be repeated as long as the spacing between the potential electrodes is less than $^1/_5$th the spacing between the current electrodes.

3. *Dipole-Dipole array:* This configuration differs greatly from the Schlumberger and Wenner arrays. In this array, the current electrodes and potential electrodes function independently. The current electrodes are placed on one side of the array with a distance *a* between them. The potential electrodes are placed on the opposite side of the array with the same distance *a* between them. The two electrode pairs are placed a known distance away from each other, not necessarily in a straight line. When the current is transmitted, the potential electrodes measure the

electric potential between them, and the resistivity value is calculated. The pairs can then be moved to new locations as long as they maintain the same spacing between them.

The Wenner and Schlumberger techniques offer better vertical resolution when measuring the resistivity of layers at depth. Dipole-Dipole, on the other hand, is better at identifying lateral changes in geology, which the Wenner and Schlumberger techniques are less sensitive to. In each case, the farther the electrodes are separated, the deeper the resistivity measurement (the electrical current flow becomes increasingly sensitive to deeper materials' resistivities).

A.3.1.2 Applications

Resistivity is increasingly being used as a nonintrusive way to characterize and monitor managed aquifers in arid regions of California and Arizona, and saltwater intrusion in coastal areas. Observing these changes in resistivity is useful to:

- Measure the lateral extent and thickness of landfills
- Determine depth to bedrock and overburden thickness
- Identify sinkholes
- Characterize subsurface hydrogeology
- Locate water bearing zones
- Delineate paleochannels
- Determine depth to groundwater
- Evaluate electrical grounding characteristics
- Map stratigraphy
- Map clay aquitards
- Map saltwater intrusion
- Map vertical extent of certain types of soil and groundwater contamination
- Map faults
- Map lateral extent of conductive contaminant plumes
- Delineate disposal areas

A.3.1.3 Advantages and Disadvantages

Substantial quantitative computer modeling is possible. The resulting models can provide accurate estimates of depths, thicknesses, and electrical resistivities of subsurface layers. Surveys can be completed to depths of several hundred feet. Large distances can be covered in a relatively short period of time. There are also, however, some disadvantages to this method. Resistivity surveys require a relatively large area far removed from power lines and grounded metallic structures. This makes surveys in urban areas particularly challenging. Profiling surveys can be more labor intensive than some other geophysical survey methods.

A.3.2 Surface Electromagnetic Methods

A.3.2.1 Description

Electromagnetic mapping techniques are similar to resistivity methods because they are sensitive to the electrical conductivity (inverse of resistivity) of materials and the subsurface. Resistivity methods use direct injection of galvanically coupled electrical currents. In contrast, EM techniques apply either pulsed or oscillating EM fields to the ground, measuring the resistivity and conductivity of the subsurface through EM induction. These EM fields interact with geologic or manmade features in the subsurface, and a secondary EM field is generated by these subsurface materials and measured by receiver sensors via EM induction. The characteristics (e.g., amplitude and phase) of these signals mostly depend on the resistivity of the subsurface materials, and these physical properties can be mapped and inversely modeled.

EM instruments consist of a transmitter coil and a receiver coil (or dipolar transmitters and receivers). The transmitter coil is connected to a power source that provides an alternating current. This current produces a magnetic field, which is called the "primary field." This field spreads out radially and penetrates into the subsurface layers. When the primary field interacts with a conducting body in the subsurface, the field generates eddy currents, which, in turn, produce a magnetic field called the "secondary field." The receiver on the EM instrument will detect both the primary and secondary fields and will record the voltage associated with both. The secondary field is separated from the primary field based on timing (for time-domain and pulsed sources) or amplitude and phase (for oscillatory sources), and the characteristics of the secondary field are used to infer the resistivity of the subsurface materials.

The receiver's ability to distinguish the secondary field from the primary field is the most important aspect of EM. There are two methods to achieve this:

1. The FDEM method is a continuous excitation method that compares the components of the secondary field that are in and out of phase to the components that are in and out of phase in the primary field.

2. The TDEM measures the primary field and secondary field at slightly different times in microseconds. TDEM measures the primary field immediately before the transmitter is turned off and measures the secondary field immediately afterward at various "time-gates" or bins of time in which the secondary induced field is captured as it decays (induced eddy currents within the subsurface decay as electrical potential energy is converted to thermal energy and dissipates as heat loss). Because there is a delay in the response of the second field to the transmitter being turned off, the TDEM method is able to measure the secondary field without the primary field.

EM surveys can be performed either as a sounding or as a profile. A sounding is used to estimate conductivity and resistivity as a function of depth at a particular location. FDEM soundings take multiple readings with various transmitter-receiver coil separations. A sounding location is assigned as the center point with a transmitter coil on one side and a receiver coil on the other side, equidistant from the center point. After each reading is taken, the spacing between the transmitter and receiver is increased. As the distance between the transmitter and receiver increases, so does the depth of investigation.

Profiling is the process of making measurements at different locations in an area of interest, while keeping the distance between the transmitter and receiver fixed. If the area of interest is known, a grid system can be established over the entire area. A profile is performed by walking the instrument along lines of the grid and continuously collecting data. This allows the data to be interpreted as a resistivity map.

A.3.2.2 Applications
EM survey applications are similar to resistivity applications with regards to groundwater. EM also has other applications, such as locating and delineating:

- Landfill boundaries and cells
- Contamination plumes
- Buried metal objects (utilities and pipes)
- Buried foundations
- Previously excavated and backfilled areas

A.3.2.3 Advantages and Disadvantages
EM techniques are generally unaffected by near surface lateral changes in resistivity and can penetrate deeper into the subsurface than a resistivity survey over the same array area. EM surveys can also typically be performed faster than resistivity techniques. As a result, a relatively large amount of data coverage can be achieved in a short amount of time. EM methods, however, are relatively susceptible to EM noise and nongeologic conducting bodies such as power lines, buried cables, and rebar. Care must be taken, therefore, in data analysis and interpretation.

A.3.3 Seismic Methods
A.3.3.1 Description
Both seismic reflection and seismic refraction are used to create images of the subsurface geologic structure. While seismic reflection and refraction are primarily used for imaging geologic and tectonic structures, these techniques can also be used to infer groundwater aquifer characteristics. These surface methods are relatively inexpensive to perform and can provide data to be correlated with borehole seismic data where available.

Both reflection and refraction surveys involve generating seismic waves that propagate into the subsurface and interact with the subsurface structures (i.e., the waves reflect, refract, and diffract off of geologic layers and interfaces) before reaching a series of surface or borehole seismic receivers (e.g., geophones, hydrophones, and accelerometers). Seismic waves are typically generated using either vibratory or impactive sources, such as a hammer or weight striking a metal source plate. If the depth of interest is very deep, explosive charges or truck-mounted vibratory sources may be used to impart more seismic energy into the ground.

Both techniques aim to determine the geologic structure of the subsurface. Refraction tomography images the seismic wave velocity distributions (e.g., the velocity of seismic wave propagation through subsurface materials). Reflection primarily images the stratigraphic structure of the subsurface (e.g., images stratigraphic interfaces between layers of differing seismic impedances).

Refracted waves are the portion of the wavefield that encounter a faster layer at depth and then critically refract and propagate along the top interface of this faster and harder layer (propagating at the velocity of the faster layer, in the form of a head wave). As this head wave propagates along the interface, it also emanates seismic waves that propagate back upwards to the geophone sensors placed along the ground surface. These refracted arrivals typically arrive before the more shallowly propagating direct waves after a certain distance, referred to as the "critical offset."

Seismic wave velocities are positively correlated with both rock density and hardness. It is assumed that rock density and hardness increase with depth, and as a result, so will the seismic wave velocities. Seismic refraction is used to characterize bedrock topology, determine lithology, map fractured areas of rock, and even locate the depth of the water table (if the water table creates a substantial interface). Seismic reflection, on the other hand, involves recording the two-way travel time for a seismic wave to go from the surface down to an interface and to be partially reflected back to geophones at the surface. Reflected waves typically travel farther than refracted waves and, therefore, will be recorded at later times.

A.3.3.2 Applications

Refraction surveys are typically used to image the uppermost few hundred feet of the subsurface (down maximum depths of up to 200 to 300 feet). Reflection seismic imaging is typically used to image deeper into the subsurface (more than 300 to 400 feet below ground surface), and this can be used to image down to depth of tens of thousands of feet into the Earth's crust. These deeper imaging techniques are typically used for oil and gas exploration within sedimentary depositional environments. Seismic reflection is very good at imaging subhorizontal sedimentary layers and interfaces but has difficulty accurately imaging subvertical structures, such as uplifted layers or near-vertical faults. This has long been an active area of research in the seismic reflection community, where imaging near-vertical layers, faults, sub-salt diaper structures, and hydrocarbon deposits are of upmost interest for oil and gas exploration.

A.3.3.3 Advantages and Disadvantages

Seismic methods provide a detailed, cross-sectional image of the subsurface. The data can indicate the presence of important geological features and their physical characteristics (orientation, seismic velocity, density). Three-dimensional depth-to-target contour plots can be generated. The data collection is nondestructive and nonintrusive. Depending on the target, seismic methods may require more field and office time to complete than other geophysical methods. Ambient noise vibrations can adversely affect the seismic data quality.

A.3.4 Magnetics

A.3.4.1 Description

Magnetic surveying is another method of imaging tectonic structures and can also be used to map shallow bedrock and other changes in geology. Magnetic surveying uses high precision instruments, called magnetometers, to detect magnetic anomalies induced in ferromagnetic materials from Earth's magnetic field, or to map lateral changes due to changes in geology. The basic theory is that geologic materials and manmade objects that have ferromagnetic, diamagnetic, or paramagnetic materials in them will have either a permanent remnant magnetization or an induced magnetization created in them from the application of an external magnetic field (e.g., Earth's magnetic field), or both.

A.3.4.2 Applications

Geological units such as magnetic ore bodies and basic igneous rocks have their own naturally occurring magnetic fields. Magnetic surveys are also commonly used to map ferrous objects, such as in utility line mapping or undetonated explosive ordinance (UXO) surveys. By taking measurements of the magnetic field at regular intervals over an area of interest (or within boreholes), a magnetic contour map can be produced. This map can be used to infer the geologic structures or objects within the subsurface.

A.3.4.3 Advantages and Disadvantages

Gradient measurements are very sensitive to small objects. Magnetic surveys are set up and conducted quite easily. Large sites can be investigated quickly. Hand-held metal detectors can be used to follow up the magnetic results to provide further information about detected objects. Exploration depth, however, is generally limited relative to other methods. Detection ability depends upon magnetic variations above and beyond those caused by above ground features. In congested, urban areas, parked cars, buildings, fences, and utilities contribute interfering magnetic signals that can mask detection of buried metal objects.

A.4 Existing Cased Wells: See-Through Casing Technologies

See-through casing well logging techniques may also help investigate groundwater quantity and quality more effectively. These techniques are often useful for identifying stratigraphy and physical and hydrologic properties of surrounding materials behind steel-cased and grouted exploration wells. This type of technology would enable stakeholders to quickly log the uppermost several hundred feet of any accessible well. It should be noted that there are typically challenges with this approach, mainly related to accessibility to wells for logging new data, the associated costs of collecting new logging data, and the depth-range that new logging data would provide (often too shallow). If attainable, new data could be correlated with surrounding log data to help update and improve 3D aquifer characterization and mapping.

The Texas Water Development Board (TWDB) and similar entities could use data from oil and gas exploration wells within the uppermost several hundred feet of the subsurface; however, oil and gas exploration and drilling companies do not typically gather this data. As most oil and gas reservoirs are several thousands of feet below ground surface, there is typically little interest in these shallow depths. These companies tend to quickly drill through overburden materials and simply case these unconsolidated depth intervals without collecting any well logging data. Moreover, these depth intervals are unstable and prone to well wall spalling and collapse.

This ubiquitous lack of logging data collection within the uppermost several hundreds of feet provides a challenge to brackish aquifer characterization, especially since these relatively shallow depth intervals correspond to the most common depths of brackish aquifers. See-through well casing technologies could prove indispensable in mapping lithology and helping to infer groundwater conditions outside of these cased wells within these shallow depth intervals.

The suite of nuclear logging techniques can sense formation characteristics behind steel casing (e.g., an existing “see-through casing” technology). These include the gamma-gamma density logging, natural gamma logging, and neutron density logging, and spectral techniques for identifying and quantifying mineralogical constituents of host rock and ionic constituents and concentrations of the saturating brackish fluid.

Some of the various existing cased hole logging techniques are described in the subsections immediately below (Crain, 2000). These tools could help fill in some of the data gaps that TWDB and other similar entities face. Specifically, these tools provide the opportunity to correlate cased hole logs with other nearby water quality and uncased log data, as well as provide the opportunity to collect data directly on porosity and bulk resistivity estimates—both key parameters for use in groundwater quality and brackish aquifer characterization analyses.

A.4.1 Cased Hole Logging Basics

A.4.1.1 History

Logging through casing began with the gamma ray log in the later part of the 1930s, and this tradition has continued to the present. The gamma ray log is used for depth correlation on many logging and wireline services. Most cased-hole logs have a gamma ray and casing collar log (CCL) for depth control. Slim-hole tools for use through tubing or hostile environments, as well as full size tools for casing or open-hole applications, are usually available. In the mid-1940s, the neutron log was added and recorded through casing. Correlation, shale volume, porosity, and gas zones could be observed with these two logs. Modern gamma ray and neutron logs are properly calibrated and scaled, but a number of environmental corrections may be required. The pulsed neutron using thermal decay time, induced gamma ray spectral logs, and natural gamma ray spectral log followed in the 1960s. With these, we could assess water saturation and lithology through casing, at least in favorable circumstances. Compensated neutron logs with some corrections for casing and average cement conditions appeared in the 1970s. This log was scaled in porosity units, so it could be used more directly for reservoir evaluation than previous neutron logs.

Compressional and shear travel time (slowness) logs appeared in the 1980s and were suitable for both open and cased hole applications. By 2004, the Schlumberger services catalog listed both cased-hole resistivity and cased-hole density logs. The modern logs that cannot be run in casing are the dipmeter, resistivity image, nuclear magnetic resonance, and SP.

A.4.1.2 Best Practices

Petrophysical analyses using these cased-hole measurements proceed along the same lines as with the equivalent open-hole logs, with only minor exceptions. The first exception is that the annulus between the casing and formation must be well cemented, with good cement fillup. Most cased-hole logs suffer from poor cement. A good cement bond or cement mapping log should be run and remedial action taken before running cased-hole logs for reservoir evaluation. The analyst needs to determine whether further borehole fluid, casing size and weight, cement sheath, or other environmental corrections are required. Some corrections are made at the time of logging, while others are not, and it varies with the age of the tool. The sections below provide a brief summary of each of the tools useful in cased-hole reservoir evaluation (condensed from the 2016 Schlumberger Services Catalog). The summary specifically addresses each tool's description, applications, and advantages and disadvantages.

A.4.2 Cased Hole Gamma Ray

A.4.2.1 Description

Gamma ray tools record naturally occurring gamma rays in the formations adjacent to the wellbore. This nuclear measurement indicates the radioactive content of the formations.

A.4.2.2 Applications

- Depth determination
- Depth correlation within the well and between wells
- Lithology identification
- Qualitative evaluation of shaliness
- Qualitative evaluation of radioactive mineral deposits

A.4.2.3 Advantages and Disadvantages

Effective in any environment, gamma ray tools are the standard device used for correlation of logs in cased and open holes.

A.4.3 Cased Hole Spectral Gamma Ray

A.4.3.1 Description

Spectral gamma ray tools provide insight into the mineral composition of formations. The total gamma ray spectra measured is separated into the three most common components of naturally occurring radiation in sands and shales—potassium (K), thorium (Th), and uranium (U). These data are used to distinguish important features of the clay or sand around the wellbore. The clay type can be determined, and sand can be identified as radioactive. The deposition of radioactive salts behind the casing by the movement of water can also be identified.

The natural gamma ray spectrometry tool uses five-window spectroscopy to resolve the total gamma ray spectra into K, Th, and U curves. The standard gamma ray (SGR) and the uranium corrected gamma ray (CGR) component are also presented. The computed gamma ray or Th curve can be used to evaluate the clay content where radioactive minerals are present.

A.4.3.2 Applications

- Cation exchange capacity studies
- Reservoir delineation
- Detailed well-to-well correlation
- Definition of facies and depositional environment
- Igneous rock recognition
- Recognition of other radioactive materials
- Estimated uranium and potassium potentials
- Lithologic analysis log input

A.4.3.3 Advantages and Disadvantages

Effective in most environments, this and other gamma ray tools are the standard devices used to correlate logs in cased and open holes. A major advantage is that this technique is capable of detecting and mapping changes in formation characteristics behind the steel casing of a well. An advantage of this particular nuclear logging tool is that it is a passive technique that simply listens to naturally occurring signals (gamma rays emitted from the formation) and does not involve the use of highly regulated and potentially hazardous radioactive sources that emit high-energy neutrons and other thermally radioactive particles. The main disadvantage, like any well logging technique, is that the data only represent the environment immediately surrounding the well and does not provide information about zones far from the well.

A.4.4 Cased Hole Porosity

A.4.4.1 Description

Cased-hole formation porosity (CHFP) services make accurate formation porosity and sigma measurements in cased wells. The measurement, based on an electronic neutron source instead of a chemical source, uses borehole shielding and focusing to obtain porosity measurements that are only minimally affected by borehole environment, casing, standoff, and formation characteristics such as lithology and salinity. The large yield of the neutron source enables the use of epithermal neutron detection and borehole shielding. Five detectors provide information for porosity evaluation, gas detection, shale evaluation, vertical resolution improvement, and borehole correction. The measurements can be performed in both cased and open holes.

Compensated neutron logs measure the hydrogen index (HI) of downhole formations. The measurements are converted to porosity values which, in combination with density tool measurements, provide an indication of lithology and gas in zones of interest. Some compensated neutron tools provide thermal and epithermal measurements. Thermal measurements require a liquid filled borehole. Epithermal measurements can be made in air- or gas-filled boreholes.

Compensated neutron logs (CNL) have traditionally been run as porosity indicators in cased wells. CNLs contain a radioactive source that bombards the formation with fast neutrons. The neutrons are slowed primarily by hydrogen atoms in the formation. Detectors count the slowed neutrons deflected back to the tool. Because the tool responds primarily to the hydrogen content of the formation, the measurements are scaled in porosity units. Both epithermal (intermediate energy) neutrons and thermal (slow) neutrons can be measured, depending on the detector design. These tools use two thermal detectors to produce a borehole-compensated thermal neutron measurement.

The dual-energy neutron log has two thermal and two epithermal detectors that make separate energy measurements for gas detection and improved reservoir description.

A.4.4.2 Applications

- Porosity determination
- Lithology identification
- Gas detection
- Correlation in cased wells

- Option to pump slim tools down drill pipe
- Formation evaluation behind casing
- Accurate hydrogen index estimation
- Clay analysis

A.4.4.3 Advantages and Disadvantages

Effective in most environments, neutron logs are very useful for correlation of logs in cased and open holes. A major advantage is that this technique is capable of detecting and mapping changes in formation and saturating fluid characteristics behind steel casing of a well. Although CNL provides a good estimation of formation porosity in most conditions, the CNL does not use a focused and highly controlled beam of neutrons and, therefore, does not allow for corrections for environmental and geometric effects (e.g., thickness of casing and cement) or correction for effects resulting from the position of the tool and casing in the borehole. For the highest possible accuracy, CHFP service is the measurement of choice.

The main disadvantage, like any well logging technique, is that the data only represent the environment immediately surrounding the well and do not provide information about zones far from the well. Another disadvantage of this technique is the radioactive nature of the source used in the tool, which requires very careful handling, and specific and expensive licensure of all operators who transport and use the instrument.

A.4.5 Cased Hole Reservoir Saturation Log

A.4.5.1 Description

Reservoir saturation tools, such as the pulsed thermal-neutron decay time (TDT) tool, are still widely used. The reservoir saturation log (RST) makes both the formation's capture cross section (sigma) and carbon/oxygen (C/O) ratio measurements, which allow the calculation of water saturation without requiring a resistivity log. Here, sigma is defined as the relative ability of a material to "capture" or absorb free thermal neutrons.

In formations with high-salinity formation water, the sigma measurement has been used for several decades to determine water saturation. The C/O ratio measurement can accurately evaluate water saturation in moderate to high porosity formations, regardless of water salinity. This calculation is particularly helpful if the water salinity is low or unknown. If the salinity of the formation water is high, the Dual-Burst Thermal Decay Time measurement is used. A combination of both measurements can be used to detect and quantify the presence of injection water of a different salinity from that of the in-situ groundwater.

A.4.5.2 Applications

- Formation evaluation behind casing
- Sigma, porosity, and C/O measurement in one trip in the wellbore
- Water saturation evaluation in old wells where modern open hole logs have not been run
- Measurement of water velocity inside casing, irrespective of wellbore angle (production logging)
- Measurement of near-wellbore water velocity outside the casing (remedial applications)
- Formation oil volume from C/O ratio, independent of formation water salinity
- Capture yields (hydrogen [H], chlorine [Cl], calcium [Ca], silica [Si], iron [Fe], sulfur [S], gadolinium [Gd], and magnesium [Mg])
- Inelastic yields (carbon [C], oxygen [O], Si, Ca, and Fe)
- Borehole salinity

A.4.5.3 Advantages and Disadvantages

Effective in most environments, neutron logs are very useful for correlation of logs in cased and open holes. A major advantage is that this technique is capable of detecting and mapping changes in formation and saturating fluid characteristics behind steel casing of a well. The main disadvantage, like any well logging technique, is that the data only represent the environment immediately surrounding the well and do not provide information about zones far from the well. Another disadvantage of this technique is that the radioactive nature of the source used in the tool requires very careful handling and specific and expensive licensing for all operators that transport and use the instrument.

A.4.6 Cased-Hole Dipole Shear Sonic

A.4.6.1 Description

Dipole shear sonic, coupled with automated sonic waveform processing for slowness determinations, provides accurate formation compressional and shear slowness measurements in cased wells. Slowness processing is based on optimally designed frequency filters and advanced signal processing.

The dipole shear sonic log combines monopole and dipole sonic acquisition capabilities. The transmitter section contains a piezoelectric monopole transmitter and two electrodynamic dipole transmitters perpendicular to each other. An electric pulse at sonic frequencies is applied to the monopole transmitter to excite compressional- and shear-wave propagation in the formation. For Stoneley wave acquisition, a specific low-frequency pulse is used. The dipole transmitters are also driven at low frequency to excite the flexural wave around the borehole.

The tool is made up of three sections: acquisition cartridge, receiver section, and transmitter section. An isolation joint is placed between the transmitter and receiver sections to prevent direct flexural wave transmission through the tool body. The receiver section has an array of eight receiver stations spaced 6 inches. (15 centimeters) apart and 9 feet (2.74 meters) from the monopole transmitter, 11 feet (3.35 meters) from the upper dipole transmitter, and 11.5 feet (3.50 meters) from the lower dipole transmitter. Each receiver station consists of two pairs of wideband-piezoelectric hydrophones aligned with the dipole transmitters.

Summing the signals recorded by one pair of hydrophones provides the monopole waveform, whereas differentiating them cancels the monopole signal and provides the dipole waveform. When a dipole transmitter is fired, the hydrophone pair diagonally in line with the transmitter is used. Four sets of eight waveforms can be acquired from the four basic operating modes fired in sequence. A special dipole mode enables recording both the inline and crossline (perpendicular) waveforms for each dipole mode. This mode, called both cross receivers (BCR), is used for anisotropy evaluation.

A.4.6.2 Applications

- Geophysics
  - Velocity calibration, time/depth conversion
  - Synthetic seismograms
  - Amplitude variation with offset (AVO) calibration
  - Shear seismic interpretation

- Anisotropy

- Petrophysics
  - Porosity estimation (also in cased hole)
  - Lithology and clay identification
  - Gas identification

- Stoneley wave measurement
  - Fracture evaluation
  - Permeability (mobility)

A.4.6.3 Advantages and Disadvantages

The various data collection and processing steps associated with this logging technique help to significantly attenuate casing arrivals to facilitate the clean extraction of formation slowness. This sonic logging tool is effective in most environments and can be very useful for correlating logs in cased and open holes. A major advantage is that this technique is capable of detecting and mapping changes in formation characteristics behind steel casing of a well. This logging technique, however, can still be vulnerable to velocity biases due to the presence of steel casing. As a result, the velocity logs can be more representative of relative seismic velocities, which are still quite useful in identifying lithologic units and contacts. This instrument is also negatively affected by variable well grout completion, where entrapped air between the well casing and the surrounding formation can prevent meaningful data collection and analysis results. Again, a main disadvantage, like any well logging technique, is that the data only represent the environment immediately surrounding the well and do not provide information about zones far from the well.

A.4.7 Cased-Hole Elemental Capture Spectroscopy

A.4.7.1 Description

Elemental capture spectroscopy logs use a standard americium beryllium (AmBe) neutron source and a large bismuth germanate (BGO) detector to measure relative elemental yields based on neutron-induced capture gamma ray spectroscopy. The primary elements measured in both open and cased holes are for the formation elements: Si, Fe, Ca, S, titanium [Ti], Gd, Cl, barium [Ba], and H.

Wellsite processing uses the 254-channel gamma ray energy spectrum to produce dry-weight elements, lithology, and matrix properties. The first step involves spectral deconvolution of the composite gamma ray energy spectrum by using a set of elemental standards to produce relative elemental yields. The relative yields are then converted to dry-weight elemental concentration logs for the elements Si, Fe, Ca, S, Ti, and Gd using an oxides closure method.

Matrix properties and quantitative dry-weight lithologies are then calculated from the dry-weight elemental fractions using empirical relationships derived from an extensive core chemistry and mineralogy database.

A.4.7.2 Applications

- Dry-weight lithology fractions (from elements)
    - Total clay
    - Total carbonate
    - Anhydrite and gypsum from S and Ca
    - Quartz, feldspar, and mica (QFM)
    - Pyrite
    - Siderite
    - Coal
    - Salt

- Matrix properties (from elements)
  - Matrix grain density
  - Matrix thermal and epithermal neutron
  - Matrix sigma.
- Clay fraction independent of gamma ray, SP, and density
- Neutron
- Carbonate, gypsum or anhydrite, pyrite, siderite, coal, and salt fractions for complex reservoir analysis
- Matrix density and matrix neutron values for more accurate porosity calculation
- Sigma matrix for cased and open hole sigma saturation analysis
- Mineralogy-based permeability estimates
- Quantitative lithology for rock properties modeling and pore pressure prediction from seismic data
- Geochemical stratigraphy (chemostratigraphy) for well-to-well correlation

A.4.7.3 Advantages and Disadvantages

Effective in most environments, this and similar nuclear logging techniques are very useful for correlation of logs in cased and open holes. A major advantage is that this technique is capable of detecting and mapping changes in formation and saturating fluid chemical characteristics behind steel casing of a well. The main disadvantage, like any well logging technique, is that the data only represent the environment immediately surrounding the well and do not provide information about zones far from the well. Another disadvantage of this technique is the radioactive nature of the source used in the tool, which requires very careful handling, and specific and expensive licensure of all operators who transport and use the instrument.

A.4.8 Cased Hole Formation Resistivity

A.4.8.1 Description

Cased-hole formation resistivity (CHFR) logs are a technology, developed by oil and gas exploration companies, that makes direct, deep reading resistivity measurements through casing and cement (Aulia et al., 2001). The concept of measuring resistivity through casing is not new, but recent breakthroughs in downhole electronics and electrode design have made these challenging measurements possible. Now the same basic measurements can be compared for open and cased holes. The effects of invasion are usually dissipated by the time the log is run, so the measurement is considered a good representation of true resistivity, as long as cement conditions are adequate.

The tool injects current into the casing with sidewall contact electrodes, where the electrical current flows both upward and downward before returning to the surface along a path similar to that employed by open-hole laterolog tools. Most of the current remains in the casing, but a very small portion of the current leaks to the formation. Electrodes on the tool measure the potential difference created by the leaked current, which is proportional to the formation resistivity.

Typical formation resistivity values are about 10^9 times the resistivity value of the steel casing. The measurement current leaking to the formation causes a voltage drop in the casing segment. Because the resistance of casing is a few tens of micro-ohms and the leaked current is typically on the order of a few milliamperes, the potential difference measured by the CHFR tool is in nanovolts range.

A.4.8.2 Applications

- Resistivity measurement behind casing in new or old wells
- Reservoir monitoring
- Location of bypassed hydrocarbons
- Determination of residual oil saturation
- Contingency logging in wells where open hole logs could not be run
- Primary evaluation where open hole logging is not possible

A.4.8.3 Advantages and Disadvantages

This logging technique addresses one of the fundamental data gaps identified (i.e., a lack of electrical resistivity information). The technique is effective in most environments and is very useful for correlation of logs in cased and open holes. This technique, however, requires calibration to other resistivity data to provide reliable and accurate absolute resistivity values. A major advantage is that this technique is capable of detecting and mapping changes in formation and saturating fluid electrical resistivity behind steel casing of a well. This is a key parameter in assessing groundwater quality, as well as for identifying changes in lithology. The resulting resistivity log can be used to fill in data gaps and can inform the various well log analysis techniques discussed in this report. The main disadvantage, like any well logging technique, is that the data only represent the environment immediately surrounding the well and do not provide information about zones far from the well. This tool can also be vulnerable to instrument drift (e.g., thermal drift) and is sensitive to external electrical noise (e.g., nonuseful signals from electrical infrastructure or radio transmission towers near the well) that can lead to erroneous values and incorrect assessments of groundwater quality.

A.4.9 Cased Hole Formation Density

A.4.9.1 Description

Cased-hole formation density (CHFD) logs make accurate formation density measurements in cased wells. A chemical gamma ray source and three-detector measurement system are used to make measurements in a wide range of casing and borehole sizes. The density measurement made by the three-detector system is corrected for casing and cement thickness.

A.4.9.2 Applications

The density data are used to calculate porosity and determine the lithology. The combination of density and neutron data is used to indicate the presence of gas:

- Porosity determination
- Lithology analysis and identification of minerals
- Gas detection
- Hydrocarbon density determination
- Shaly sand interpretation
- Rock mechanical properties calculations
- Determination of overburden pressure
- Synthetic seismogram for correlation with seismic

A.4.9.3 Advantages and Disadvantages

Effective in most environments, this and similar nuclear logging techniques are very useful for correlation of logs in cased and open holes. A major advantage is that this technique is capable of detecting and mapping changes in formation density behind steel casing of a well, which is useful in determining lithology, and for assessing formation porosity based on other knowns (e.g., expected density of constituent minerology, as inferred from elemental capture spectroscopy measurements). Density values can be biased due to the presence of vertically variable well cement bonding (e.g., missing grout and entrapped air pockets between the well casing and surrounding formation can lead to anomalously low and inaccurate density values). The main disadvantage, like any well logging technique, is that the data only represent the environment immediately surrounding the well and do not provide information about zones far from the well. Another disadvantage of this technique is the radioactive nature of the source.

A.5 Geophysical Borehole Logging Techniques

This section presents a quick review of the most common well logging tools and techniques that are most relevant to groundwater exploration and characterization. These primarily include geophysical well logging tools, but also include other deductive and nongeophysical techniques for characterizing fluids in the subsurface (e.g., pumping tests, and noise monitoring for casing leaks or fluid production and turbid flow entering the well from focused fracture networks).

A wide range of geophysical survey methods can be used to investigate and characterize brackish aquifers. Common physical and chemical properties, such as intrinsic porosity, material type, salinity, TDS concentrations, permeability, storativity, transmissivity, effective porosity, and vertical or lateral extent, can be estimated by geophysical logging surveys (Reclamation, 2016). Geophysical borehole logging techniques have been developed to provide subsurface condition information to enhance understanding of geological formations, groundwater, and environmental and geotechnical aspects. Geophysical well logging has become a standard practice in oil and gas, groundwater, and geothermal exploration to delineate hydrogeological units, define groundwater quality, and determine well construction and conditions (Keys 1990).

Typical geophysical well logging methods include electrical logs (resistivity and borehole imaging), porosity logs (density, neutron porosity, and sonic), lithology logs (gamma ray, SP), caliper logs, nuclear magnetic resonance logs, spectral noise logs, logging while drilling, and memory logs. Other geophysical logging methods, such as downhole gravity, magnetic gradiometry, and downhole ground-penetrating radar, are not discussed here because they are second-order techniques not widely used in groundwater exploration and brackish groundwater characterization efforts.

Interpretations of borehole logs are conducted using the combination of several geophysical borehole logging techniques, and the combined interpretation of the logging data will provide more accurate information than would a single logging method to measure physical, chemical, and structural properties of geological formations.

Geophysical well logging in groundwater development could reduce project costs and is often straightforward; however, the application is limited due to the lack of developed interpretation techniques. To enhance the value of geophysical logs in groundwater wells, simplified or refined interpretation techniques for applying logger response to hydrology and hydrogeological issues are essential. The most common questions in groundwater well logging are:

1. Where should well screens be installed?
2. How much groundwater will the well yield?
3. What is the water quality in the aquifer?

Information related to the permeability of the aquifer formation and the resistivity of the formation water will be needed to answer these questions. The use of groundwater well logging has frequently been limited to relatively estimate quantity and quality due to insufficiently developed interpretation techniques. The neutron logging technique provides a good source of porosity data. This logging technology is a vital tool that is used for delineation of porous formations of complex lithology and the determination of the porosity of a formation. There are three processes in neutron logging: neutron emission, neutron scattering, and neutron absorption (Hudson, 1996).

Natural gamma ray logging is a method of measuring gamma radiation to characterize the rock or sediment in a borehole and is used primarily for identification of lithology and stratigraphic correlation. There is an issue with determining clay content using gamma ray logs because clay and sand gamma response values are very local. Clean-sand and clay response levels must often be updated (Hudson, 1996). Natural gamma logging measures gamma radiation emitted from rock layers. This gamma logging tool can be used in either open or cased holes and is used to identify lithology.

Normal resistivity logs are often used to distinguish between hydrocarbon or water bearing zones, indicate permeable zones, and determine resistivity porosity. The rock resistivity increases as the hydrocarbon saturation of the pores increases. Normal and lateral resistivity logging measures the resistivity in ohm-meters as applying a constant current across two electrodes and measuring the potential between two other electrodes (Stanton et al., 2007). These tools can help delineate and quantify areas of fresh versus relatively brackish water in single-phase reservoirs (i.e., aquifers with only water saturation).

Caliper logging records well diameter in uncased holes and can be used to detect fracture openings or changes in borehole diameter (Keys, 1990).

Fluid logging measures properties of the groundwater in a borehole, including fluid resistivity and temperature. The changes in the fluid resistivity and temperature are evidence of groundwater-producing and groundwater-receiving zones in a well. Flowmeter logging measures the direction and magnitude of vertical fluid flow in a borehole to identify water-producing or water-losing fractures in a well. Camera logging measures both downhole and side views of a borehole and performs inspection of the borehole wall and details of the well construction. Optical televiewer (OTV) logging provides oriented color digital images with high resolution of a borehole wall (Stanton et al., 2007).

A.5.1 Resistivity Logs

One of the primary material properties of interest in groundwater exploration and aquifer characterization is bulk resistivity (or electrical conductivity) of the materials surrounding a borehole, usually measured with electrical or EM methods (e.g., resistivity logging or EM induction logging). Various tools for measuring this key material property use various techniques to separate and remove the influence of drilling fluids or grout on the measured values. The goal is to directly measure the bulk resistivity, which is primarily a function of the host material's mineralogical and chemical makeup, as well as the saturating fluid's conductivity (e.g., a freshwater saturated sand is much more electrically resistive than a brine-saturated clay).

Normal resistivity logs are used to determine hydrocarbon versus water-bearing zones, indicate permeable zones, and determine resistivity porosity. The rock resistivity increases as the hydrocarbon saturation of the pores increases. Normal and lateral resistivity logging measures the resistivity in ohm-meters by applying a constant current across two electrodes and measuring the potential between two other electrodes.

Resistivity logging measures resistivity in the subsurface in ohm-meters by using two current electrodes. This differentiates between formations filled with salty water, a good conductor of electricity, and those filled with hydrocarbon, a poor conductor of electricity. Measurements of resistivity and porosity are used to calculate water saturation. When a geological formation contains high porous media and salty water, the resistivity will be low. When the geologic formation contains hydrocarbon and very low porosity, the resistivity will be high.

The resistivity logs measure the geological formation at shallow, medium, and deep depths. The shallow, medium, and deepest reading profile of the logging results show the resistivity of the flushed zone, invaded zone, and uncontaminated zone surrounding the borehole (figure A-9). The diameter of invasion by the mud filtrate and relatively permeable zones can be evaluated using these reading profiles (Schlumberger, 2011).

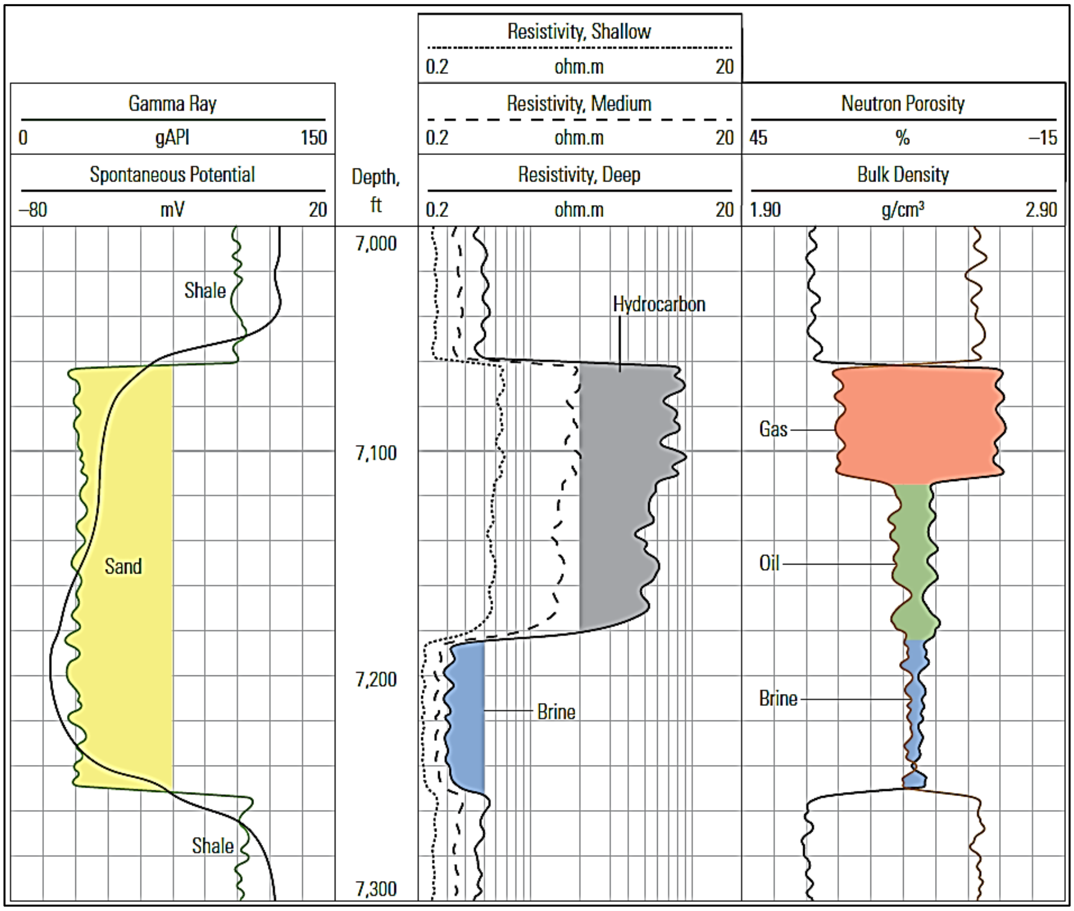


Figure A-9. A basic logging including SP, gamma ray, resistivity, neutron, and density profiles.

A.5.2 Borehole Imaging Logs

Borehole imaging is a rapidly advancing technology in wireline well logging methods. Borehole imaging logging can aid in hydrocarbon recovery, identify major fractures, analyze small-scale sedimentological features, identify thinly bedded formations, and evaluate irregularities in the borehole wall. The borehole imaging logs include OTV imaging, acoustic televiewer imaging, and electrical imaging techniques.

Acoustic televiewers use the acoustic signal from a rotating sonar transducer and provide high-resolution, oriented images of the borehole walls. OTVs use a high-resolution digital color camera with a light source and provide a continuous, detailed, and true color image of the borehole walls that constitute a 360-degree view. The televiewers use a unique optical imaging system to obtain dip, strike, frequency, and fracture aperture of geologic formations. Figure A-10 presents the composite image of borehole-geophysical logs collected in a monitoring well.

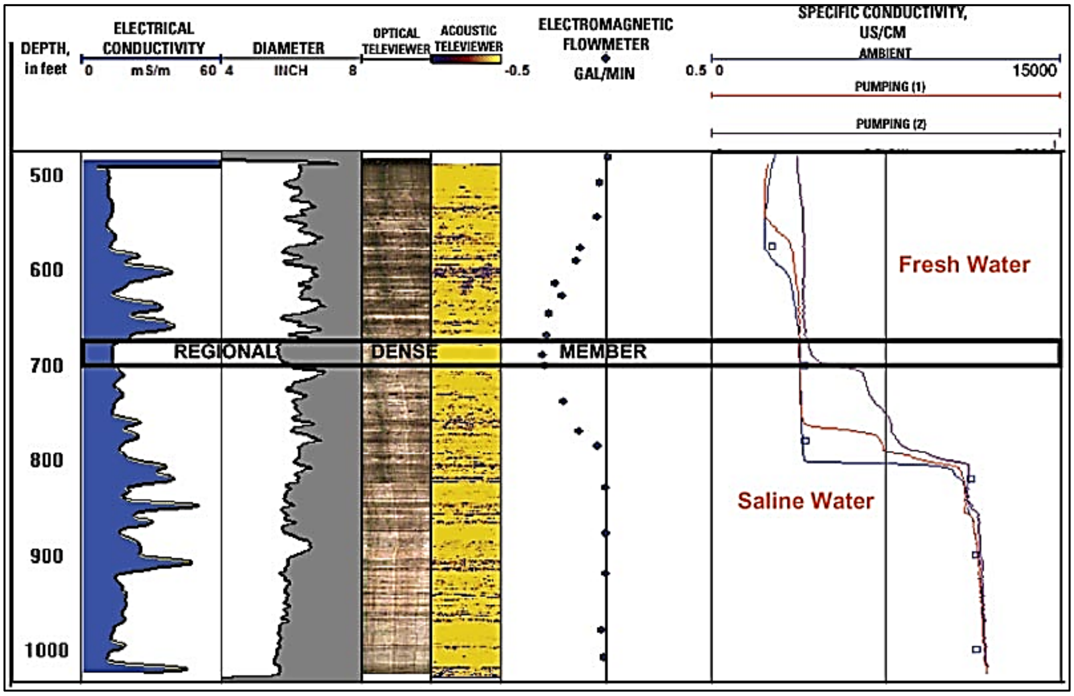


Figure A-10. Composite image of borehole-geophysical logs collected in a monitoring well.

A.5.3 Density (Gamma-Gamma) Logs

Density logs or gamma-gamma logs provide a continuous record of a geologic formation's bulk density along the length of a borehole to determine porosity. The bulk density is a function of the density of the minerals that form the rock and the fluid enclosed in the pore spaces; thus bulk density logging, neutron porosity logging, and sonic logging methods are commonly used to calculate porosity of geologic formations in boreholes.

The geological formation bulk density is a key component to determine porosity of a formation. The porosity is the fraction or percentage of pore volume in a volume of rock. The bulk density of a formation is calculated based on the ratio of a measured mass to the volume. In general, porosity is inversely related to the density of the rock. The bulk density measurement of a formation is derived from the electron density of a formation. Density logs measure formation density using a logging device that emits gamma rays into the formation with a radioactive source. The gamma rays collide with electrons in the formation, giving off energy and scattering in a process known as Compton Scattering. The number of such collisions is directly related to the number of electrons in the formation. In low-density formations, more of these scattered gamma rays are able to reach the detector than in formations of higher density (Schlumberger, 2011). The density log records the amount of gamma radiation returning from the formation. An example of the bulk density logging profile along a geologic formation of a borehole is shown in figure A-11.

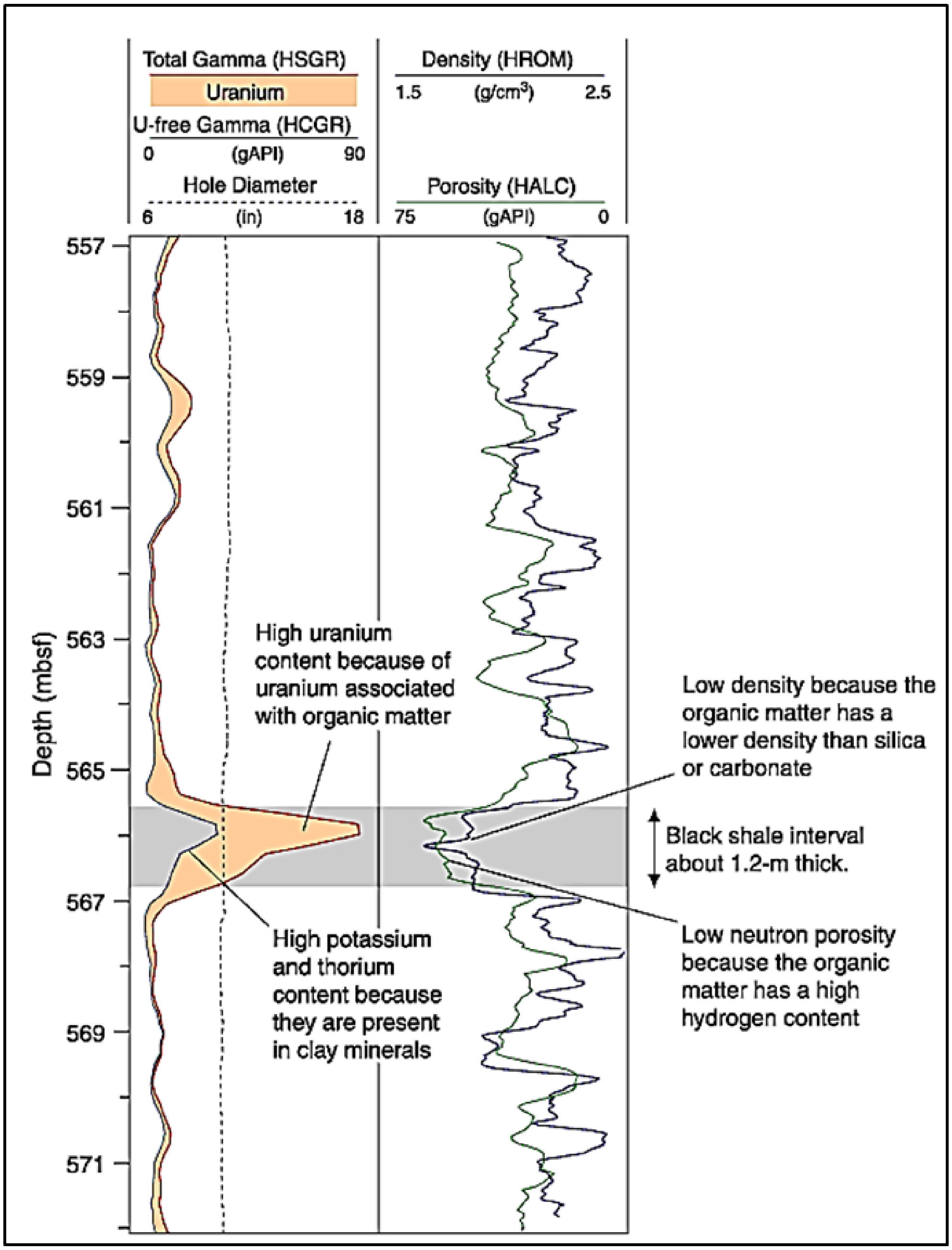


Figure A-11. Gamma radiation, density, and porosity logs around black shale interval (HSGR = total spectral gamma ray, HCGR = computed gamma ray, HROM = high resolution bulk density, and HALC = high resolution array porosity).

A.5.4 Neutron Porosity Logs

Neutron logging can be used to estimate the porosity of geologic formations. Neutron logging uses neutron emission, neutron scattering, and neutron absorption measurements to delineate porous formations of complex lithology and determine the porosity of a formation.

The concentration of hydrogen atoms can be used to determine the fluid-filled porosity of a geologic formation because hydrogen is a major component of water and hydrocarbons concentrated in rock porous media. Hydrogen has nearly the same mass of atoms as that of neutrons. The neutron logging technique emits neutrons using an electronic neutron generator. When the neutrons collide with hydrogen atoms in geologic formations, the neutrons lose energy through elastic scattering and reach a very low energy or thermal state. The rate that neutrons reach the thermal state is proportional to the HI. Neutron porosity tools detect the hydrogen concentration, gamma ray of capture, scattered thermal neutrons, or high energy epithermal neutrons. The neutron porosity log is sensitive to the quantity of hydrogen atoms in a particular geologic formation. The HI generally corresponds to rock porosity and is converted to neutron porosity (Schlumberger, 2011). The difference between neutron porosity and electrical porosity measurements indicates the presence of hydrocarbons in the formation fluid. An example of a neutron porosity logging profile along a geologic formation of a borehole is shown on the far right in figures A-9 and A-12.

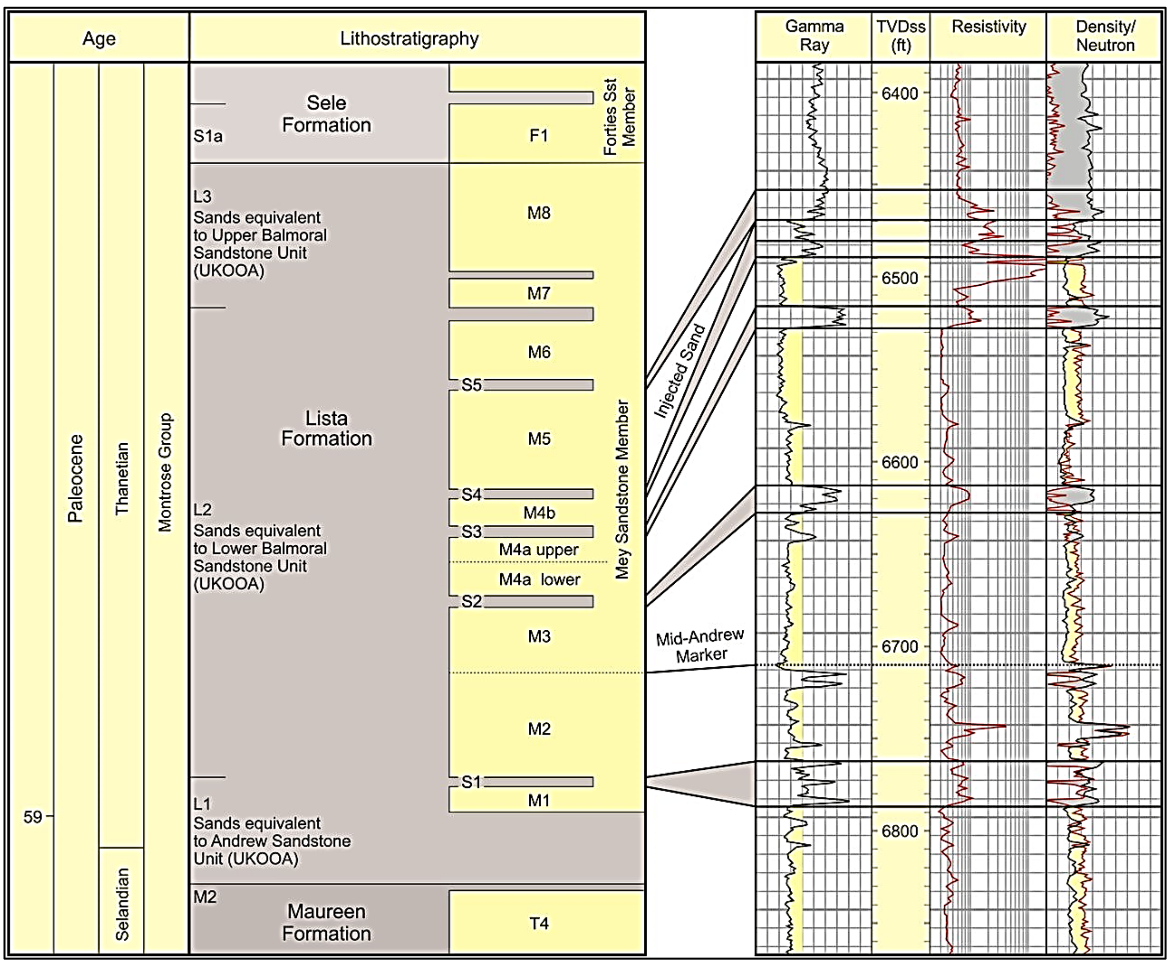


Figure A-12. A basic logging including gamma ray, resistivity, neutron and density profiles.

A.5.5 Sonic (Acoustic) Logs

Sonic or acoustic logs can be used to determine porosity of geologic formations by measuring acoustic velocity. The sonic log provides a formation interval transit time, which is typically a function of lithology and rock texture, but particularly, porosity. The sonic logging tool consists of a piezoelectric transmitter and receiver. The formation interval transit time, which is a measure of a formation's capacity to transmit seismic waves, is recorded for the compressional sound wave to travel the fixed distance between the transmitter and receiver.

Sound waves generally travel faster through the formation than through the borehole mud. Lithology, rock textures, and porosity affect the formation interval transit time. Dense and consolidated formations at depth generally result in a faster (shorter) transit time, while fluid-filled porosity results in a slow (longer) transit time (Schlumberger, 2011).

The sonic log can be used only in open and uncased holes. The formation interval transit time will be decreased with an increasing effective porosity. This indicates that a sonic log can be used to calculate the porosity of a formation if the acoustic velocity of the rock matrix and pore fluid are known. Figure A-13 shows an example of the sonic logging profile along a borehole.

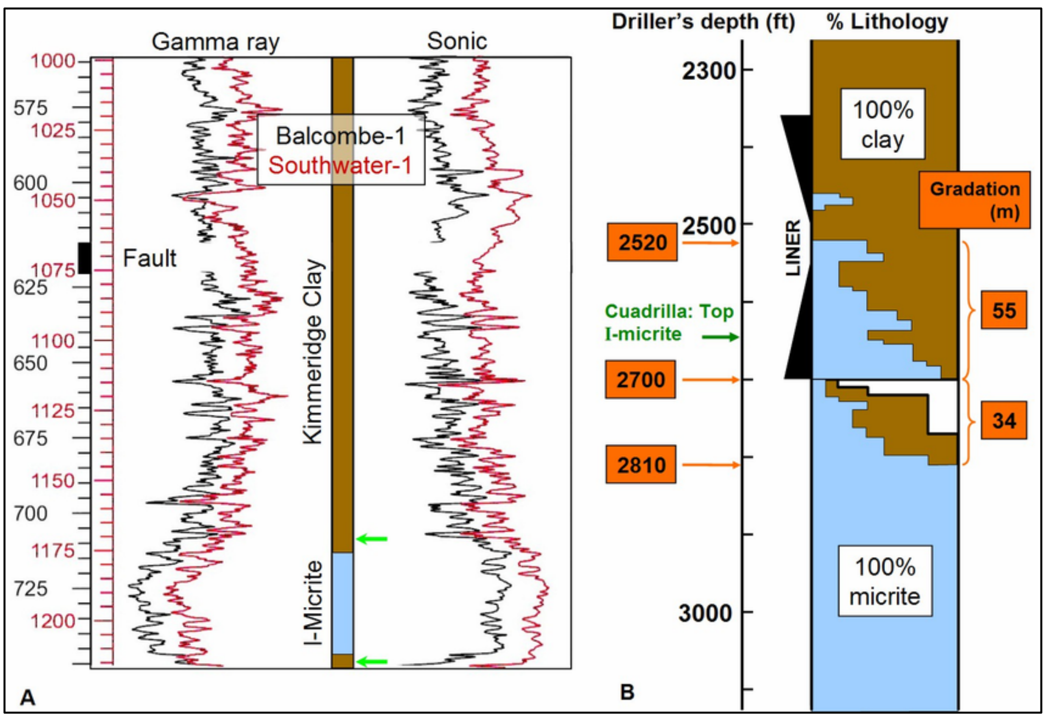


Figure A-13. Sonic and gamma ray logs through Kimmeridge Clay.

A.5.6 Gamma Ray Logs

Gamma ray logs (also commonly referred to as "natural gamma logs") measure naturally occurring gamma radiation to characterize the rock or sediment composition in a borehole and are used primarily for identification of lithology and stratigraphic correlation. Natural gamma logging measures gamma radiation emitted from rock formations. Gamma ray logging tools can be used in either open or cased holes to identify lithology. As with any petrophysical or chemical property of naturally occurring materials and mixtures of materials, spatial variations and overlaps in these properties for a given set of soil or rock types can create issues when attempts are made to quantitatively separate volumetric percentages of constituent materials. The same can be said for the use of gamma ray logging for the direct quantitative assessment of volumetric clay content versus depth within a formation. Most project sites, however, are localized enough that their site-specific gamma ray signatures of sand versus clay can be easily defined in gamma ray logs, and very detailed sedimentary stratigraphy logs can be produced. These detailed logs can help to identify aquifer material unit thicknesses and lateral extents very precisely.

The gamma ray, neutron, and density logs measure radioactivity from the formation. The radioactivity of rocks has been used to evaluate the lithology of the formation. Naturally occurring radioactive materials include uranium, thorium, potassium, radium, and radon. The primary radioactive component in rocks is potassium, which is commonly found in clays. As there is a general correlation between the radioactive isotope content and mineralogy, logging tools have been developed to read the gamma rays emitted by these elements and interpret lithology from the collected data. Typically, the greater the ionic strength (i.e., salinity), the higher the radium content.

Different types of rock emit different amounts of natural gamma radiation. Radioactive potassium is a common component in clay content, and the cation exchange capacity of clay causes the clay to absorb uranium and thorium. As a result, shales and clays typically contain naturally occurring radioactive elements and emit more gamma rays than other sedimentary rocks of sandstone, gypsum, salt, coal dolomite, or limestone. Shales and clays are more radioactive than clean sandstones and carbonates, whereas quartz and calcium carbonate produce almost no radiation. This difference in radioactivity between shales and sandstones and carbonate rocks allows the gamma tool to distinguish between shales and nonshales.

An advantage of the gamma log, relative to other types of well logs, is that it works through the steel and cement walls of cased boreholes. Although concrete and steel absorb some of the gamma radiation, enough radiation travels through the steel and cement to allow qualitative determinations. Figures A-9 (Schlumberger, 2011), A-13 (Andrews, 2013), and A-14 (Takahashi et al., 2009) show an example of the gamma ray logging profile along a borehole.

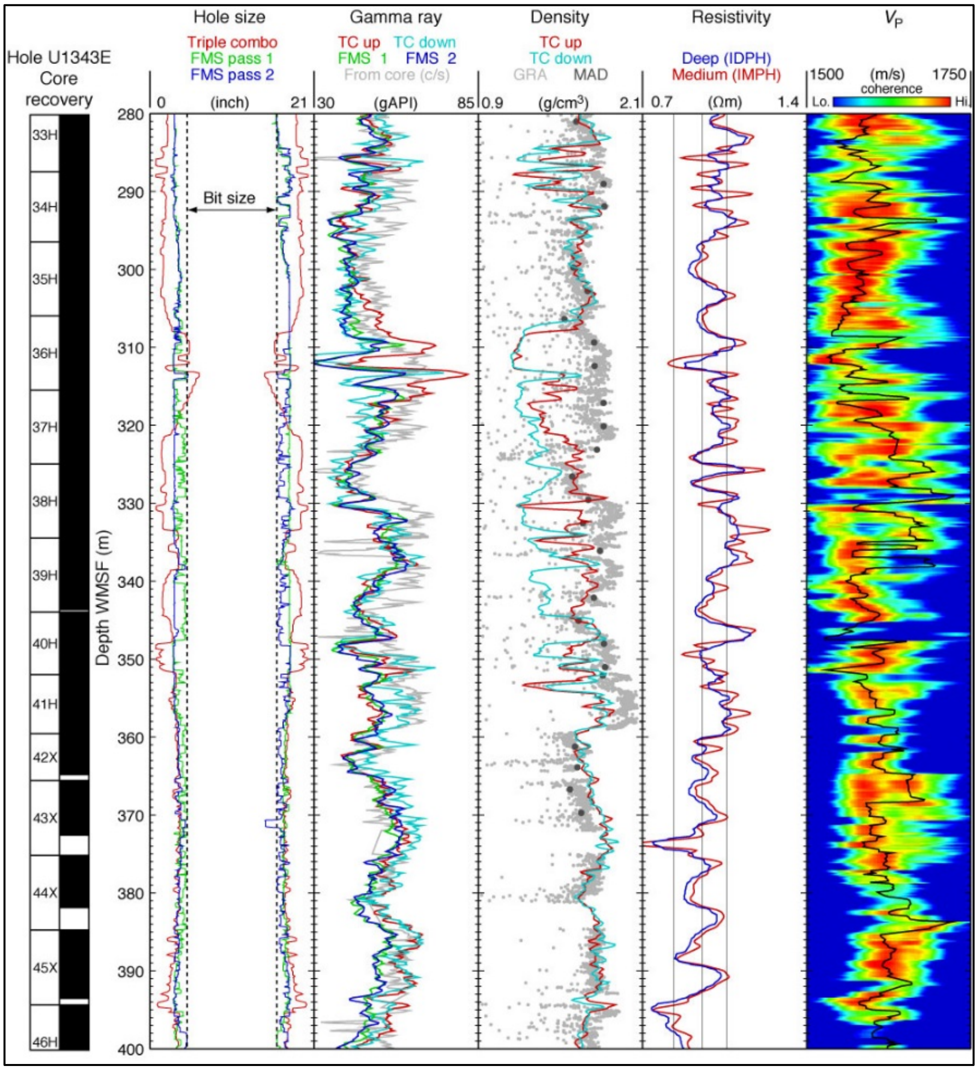


Figure A-14. Gamma ray, density, and resistivity logs.

A.5.7 Spontaneous Potential Logs

The SP log records the potential or voltage difference between the borehole fluid and the surrounding rock formation without any applied current. It was one of the first wireline logs to be developed and can be used to determine lithology and water quality. SP logs are limited to water- or mud-filled open holes. SP logs cannot be used in nonconductive drilling muds, with oil-based mud, or in air-filled holes. The most useful component of this potential difference is the electrochemical potential because it can cause a significant deflection in the SP response opposite permeable beds.

The magnitude of this deflection depends mainly on the salinity contrast between the drilling mud and the formation water and the clay content of the permeable bed; therefore, the SP log is commonly used to detect permeable beds and to estimate clay content and formation water salinity. The SP log can be used to distinguish between impermeable shale and permeable porous sands.

The SP logging technique was developed congruently with resistivity logging and is typically presented with resistivity logs. The SP is a continuous recording of the voltage difference between a movable electrode in the borehole and the surface. This electrical potential is primarily generated as a result of exchanges of fluids of different salinities at the mud and formation. The magnitude of the SP deflection is influenced by a number of factors, including permeability, porosity, formation water salinity, and mud filtrate properties. As shown in figure A-15, the SP deflection curve can indicate which formations are permeable zones. A permeable formation with a high resistivity tends to contain hydrocarbon (Schlumberger, 2011).

The SP curve is usually flat opposite shale formations because there is no ion exchange due to the low permeability and low porosity properties. Tight sandstone and carbonates other than shale will also result in poor or no response on the SP curve because of no ion exchange. The SP data can be used to find depths of permeable formations, the boundaries of these formations, correlation of formations when compared with data from other analogue wells, and values for the formation-water resistivity. Figures A-9 and A-15 show an example of the SP logging profile along a geologic formation of a borehole.

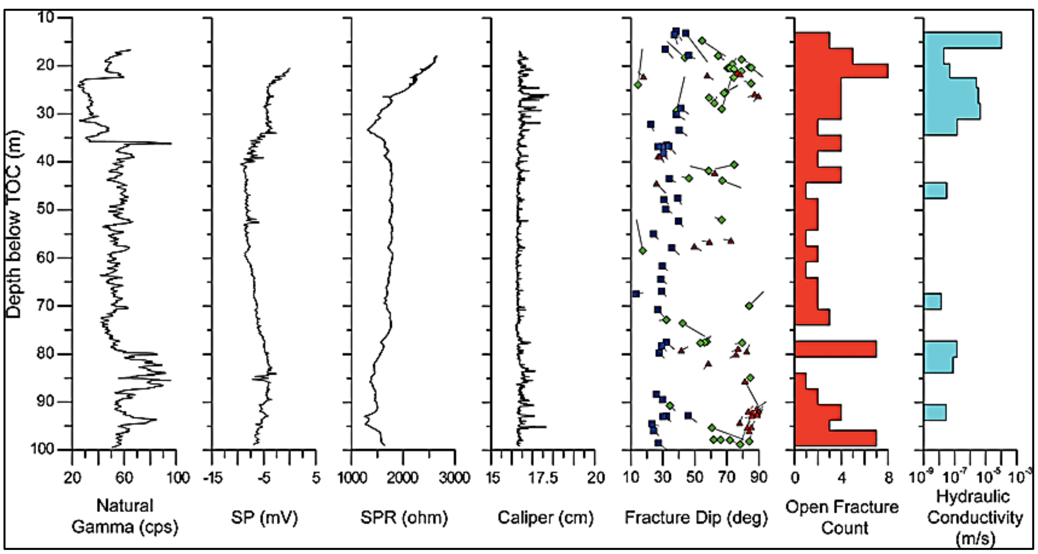


Figure A-15. Composite image of geophysical logs.

A.5.8 Caliper Logs

A caliper logging measures borehole or well diameter and shape at depths and is commonly used in hydrocarbon exploration when wells are drilled. The caliper logging measurements can be an important indicator of shale swelling in the borehole. The changes in borehole diameter are related to well construction such as casing, drilling, fracturing, or caving along the borehole formation. The caliper log provides a useful context for analyzing other geophysical logs because the borehole diameter affects log response (Keys, 1990). Figure A-16 shows a SP potential logging profile along a geologic formation of a borehole.

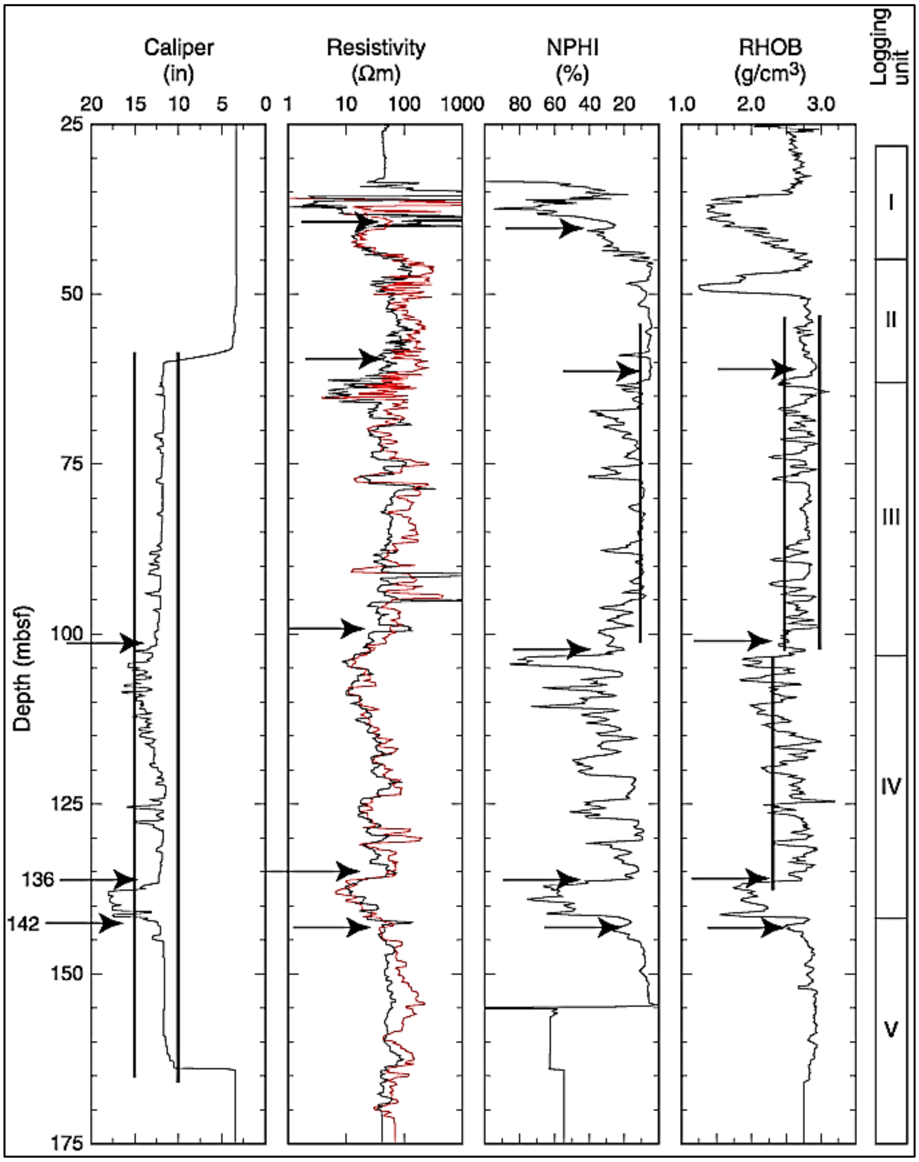


Figure A-16. Caliper geophysical logging data (NPHI = neutron porosity, and RHOB = gamma ray bulk density).

A.5.9 Nuclear Magnetic Resonance Logs

Nuclear magnetic resonance (NMR) logging uses the NMR response of a formation to directly determine its porosity and permeability along the length of the borehole. The main application of the NMR tool is to determine moveable fluid volumes of a rock.

Borehole NMR measurements can help determine information about different types of geologic formations and be used to determine the type of fluids within the formation, such as water, gas, or oil. Important advances have been made in applying NMR measurements to detect and differentiate all formation fluids, such as free water, bound water, and differentiating gas from oil in hydrocarbon bearing reservoirs (Schlumberger, 2011). Figure A-17 shows a NMR log along a borehole.

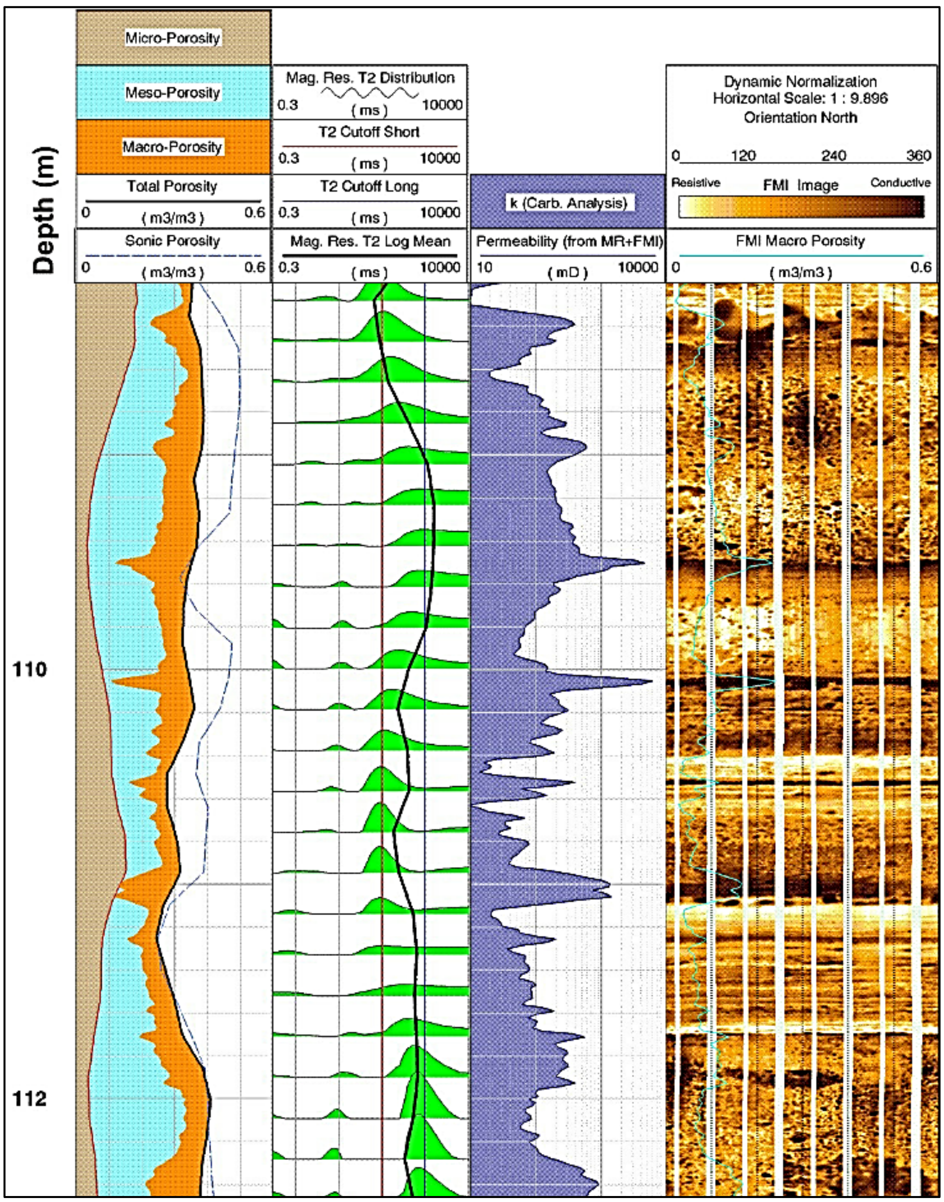


Figure A-17. NMR logging profile.

A.5.10 Spectral Noise Logging

Spectral noise logging (SNL) is a powerful tool designed to record sound within a frequency range of 8 hertz to 60 kilohertz and to detect any small fluid noise—even behind multiple barriers of pipes and cement in the wellbore. SNL enables analysts to locate the source of small leaks by identifying the cross-flows, lateral flows, and cement channels behind multiple casing barriers.

An acoustic noise measuring technique is used for well integrity analysis, identification of production and injection intervals, and hydrodynamic characterization of the reservoir. SNL records acoustic noise generated by fluid or gas flow through the reservoir or leaks in downhole well components. Noise logging tools have been used in the petroleum industry for several decades. Downhole noise logging tools proved effective in inflow and injective profiling of operating wells, leak detection, location of crossflows behind casing, and even in determining reservoir fluid compositions. Figure A-18 shows a spectral noise log along a geologic formation of a borehole.

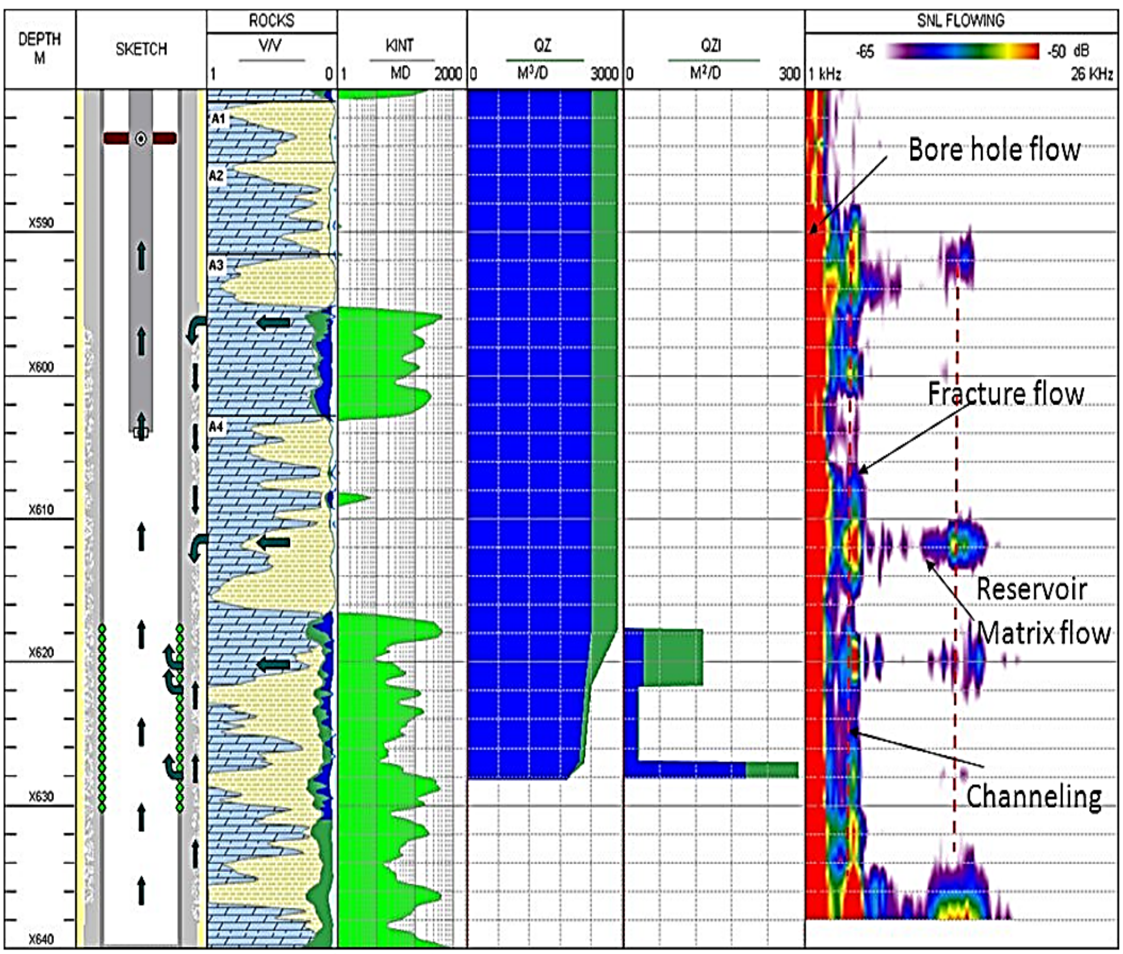


Figure A-18. SNL profile.

A.5.11 Logging While Drilling and Measurement While Drilling

Logging while drilling (LWD) conveys well logging tools into the well borehole to work with a measure while drilling (MWD) system to transmit partial or complete measurement results to the surface, while the LWD tools are still in the borehole to obtain the real-time data. Complete measurement results (i.e., the record of the real-time activity as memory data) can be downloaded from LWD tools after they are pulled out of the hole.

Conventional logs were obtained from logging tools lowered into the wellbore using a logging cable. Now, however, sensors embedded in the wellbore drill collars of MWD systems and LWD tool strings provide alternatives to wireline tools. LWD allows drillers and engineers to obtain well information, such as porosity, resistivity, acoustic waveform, and borehole direction, so they can use this information to make immediate decisions about the future of the well and the direction of drilling. This well information is similar to that obtained through conventional wireline logging, but it is achieved by lowering sensors into the well at the end of wireline cable. The sensors are integrated into the drill string, and the measurements are made and transmitted to the surface in real time. LWD has the advantage of measuring properties of a formation before drilling fluids invade deeply. LWD is now widely used for drilling and formation evaluation.

Even though manual interpretation of log data is common, modern log analysis and evaluation using computer processing have evolved beyond calculations using Archie's water saturation equation (Schlumberger, 2011). Figures A-19 and A-20 show configurations of LWD and log profiles along a geologic formation.

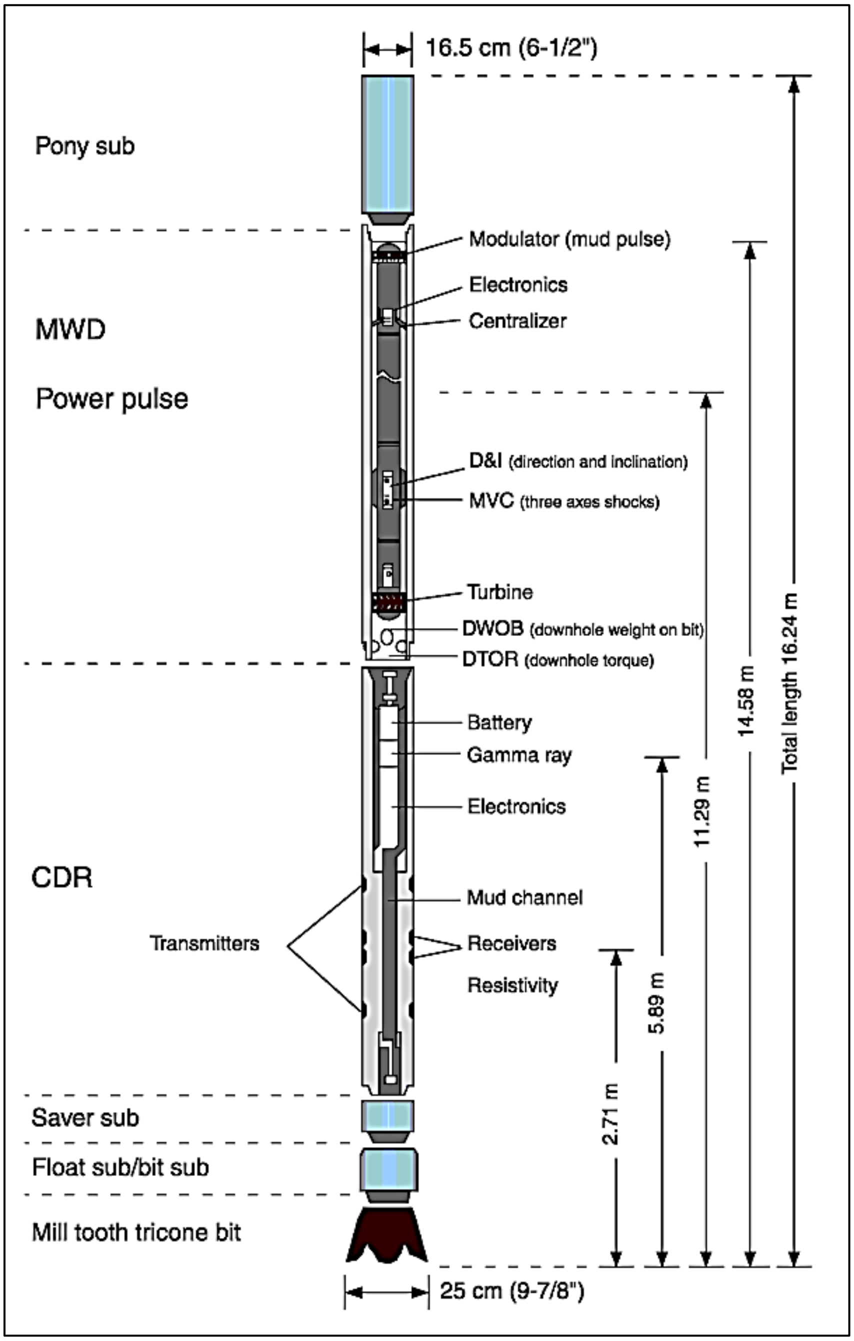


Figure A-19. Configuration of the drill string used for LWD operations.

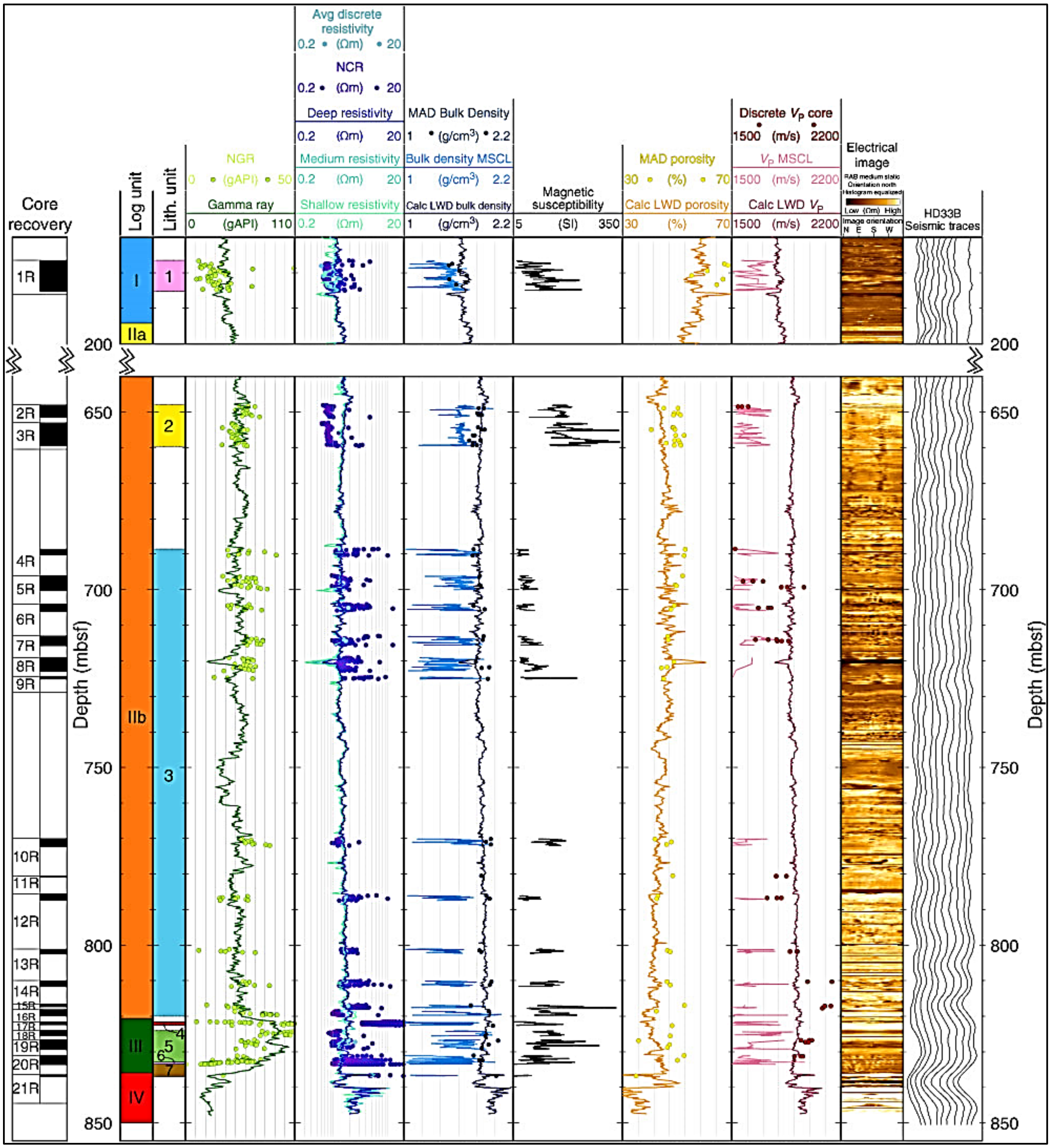


Figure A-20. Overview of core-log-seismic integration (NGR = natural gamma radiation, NCR = noncontact resistivity, MAD = moisture and density, and RAB = resistivity-at-the-bit).

Appendix B

Summary of Bibliography Entries and Key Inferred Parameters

Acronyms and Abbreviations

AEM	airborne electromagnetic
BHT	borehole temperature
CPT	cone penetrometer testing
CVES	continuous vertical electrical sounding
DP	direct push
DPIJ	direct push injection logger
EC	electroconductivity
EM	electromagnetic
ERT	electrical resistivity tomography
FDEM	frequency domain electromagnetic
GE	geoelectric
GEM	geoelectromagnetic
GIS	geographic information system
GPR	ground penetrating radar
GPS	global positioning system
HEM	helicopter electromagnetics
HPT	hydraulic profiling tool
IR	infrared
LiDAR	light detection and ranging
MRS	magnetic resonance soundings
SP	spontaneous-potential
TDEM	time domain electromagnetic
TDS	total dissolved solids

Table B-1. Bibliography Entries with Key Inferred Parameters for Well Log Analysis of Groundwater Total Dissolved Solids

Reference	Year	Parameter(s) Inferred	Method(s) Used
Abdalsamad Abdalsatar et al., 2014	2014	Soil salinity	Visible near IR, portable X-ray fluorescence, remote sensing
Abraham et al., 2012	2012	Lithology	Airborne FDEM
Adeoti et al., 2012	2012	Layering, water table	Seismic refraction
Alger, R.P., 1966	1966	R_w, NaCl parts per million, grain size, permeability, porosity	Resistivity and SP
Alger, R.P., and Harrison, C.W., 1989	1989	Porosity, water resistivity, effective grain size, hydrogeological parameters	Resistivity, SP
Al-Senafy et al., 2015	2015	Groundwater discharge	Tracer
Archuleta, E.G., 2015	2015	Desalination	Desalination concentrate management
Ayers, J.F., and Clayshulte, R.N., 1985	1985	Water quality	Seismic-refraction profiling, earth-resistivity sounding
Ball et al., 2015	2015	Water quality, lithology	FDEM
Bang, N.H., 2004	2004	Water quality, lithology, water layering, hydrologic characterization	Normal resistivity, single point resistivity, SP, natural gamma, temperature, hydrogeological logging probe
Bedrosian et al., 2014	2014	Lithology, flow features	Airborne FDEM, surface TDEM
Bellona, C., 2015	2015	Desalination	Membrane process, evaporation, sorption, flotation, electrowinning
Bergstrom, E.J., and McKinley, K., 2004	2004	Porosity, void spaces, fracture zones	Borehole GPR
Broska, J.C., and Barnette, H.L., 1999	1999	Lithology, water quality, production zones	Aquifer testing, natural gamma, flow logs, resistivity, temperature
Burgess, K., and Bedrosian, P.A, 2014	2014	Lithology	Transient TDEM, gravity
Cather M., and Gallegos, C., 2014	2014	Water database	Data processing
Chen, J., 2001	2001	Hydraulic conductivity, correlation between hydrologic and geophysical logs	GPR tomography, seismic tomography, small-scale resistivity logs, large-scale EM surveys
Chongo et al., 2011	2011	Groundwater salinity, water quality, flow features, lithology	TDEM, CVES, modeling

Table B-1. Bibliography Entries with Key Inferred Parameters for Well Log Analysis of Groundwater Total Dissolved Solids

Reference	Year	Parameter(s) Inferred	Method(s) Used
Chua et al., 2007	2007	EC, pH	Tracers
Church, P.E., and Brandon, W.C., 1999	1999	Flow features, water quality	TDEM, water sampling, resistivity, natural gamma
Clinton, T., 2007	2007	Water quality	Water sampling
Collier, H.A., 1993	1993	Water quality, groundwater reservoir parameters	Standard suites of borehole geophysical and hydrologic logs
Collin et al., 2010	2010	Water quality	LiDAR
Cunningham et al., 2004	2004	Lithology, porosity, permeability, water quality	GPR, geophysical logs, lithologic logs and samples, aquifer testing
Daniels, D.J., ed., 2004	2004	Lithology, flow features	GPR
Dannowski, G., and Yaramanci, U., 1999	1999	Water content, porosity	GPR, radar, geoelectrics
Darnet et al., 2003	2003	Lithology, aquifer hydraulic properties	SP, aquifer tests, streaming potential anomalies
Estepp, J., 2010	2010	Groundwater quality, permeability, porosity, log corrections, lithology identification, salinity (total dissolved solids [TDS])	SP, resistivity, Alger-Harrison method, mean R_o method, Guyod equation, Estepp method
Ezzedine, S., and Rubin, Y., 2001	2001	Lithology, subsurface characterization	Bayesian approach to melding geophysical and hydrologic data, well logs, geophysical survey
Fitterman, D.V., and Stewart, M.T., 1986	1986	Lithology, fresh/brackish interface	TDEM
Forrest et al., 2005	2005	BHT, geothermal gradients and subsurface temperatures	Temperature
Fraser, D.C., and Fogarsi, S.L., 1992	1992	Hydrologic characterization	TDEM, image processing
French, R.B., 2002	2002	General discussion of process and advantages, EC	TDEM
Glenn et al., 2010	2010	Groundwater discharge and nutrient fluxes	Aerial IR imaging, in-situ sampling
Goes et al., 2009	2009	Water quality	Samples, electric borehole logs, CPT, CVES, TDEM
Goldman, J.E., 2013	2013	Osmosis, inter-stage ion exchange	Salt water recovery
Goldman, M., and Kafri, U., 2004	2004	Hydrogeological parameters	GE, GEM

Table B-1. Bibliography Entries with Key Inferred Parameters for Well Log Analysis of Groundwater Total Dissolved Solids

Reference	Year	Parameter(s) Inferred	Method(s) Used
Groen et al., 2000	2000	Water quality	Geochemical and isotopic tracers
Hamlin, S.H., and de la Rocha, L., 2014, 2015	2014, 2015	R_w, groundwater salinity, lithology	Electric logs, resistivity
Harrington et al., 2014	2014	Groundwater discharge	Tracers, isotopes, AEM
Helgeson, T., and McNeal, M., 2009	2009	Water quality	Water quality sampling
Hem, J.D., 1985	1985	Relating water soluble to lithology	Geochemistry and hydrology
Hendrickx et al., 2002	2002	Field resistivity, mass balance of salts	EM induction, borehole geophysics, water quality
Hubbard et al., 1998	1998	Permeability, pressure, saturation	GPR, seismic refraction, Bayesian technique
Hudson, J.D., 1996	1995	Permeability, water quality, correction to formation factor	Resistivity and neutron logs
Hughes, D., 2002	2002	In-situ borehole database	Caliper, natural gamma, resistivity, induction, shear-wave seismic velocity logs
Jachens and Langenheim, 2014	2014	Lithology, water quality	Gravity, TDEM, borehole geophysics, tracers and geophysics
Johnson et al., 2004	2004	Lithology	GPR tomography, ERT, borehole GPR, time-lapse imaging
Jordahl, J., 2006	2006	Water quality	Water reuse and desalination
Jorgensen, D.G., 1989	1989	Porosity, water resistivity, intrinsic permeability	Dual-porosity log, gamma-ray trace, resistivity, SP, neutron log
Jorgensen, D.G., 1991	1991	Coefficient of diffusion, formation factor, cementation exponent, hydraulic conductivity, water content, specific yield	Resistivity, SP method
Jorgensen, D.G., and Petricola, M., 1995	1995	Specific yield, water quality, lithology, permeability, resistivity	Seismic refraction, transient EM (ongoing research project)
Kent, D.C., and Hall, R.V., 1993	1993	Well construction, well efficiency	Neutron, gamma-gamma, natural gamma, density logs
Keys, W.S., 1990	1990	Holistic overview of most parameters inferred from geophysical well logs	All fundamental geophysics well logs and interpretation
Klein, J., and Lajoie, J., 1992	1992	Hydrologic characterization	AEM, TDEM
Kwader, T., 1985	1985	Permeability, porosity, cementation factor	Resistivity

Table B-1. Bibliography Entries with Key Inferred Parameters for Well Log Analysis of Groundwater Total Dissolved Solids

Reference	Year	Parameter(s) Inferred	Method(s) Used
Kwader, T., 1986	1986	Water quality	Resistivity
Langenheim and Jachens, 2014	2014	Hydrologic characterization	Gravity
Langenheim et al., 2016	2016	Lithology, flow features	Gravity, seismic refraction
Leake, S.A., 2010	2010	Groundwater availability	Methods for regional groundwater assessments using existing data
Lepley, L.K., and Adams, W.M., 1971	1971	Electromagnetic reflection properties	Temperature
Levi et al., 2008	2008	Water quality	TDEM
MacCary, L.M., 1978	1978	Porosity, nonconnected porosity, rock composition, bulk density, R_w, cementation exponent	Resistivity and porosity logs (sidewall neutron and sonic)
MacCary, L.M., 1980	1980	Cementation exponent, water quality, porosity, hydrology parameters	Resistivity and porosity logs (neutron and sonic)
Mackey, E.D., and Seacord, T., 2008	2008	Water quality	Concentrate disposal and management
Maliva et al., 2009	2009	Porosity, hydraulic conductivity, salinity, mineralogical composition	Neutron-gamma ray spectroscopy, Microresistivity imaging, nuclear magnetic resonance
Mariita, N.O., 2007	2007	Lithology, void space, bulk density	Magnetic, gravity
McMahon et al., 2007	2007	Regional water quality assessment	Well records
Meyer et al., 2012	2012	Water quality, porosity, permeability, hydrology parameters	Hydrology, SP, gamma ray, neutron, resistivity
Meyer et al., 2014	2014	Water quality, porosity, permeability, hydrology parameters (specific yield, net sand volume)	Hydrology, AEM, well log database
Mickley, M., 2013	2013	Desalination	Desalination concentrate and salt management
Morin et al., 1988	1988	Fluid velocity, hydraulic head, hydraulic conductivity	Concurrent injection with caliper, acoustic televiewer log, heat-pulse flowmeter, spinner flowmeter

Table B-1. Bibliography Entries with Key Inferred Parameters for Well Log Analysis of Groundwater Total Dissolved Solids

Reference	Year	Parameter(s) Inferred	Method(s) Used
National Groundwater Association, 2010	2010	Water quality, desalination	Distillation and reverse osmosis
Nyako et al., 2016	2016	Lithology, porosity	Long-short normal resistivity, SP, natural gamma logs
Paillet, F.L., and Reese, R.S., 2000	2000	Hydraulic properties	Lithologic logs, geophysical logs, hydraulic tests
Paine et al., 2004	2004	Apparent conductivity	TDEM induction
Paprocki, L., and Alumbaugh D., 1999	1999	In-situ soil moisture	Cross-borehole GPR
Patten, E.P., 1963	1963	Lithology and water quality	Resistivity, SP, natural gamma, fluid-conductivity
Peterson, R.N., Burnett, W.C., and Glenn, C.R., 2009	2009	Groundwater discharge and flux	Natural geochemical tracers
Powars, D.S., and Bruce, T.S., 1999	1999	Lithology	Lithology cores, seismic refraction, single-point resistance, natural gamma, multiple-point resistivity, 6-foot lateral resistivity, SP
Reese, R.S., 2004	2004	Water quality, flow features, lithology	Well logs, water level records, pumping records, water quality samples, formation resistivity
Risch, M.R., and Robinson, B.A., 2000	2000	Water quality, lithology	Monitoring well records, water quality sampling, natural gamma, EM-induction logs, EM surveys
Saad et al., 2013	2013	Lithology, water table	Induction, seismic refraction, electrical resistivity
Schlumberger, 2009	2009	Charts to correct parameters for almost all tools	All fundamental geophysics well logs and interpretation
Schmelzbach et al., 2011	2011	Lithology, hydraulic conductivity, porosity	GPR, DP data, CPT, HPT, DPIJ
Senior et al., 2005	2005	Geophysical log database, water quality	Geophysical logging, aquifer testing, water-level monitoring, streamflow measurements
Shahid et al., 2010	2010	Soil salinity	Soil salinization remote sensing, GIS, modeling, EC

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Reference	Year	Parameter(s) Inferred	Method(s) Used
Sloto et al., 2002	2002	Geophysical and hydrologic properties, water quality, water level data	Caliper, natural gamma, single-point resistivity, fluid resistivity, fluid temperature, heat-pulse flowmeter, borehole television survey, aquifer-isolation tests, water quality sampling
Smith et al., 2007	2007	Lithology, flow features, water quality	Aerial HEM, aerial magnetic, GPS
Smith, D.G., and Jol, H.M., 1995	1995	Penetration depths, controlling parameters	GPR
Spechler, R.M., 1996	1996	Spring discharge, lithology	Aerial IR imaging, in-situ sampling, marine seismic reflection
Staub, W.P., 1969	1969	Lithology	Seismic refraction
Stufyzand, P.J., and Stuurman, R.J., 1994	1994	Water quality, salinity	Semi-natural tracer
Thomas et al., 2013	2013	Water quality	Resistivity
Tillman et al., 2008	2008	Groundwater level trends	Historic water level data
Tillman et al., 2011	2011	Indicators for groundwater level trends and availability	Historic water level data
USDA, 2016	2016	Soil suitability maps	GPR
Van Blaricom, R., ed., 1992	1992	Geophysical log database	Geophysical logs
Vouillamoz et al., 2012	2012	Specific yield, hydraulic conductivity, water quality	MRS, electrical resistivity, transient EM and MRS
William et al., 2014	2014	Water availability, aquifer and water quality characterization	Lithologic logs, borehole geophysical log, TDEM, seismic reflection, gravity, magnetotellurics
Williams et al., 2013	2013	Geophysical log database	Well logs, geophysical logs

Data Sets Supporting the Final Report

Electronic deliverables and data sets associated with this research are available:

- Share Drive folder name and path where report is stored: https://drive.google.com/open?id=1N7oDJps4l-zwaIUuXjAWxgSQXj-HMibI
- Point of contact name, email, and phone: Justin B. Rittgers, 303-445-3010, jrittgers@usbr.gov
- Keywords: brackish groundwater, geophysical well log interpretation
- Approximate total size of all files: 1 File, 10Mb