Aquifer Performance Test Procedures for Hazardous Waste Facilities in New Mexico

New Mexico Environment Department

Revision History Table

Revision #	Revision Date	Revised By	Reason for Revision

Table of Contents

1 INTRODUCTION

An aquifer test is a controlled field experiment that determines the hydraulic properties (parameters) of water-bearing geologic formations (aquifers) by measuring water level or pressure responses that result from stressing a well in a controlled manner. The preferred aquifer test is one in which one well is pumped (the control or test well) and another well (or wells) is used to measure water level or pressure responses (observation well(s)) to obtain accurate estimates of aquifer parameters (Osborne, 1993). This is known as a multi-well pumping test and is referred to in this document as an Aquifer Performance Test (APT). Single-well pumping tests and slug tests may also serve as aquifer tests when obtaining aquifer parameters is required but conducting an APT has been determined to be unwarranted or infeasible. Slug tests may also be used to plan an APT (Osborne, 1993).

In conducting an aquifer test, it is imperative to control or correct for variables known to alter aquifer water levels (total heads) so that the measured responses can be attributed to the test only. Analytical and/or numerical solutions can then be confidently applied to the water-level responses to determine the aquifer parameters. While modern software and diagnostics facilitate test analysis, the effort designing and executing an aquifer test that adequately adheres to theory and industry standards remains the main encumbrance to successful testing. Successful testing includes three phases: Test Design, Field Procedures, and Data Analysis (Stallman, 1971; Osborne, 1993).

The New Mexico Environment Department (NMED) Hazardous Waste Bureau (HWB) developed this Aquifer Test Guidance (Guidance) to instruct the regulated facilities on the appropriate steps required to develop an aquifer test work plan for HWB review. Section 1 of the Guidance provides the background, purpose, uses, and limitations of the Guidance. Section 2 provides the acronyms used in the Guidance. Section 3 provides the main considerations and testing components to design and conduct an aquifer test. Section 4 outlines test requirements and equipment. Section 5 discusses different aquifer test types, methods, and procedures. Section 6 discusses aquifer test theory and analyses. Section 7 provides references and Sections 8 include examples of the recommended field forms. Although the guidance provides examples of commercially available products for various testing types, NMED does not specifically endorse the use of any particular product or brand.

1.1 Background

The NMED HWB currently regulates 19 permitted hazardous waste facilities throughout New Mexico that include 11 federal facilities and eight private commercial facilities. At each of these 19 facilities (and at potential future facilities), the HWB ensures that hazardous waste is managed, and the cleanup of contaminated sites are conducted, in a manner that is protective of human health and the environment. Nine of the 11 federal facilities and five of the eight private facilities have known groundwater contamination, indicating that 14 HWB-regulated facilities may require aquifer testing to characterize the impacted groundwater system for remediation purposes.

Facilities with hazardous waste contamination in groundwater need to conduct rigorous aquifer characterization to understand the site conditions in order to achieve the required nature and extent evaluation upon which remediation goals are based. Each facility must have developed a preliminary conceptual site model (CSM) that is accepted by the HWB before implementing this Guidance. The facility will use the preliminary CSM and this Guidance to design an aquifer test, then prepare and submit an aquifer test work plan for HWB review. The CSM defines the aquifer type (e.g., confined, unconfined, or leaky confined), depth, thickness, areal extent, boundaries, and lithology to provide the basis to determine the most appropriate aquifer test to consider and which mathematical model should be used to estimate the most important aquifer parameters for the site (Osborne, 1993). Other criteria to consider for test selection include the contamination concentration, distribution, and contaminant migration/retention within the hydrogeologic units.

Each facility should coordinate with the HWB in implementing this Guidance to develop meaningful aquifer test work plans that lead to tenable results for their site to facilitate efficient HWB review and approval.

The primary focus of this Guidance involves conducting an APT. The common aquifer parameters obtained from properly conducted APTs typically include aquifer transmissivity (T) and storativity (S). Hydraulic conductivity (K) is calculated from T, derived from the aquifer test, and the aquifer thickness (b), determined using the CSM. Anisotropy may also be determined if a suitable number of observation wells at suitable orientations with respect to the pumping well are available. Guidance is also provided on conducting single-well pumping tests and slug tests.

The numerous options in selecting the most appropriate test and solution methods may overwhelm those without sufficient understanding and experience in implementation of aquifer tests. Conducting aquifer tests and analyzing the acquired data require some preliminary knowledge of the system being studied, specifically, whether the aquifer is confined, unconfined, or leaky confined. Such knowledge is essential to determine how long to run the test to observe the anticipated responses and the best solution to apply to the test data, especially for unconfined aquifers with delayed yield and leaky confined aquifers. Although determination of test duration is best made using real-time analysis, other testing constraints (e.g., water rights or storage capacity) may play a role. Additionally, the adequacy of the proposed test well and observation well network available for inclusion in the test and the test goals will determine what test (e.g., slug test, single-well pumping test, or APT) and solution method are most appropriate for the facility. Each facility shall propose and justify in the work plan the anticipated test method and solution for each test. Because of such considerations, it is imperative that each facility work closely with the HWB to develop the most appropriate work plan to ensure efficient approval.

For further background and consideration in developing aquifer test work plans that involve pumping tests, the HWB suggests the facility consult:

- *Suggested Operating Procedures for Aquifer Pumping Tests* (Osborne, 1993),
- *Standard Guide for Selection of Aquifer Test Method in Determining Hydraulic Properties by Well Techniques* (ASTM D4043),

- *Standard Test Method (Field Procedure) for Withdrawal and Injection Well Tests for Determining Hydraulic Properties of Aquifer Systems* (ASTM D4050)*,*
- *Theory of Aquifer Tests* (Ferris et al., 1962),
- *Aquifer-Test Design, Observation and Data Analysis* (Stallman, 1971),
- *Groundwater and Wells (Driscoll, 1986),*
- *Analysis and Evaluation of Pumping Test Data* (Kruseman and de Ridder, 2000), and
- *The Relation Between the Lowering of The Piezometric Surface and The Rate and Duration of Discharge of a Well Using Ground Water Storage* (Theis, 1935).

In the case of conducting aquifer tests using the slug test method, the HWB refers facilities to the following publications to provide a proper background for developing a slug test work plan:

- *The Design, Performance, and Analysis of Slug Tests, 2nd Ed*. (Butler, 2019),
- *Standard Test Method (Field Procedure) for Instantaneous Change in Head (Slug) Tests for Determining Hydraulic Properties of Aquifers* (ASTM D4044), and
- *Conducting an Instantaneous Change in Head (Slug) Test with a Mechanical Slug and Submersible Pressure Transducer*—GWPD 17 (Cunningham and Schalk, 2011).

1.1.1 Single-Well Aquifer Tests

A single-well aquifer test can be conducted as a slug test, a step-drawdown test, or a constant-rate pumping test. Each of these tests provide limited understanding of large-scale aquifer hydraulics because responses to the applied stress are not recorded at remote observations points in the aquifer that provide more robust aquifer parameter estimations and insights to other aquifer hydraulic properties. Aquifer storativity (S) cannot be reliably estimated from single-well aquifer tests and should not be included in CSM and groundwater model development.

1.1.2 Multi-Well Aquifer Performance Tests

While aquifer characterization involves many exploratory activities, such as drilling, borehole geophysics, lithologic and stratigraphic characterization, and correlation across the site, a well-planned and properly conducted large-scale, multi-observation well APT provides the most substantive method for determining aquifer parameters and large-scale aquifer hydraulics. These are necessary to both understand the system, to develop and refine a CSM, and to perform history matching of groundwater flow models to actual past conditions. Unlike a single-well test, an APT typically consists of pumping a single test well at a constant rate while responses to the pumping (drawdown) and to the cessation of pumping (recovery) are recorded at a distant observation well(s) and/or piezometer(s). Analysis of the distant responses provides information on anisotropy, heterogeneity, and storativity not obtainable from a single-well test. A properly conducted APT also provides a basis for the development and history matching of analytical and numerical computer-generated groundwater flow models. While the benefits of an APT over a single-well test are significant, conducting an APT is a significantly more complex endeavor that involves much greater cost and more considerations in test design and preparing the work plan.

The HWB notes that while it is possible to perform slug tests and step-drawdown tests while measuring responses in observation wells, such tests are not common and are not included in this Guidance. The HWB may consider the use of one or more observation wells with an approved step-drawdown test to also constitute a variable-rate multi-well aquifer performance test if the proposed step rates and durations are well-documented and will be sufficient to produce measurable and analyzable responses at the observation well(s).

1.2 Purpose

The purpose of this Guidance is to provide each facility with information to develop a viable aquifer testing work plan for HWB consideration and to assist a facility in preparation of a facility-specific Standard Operating Procedure (SOP). This Guidance outlines the methods that will be used to obtain the necessary data for understanding the hydrogeologic system for development of CSMs, deriving aquifer parameters, defining preferential pathways, groundwater model development and history matching, and other aquifer hydraulic characteristics. This Guidance conveys appropriate industry standard testing methodologies regardless of the differing hydrologic conditions that may be present among the different facilities, except for aquifers where non-Darcian groundwater flow conditions predominate.

Each permitted facility must use this Guidance when developing specific work plans to conduct hydraulic testing for site characterization. Development of each proposed work plan will be subject to input and approval by the HWB before any work is to be conducted. Each proposed aquifer test work plan submitted by a facility to the HWB must be generated using this Guidance and, at a minimum, include the following components:

- *Summary*……
- *1.0 Introduction*……
    - *1.1 Hydrogeologic Setting/Conceptual Site Model* ……
    - *1.2 Study Objectives* ……
    - *1.3 Scope of Activities* ……
    - *1.4 Test and Observation Well Construction and Selection Rationale*……
- *2.0 Aquifer Tests-Field Activities* ……
    - *2.1 Establish Background Conditions* ……
    - *2.2 Slug Test* (if proposed) ……
    - *2.2 Step-Drawdown Test* (if proposed) ……
    - *2.3 Single-well Constant Rate Pumping Test* (if proposed) ……
    - *2.4 Multi-well Constant Rate Aquifer Performance Test* (if proposed) ……
    - *2.5 Interval Sampling* ……
    - *2.6 Management of Discharge Water* ……
- *3.0 Data Quality Evaluation* ……
    - *3.1 Barometric Compensation* ……

Each facility must work with the HWB to evaluate whether conducting slug tests, single-well pumping tests, and/or an APT is most appropriate for their site based on the CSM and objectives. While an APT provides the best information, it often involves engaging in an expensive, time consuming, and complex undertaking that may not be appropriate for every facility or study objective. In contrast, slug tests and single-well pumping tests may offer a more cost-effective alternative to an APT, but only provide small-scale results that are of limited use compared to an APT. Additionally, single-well slug tests produce virtually no investigative-derived wastes (IDW) that may require proper disposal under the Resource Conservation and Recovery Act (RCRA). The HWB refers each facility to the *Standard Guide for Selection of Aquifer Test Method in Determining Hydraulic Properties by Well Techniques* (ASTM D4043) when formulating their decision regarding the appropriate aquifer test type to run for their site hydrogeologic conditions and before preparing and submitting the work plan to the HWB.

1.3 Potential Uses

An APT can be used to evaluate aquifer anisotropy, aquifer boundary conditions, preferential pathways, radius of influence, leakance, and delayed yield as well as many other useful aquifer conditions to consider when characterizing an aquifer and/or designing a remediation system. An APT can also be set up to perform distance-drawdown analyses if multiple observation wells are linearly arranged with increasing distance from the test well. The responses and mathematical analyses applied to the data from an APT are invaluable to refine a CSM by using the multiple aquifer parameters and conditions that are obtained from such a complex test. In contrast, a single-well test is not appropriate to estimate aquifer storativity, boundary conditions, or preferential pathways.

The HWB does not rely on the use of groundwater models as part of the decision-making process because of the numerous uncertainties but does acknowledge the benefit of a properly calibrated model. Consequently, the HWB does not make decisions based on, nor advocate for, the development of groundwater models. However, the cleanup of groundwater at hazardous waste sites may benefit from the careful development of well-calibrated groundwater models that have demonstrated successful history matching to known stresses like APTs to:

- demonstrate an understanding of the hydrologic systems and CSMs,
- identify preferential pathways and groundwater flow paths that contaminants released from the facility would likely migrate within and along,
- identify the direction and rate of the flow paths, and

- simulate groundwater flow and contaminant transport along the flow paths.

Aquifer testing and other data from wells completed within all hydrostratigraphic units of the affected hydrologic system provide hydrogeologic information that can be used for groundwater model development, calibration, and history matching. The data that may be acquired include, but are not limited to:

- hydraulic parameters, e.g., hydraulic conductivity (K) and transmissivity (T), storativity (S), flow dimension (n), inferred from well tests used to define parameter distributions within groundwater models,
- transient head responses from observation wells during long-term pumping tests that can be used during groundwater model calibration to infer hydraulic properties in areas where no wells may exist,
- hydraulic boundary conditions,
- aquifer anisotropy and directional changes in T,
- fluid specific gravities (or densities) used in calculation of hydraulic head gradients, and
- water-quality analyses that may be useful in inferring flow directions and fluid sources.

1.4 Limitations

This Guidance is intended to steer the experienced licensed professional (e.g., Professional Geologist or Engineer) in formulating a tenable work plan suitable for submittal to the HWB for review and approval to conduct hydraulic testing at HWB-regulated facilities. The HWB may revise this Guidance if warranted at any time.

This Guidance is not an SOP nor is it a tutorial on how to conduct an aquifer test and does not address every situation where an aquifer test is required. This Guidance is to be applied on a case-by-case basis. This Guidance does not replace existing SOPs established by facilities to conduct aquifer tests, nor does it replace specific aquifer testing procedures and/or SOPs provided in a consent order between the HWB and the facility. In those cases where SOPs are established, the facility should use this Guidance to enhance their aquifer test SOP when preparing aquifer testing work plans for HWB approval.

This Guidance is inclusive of only constant-rate pumping tests and slug tests conducted in vertical wells screened in saturated porous and/or highly fractured media within which movement of groundwater exhibits Darcian flow.

The HWB regulates facilities where groundwater is subject to Title 20, Chapter 6, Part 2 of the New Mexico Administrative Code (NMAC) Sections 20.6.2.3000 through 20.6.2.3114, which protects waters with a quality of 10,000 milligrams per liter (mg/L) or less of total dissolved solids (TDS). The quality of the protected groundwater is thus inclusive of both fresh and brackish water. However, the Guidance explicitly considers groundwater at the reference density normally used in hydrologic investigations, which is groundwater at standard temperature and pressure conditions with a density equal to 1 gram per cubic centimeter (g/cc) (Spane and Mercer, 1985) and temperature of 15.6° Celsius (Fetter, 1989). Facilities with groundwater where the reference density cannot be assumed must address how it will correct the measured water levels or observed hydraulic head values to this reference density fluid referred to as a freshwater head (Spane, 1999).

This Guidance does not cover less common test methods such as constant-head tests, pumping tests that involve multiple pumping wells, pumping tests conducted using angled and horizontal wells, and conducting tests in non-Darcian flow regimes (e.g., karst and cavernous formations). If a facility prefers to employ these less-common test methods, the facility must notify the HWB of the constraints preventing the use of more common methods or advantage of the desired test over the more widely used constant-rate pumping test or slug test described herein. While the Guidance defines some common hydrogeologic terms and details some basic concepts in slug and aquifer testing, it is not intended to educate an end user who is unacquainted with standard methods and theory in aquifer testing.

2 ACRONYMS AND DEFINITIONS

APT	aquifer performance test (long-term, multi-well, constant-rate pumping test)
APV	access port valve
BE	barometric efficiency
CSM	conceptual site model
DAS	data-acquisition system
DHSIV	downhole shut-in valve
DOE	(U.S.) Department of Energy
DOD	(U.S.) Department of Defense
DST	drillstem test
EPA	(U.S.) Environmental Protection Agency
ft/d	feet per day
gal	gallons
g/cc	gram per cubic centimeter
gpm	gallons per minute
GWPD	U.S. Geological Survey groundwater technical procedures document
HA	hazard analysis
HWB	Hazardous Waste Bureau
IARF	Infinite-acting radial flow
ID	inside diameter
IDW	investigative derived wastes
I/O	input/output
K	hydraulic conductivity
mg/L	milligram per liter
NMAC	New Mexico Administrative Code
NMED	New Mexico Environment Department
NMOSE	New Mexico Office of the State Engineer
n	flow dimension
psi	pounds per square inch
psia	pounds per square inch absolute
psig	pounds per square inch gauge
QA	quality assurance
RCRA	Resource Conservation and Recovery Act
RTU	remote terminal unit
S	storativity
SIT	shut-in tool
SOP	Standard Operating Procedures
SSST	sliding-sleeve shut-in tool (e.g., Baski's Access Port Valve)
T	transmissivity
TDS	total dissolved solids
UPS	Uninterruptible Power Supply
VFD	variable frequency drive

3 AQUIFER TEST DESIGN AND CONSIDERATIONS

This Guidance includes different aquifer test types that range from small-scale slug tests to large-scale APTs. Each test has specific requirements that must be met for results to be approved by the HWB. This section provides the considerations the regulated facility must address to design an aquifer test and prepare the work plan for submittal to the HWB for review.

The regulated facility must coordinate with the HWB during the design of the aquifer test and during preparation of an appropriate aquifer test work plan. To facilitate HWB approval of an aquifer test work plan, it is of utmost importance that the facility collaborates with the HWB in the development of the testing work plan. The main components to consider in the test design include development of the aquifer CSM, available and planned wells, test type, methods, procedures, pumping test discharge rate, containment of discharge, test data acquisition, assessment of data validity, and analysis.

The facility must evaluate the test aquifer conditions, existing test and observation well construction information (e.g., screened interval, total depth, well diameter, filter pack, seal, lithology, completion data, etc.), and data from previous pumping tests and/or well-development pumping to design a hydraulic test to meet the objectives for both the location and interval being tested. Following selection of the aquifer test type and duration to be run in an individual well, the appropriate test tools (pump, packer(s), shut-in tool, etc.) will be installed in the test well (discussed further in Section 4.2). In the case of extensive groundwater contamination migrating through geologically complex aquifers that require remediation, the design is critical to get right at the start of the evaluation or a considerable amount of time and money can be wasted. Facilities with highly complex sites are encouraged to seek consultation from experts in groundwater characterization.

3.1 Wells

Wells serve two purposes in aquifer testing; they can act as the control or test well, the well in which the stress is initiated on the aquifer through pumping or through slug insertion and removal, and as an observation point where measurements from the stress propagating through the aquifer from the test well are measured over time. In the case of single-well aquifer tests, one well serves both purposes.

Of paramount importance is the construction, yield, location, and purpose of the test well to provide for acquisition of representative aquifer information required for successful and meaningful testing. The design and placement of the test well, and the configuration of observation wells around the test well must be approved by the HWB before an APT can be conducted and before any derived data is analyzed for use in groundwater models or to fulfil other site characterization requirements. The HWB refers each facility to Osborne (1993) to assist in evaluating the suitability and the spacing of test and observation wells to be included in an aquifer test.

Providing specifics on well drilling, construction, and development are beyond the scope of this Guidance. Each facility must design and install test and observation wells in accordance with industry standards for inclusion in an aquifer test. Each facility may conduct a formal well network evaluation to also assess their existing well network for suitability to serve as either test or observations wells. The following sections describe factors to be considered for inclusion of a well in an aquifer test.

3.1.1 Design

The suitability of a well to serve as a test well or observation well will rely on the inside diameter, depth, screened interval, screen length and slot size, filter pack, sealed intervals, development, and location with respect to the area of interest. If a properly designed and constructed monitoring well is to serve as the test well, a small-scale test such as a slug test or single-well pumping test should be considered in lieu of an APT because of the typically limited capacity of these well types to test large portions of the aquifer and the likely partial-penetration effects that will result from pumping the limited portions of the aquifer typically screened by monitoring wells. Providing the proper design and construction specifications for test and observation wells and piezometers to conduct aquifer testing is beyond the scope of this Guidance. However, each well and piezometer is required to provide representative values of total head in the aquifer or correction of the data will be required. In addition, the work plan shall demonstrate that each well to be included in the test design is suitable for its purpose as either the test well, observation well or both. This entails confirmation that the well construction, development, condition, and response are sufficient for the test assumptions.

To conduct an APT, a properly designed test well must be selected or installed that reasonably fully penetrates the aquifer and is capable of sustaining pumping rates that will create measurable responses at distant observation monitoring wells and piezometers. Many times, existing production wells can serve as test wells. However, the decision will largely be on a case-by-case basis and the following suggested references may guide the facility in the construction and determination of suitability for such wells to serve as test wells:

- *Groundwater and Wells* (F.G. Driscoll, 1996.)
- *Handbook of Ground Water Development* (Roscoe Moss Company, 1990.)

A fully penetrating test well is necessary to produce yields high enough to adequately stress the aquifer and to induce non-steady, horizontal, laminar flow in the aquifer toward the pumping test well. According to Kruseman and de Ridder (2000), a general rule for what constitutes a fully penetrating well is when the screen slots of the test well are in direct physical [and hydraulic] contact with at least 80 percent of the total thickness of a confined and leaky confined aquifer or the bottom third to half of an unconfined aquifer total thickness. Kruseman and de Ridder (2000) reason that an 80 percent well screen penetration allows 90 percent or more of the maximum yield to be obtained, and more importantly, groundwater flow toward the test well can be assumed to be horizontal, an assumption that underlies almost all well-flow equations (Theis, 1935).

In cases where criteria are not feasible, the aquifer test must be designed to accommodate for partial-penetration conditions and use solutions that account for the vertical flow component induced by partial penetration. This will limit the facility to fewer analytical solutions in analyzing both drawdown and recovery data. Some partial-penetration solutions require the test well screen to be centered within the total thickness of the aquifer. This must be taken into consideration when selecting or designing the test well when partial penetration will be a factor in the test analysis.

The facility must evaluate the viability of using existing wells at their site for both test and observation wells and should be able to demonstrate the wells are properly constructed following the New Mexico Office of the State Engineer (NMOSE) issued permit. If it is deemed that new wells are required for conducting a suitable aquifer test, the HWB must approve of the design and construction of new wells. As previously discussed, the ideal test well screen should fully penetrate the aquifer. Observation wells should have screen lengths of at least 5 to 20 feet (Osborne, 1993). The following monitoring well and piezometer construction guidance documents may provide a good starting point to design and designate the observation wells and piezometers for use in aquifer tests:

- New Mexico Environment Department, March 2011.
- RCRA Groundwater Monitoring: Draft Technical Guidance, U.S. EPA, November, 1992.
- RCRA Groundwater Monitoring Technical Enforcement Guidance Document, U.S. EPA, September, 1986.
- Handbook of Suggested Practices for the Design and Installation of Groundwater Monitoring Wells, U.S. EPA, March 1991.
- California Environmental Protection Agency, June 2014.

Most wells are constructed as a single completion design that has only one screened interval. However, a facility may use alternative well designs that consist of multiple screens such as dual completion installations, where two tubes are placed down hole in parallel (side by side) that monitor two separate zones in the aquifer with bentonite seals between zones, or well designs that consist of multiple screens placed in series (one on top of another) that are sealed off in the annulus and in the well bore from each other to monitor separate zones of the aquifer individually. The latter design is commonly monitored using Baski, Inc. or Westbay® Instrument sampling systems that consist of inflated packers between each monitoring zone to seal off each zone, and sampling ports such as Baski, Inc.'s Access Port Valve (APV) and pressure transducers within each sampling zone for monitoring. All construction and inclusion of existing wells into APT and single-well tests must be conducted with HWB involvement and approval.

3.1.2 Development

Well development is part of the drilling procedure and follows the completion of well drilling and installation. All drilling methods alter the hydraulic characteristics of formation materials in the vicinity of the borehole. Formation fines (e.g., clay and silt passing a #200 sieve) and drilling fluids remain in the borehole following drilling. These undesired materials clog the pores of the surrounding aquifer and typically form a cake or skin along the borehole wall that results in formation damage. This damage negatively affects well performance and results in lower well yield and poor hydraulic connection with the aquifer. Development procedures are designed to restore or improve these problems to maximize the performance of the well by removing the fines and additives, and to allow the gravel pack to settle and consolidate.

The performance of a well can be measured by well efficiency. Well efficiency can be estimated by performing a step-drawdown pumping test. A step-drawdown test can also be used to evaluate when well development is complete by plotting specific drawdown (i.e., specific capacity of each step) against discharge (i.e., pumping rate of each step) (Williams, 1985). Williams (1985) deems a well to be still undergoing development (underdeveloped) when the specific drawdown versus discharge plot has a negative slope. In this case, development or rehabilitation of the well must continue for the well to be suitable as a test well.

Facilities should be aware of common well development methods provided below and the advantages and disadvantages of each:

- Over-pumping.
- Surging.
- Air surging and pumping.
- Jetting.
- Jetting and simultaneous pumping.
- Hydraulic fracturing.

3.1.3 Spatial Configuration

Consideration of observation well configuration, or array, around the test well is pertinent to APTs. If only one observation well is to be used in an APT, it should be located between 50 feet and 300 feet from the test well (Osborne, 1993) and be screened in the same geologic formation and horizon as the test well screen. Another rule of thumb to locate an observation well is to place it at a distance from the test well equivalent to 150 percent of the aquifer thickness (NJDEP, 2012). However, known site hydraulics may dictate closer or further placement of the observation well, so that each test situation may be best evaluated individually by response prediction using type curves (Stallman, 1971) or other methods. The rationale for observation well placement must be provided in the work plan.

If the APT design requires multiple observation wells, the wells should be oriented along multiple lines such that any horizontal anisotropy in the aquifer can be defined using a method like Hantush (1966) or Grimestad (1995).

In the case of suspected boundaries, the observation wells need to be placed where they can help to identify the location and effect of the boundaries. If the location of the boundary is suspected before the test, it is desirable to locate most of the wells along a line parallel to the boundary and running through the test well (Osborne, 1993).

Another common consideration for observation well placement in planning an APT is the need to evaluate vertical K in highly stratified aquifers and for leakance in a leaky confined aquifer. In the case of highly stratified aquifers, observation wells screened within discrete lithologic units that are also penetrated by the test well screen are required to observe the differing responses among the strata, to evaluate for preferential pathways along strata, and the degree of the heterogeneity due to layering of the aquifer. In the case where vertically adjacent aquifers to the test aquifer are known to be present and separated by a leaky confining unit, observation wells should be placed in those (over or underlying aquifers) in addition to the observation wells in the test aquifer.

3.2 Pumping Rate

Pumping rate considerations do not apply to slug tests. Constant-rate pumping tests need to be performed in test wells capable of sustaining an adequate pumping (or discharge) rate for the entirety of the pumping phase of the APT and single-well pumping test. The pumping rate shall be sufficient so that an adequate cone of depression will develop across the test area while also maintaining the rate throughout the entire pumping phase of the test without fully opening the discharge gate valve.

In practice, the pumping rate is typically determined from discharge information obtained during well drilling, from well development rates, by conducting a step-drawdown or other pre-test pumping tests, and from knowledge from previous pumping tests at the facility. Less likely, analytical equations and numerical models may be of some use in determining a target pumping rate.

A properly sustained constant pumping rate is essential to create the non-steady radial flow required by the underlying theory (Theis, 1935) and mathematical solutions applied to constant-rate pumping test data. As drawdown progresses during constant-rate pumping, the pump loses efficiency because it must work against an increasing depth to water in the well to the discharge point, known as “head” or “lift” in pump curves. To compensate for this fact, adjustments to the pump speed or discharge valve are required to maintain a constant rate. This relationship is illustrated in the pump curve of the selected test pump.

The discharge rate during a pumping test must be constant within approximately five percent (Osborne, 1993) and must be measured and recorded in a log, preferably at the same regular intervals that drawdown is measured and at times of adjustments or changes in the pumping rate, or at a minimum in accordance to the schedule provided in Section 4.1.3. If the pumping rate merits alteration during the pumping test, the time of the change and the final rate following the change must be documented. Modern software, discussed in Section 6.1, can adjust for a necessary alteration in the pumping rate without compromising the analysis if the change is well documented and imported into the software. Otherwise, the test will have to be repeated at an appropriate constant rate.

Fluctuations in the pumping rate make the test analysis very difficult and will raise questions as to whether deviations in the data are due to flow boundaries or other hydrogeologic features. Maintaining a constant discharge rate is critical and is best accomplished using a variable-speed electrically powered submersible pump controlled by a variable frequency drive (VFD) that is part of a data-acquisition system (DAS) when used with an electronic flowmeter (Section 4.2.1.6) that provides feedback to the VFD. The DAS-VFD system described in Section 4.2.1.6 automatically maintains a constant pumping rate with continuous records if the pump is not driven beyond its capacity.

It is required for facilities that have identified difficulty in maintaining a true constant discharge rate during pumping tests, such as due to a significant depth to water, use a DAS-VFD system and must provide a description in the work plan of the system and how the facility will implement its usage. Other facilities may propose in the work plan the use of a conventional system such as a mechanical flow meter and gate valve to maintain a constant pumping rate in lieu of the DAS-VFD system if the facility demonstrates in the work plan how it will implement and maintain a constant pumping rate in the field from the test well and that it has not had issues in the past maintaining a constant pumping rate using the specified equipment.

3.3 Heads

Collection of head data, whether in the form of water levels or pressures, from the test well and from observations wells and piezometers, if employed, is critical during all aquifer tests (slug and pumping). The proper acquisition of head data requires careful planning. Each facility to provide in the work plan (outlined in Section 1.2) the planned acquisition, processing, and quality assurance for head measurements.

The concept of water-level measurement appears straightforward. However, when measured in open standpipe wells, it is more involved than most may realize. There are several elements to water levels that need to be considered in Section 3 of the aquifer test work plan:

- the method(s) used to collect water levels
- the error each method will have on the quality of the collected data
- the frequency water levels will be collected throughout the test
- the interferences on water levels that will impact the quality and representativeness of the measurement, and
- the fluid density and temperature.

There are several different methods to measure heads in wells, specifically use of a steel tape, an electronic tape or sounder, pressure transducers, and air lines. The HWB-preferred approach is to use downhole electronic pressure transducers and dataloggers with supplementary measurements made using electronic tapes and sounders. The use of steel tape and air line is comparatively slow and cumbersome, and air lines are typically not nearly as accurate as the other common methods of water level measurements.

The use of pressure transducers as the primary mode of head data acquisition supported by manual water-level measurements made using electronic tape follows the standardized technical procedures in U.S. Geological Survey Groundwater Technical Procedures GWPD 16 “Measuring water levels in wells and piezometers by use of a submersible pressure transducer”, GWPD 4 “Measuring water levels by use of an electric tape”, and GWPD 3 “Establishing a permanent measuring point.” However, the HWB realizes some existing wells that a facility desires for inclusion in an aquifer test work plan may be sealed but fitted with an air line, and that some facilities prefer to acquire supplementary water levels using steel tapes. In these cases, the work plan must incorporate U.S. Geological Survey Groundwater Technical Procedures GWPD 13 “Measuring water levels by use of an air line” and GWPD 1 “Measuring water levels by use of a graduated steel tape.” In all methods, the facility must provide in the work plan the limitations and errors of each method and the steps the facility will take to minimize or account for these issues.

3.4 Test Interferences

Test interferences typically involve one or more uncontrollable variables that affect groundwater levels at the facility that must be either avoided or corrected before aquifer test analyses are applied to the data. These interferences can impact the quality of the data collected during long-term pumping tests. However, they are less likely to affect step-drawdown and slug tests because these tests are typically conducted over much shorter timeframes. These interferences can include effects from:

- local groundwater withdrawals and injection,
- local groundwater level trends,
- meteorological influences,
- climatological influences such as seasonal changes and droughts,
- earth tides,
- surface loading,
- seismic events,
- subsidence.

The most common interference at any site is of meteorological origin, specifically atmospheric pressure changes. The following sections provide some guidance and consideration to avoid and compensate, when necessary, for these influences on data before analysis is conducted.

3.4.1 Local Pumping and Groundwater Level Trends

The most common approach to evaluate off-facility influences on water levels and regional trends is to monitor ambient “background” water levels over an extended period no less than one week before and after the pumping test is conducted. Additionally, long-term hydrographs of each observation well at the facility, especially those situated between any known off-site operation that involves pumping and the pumping test area, should be evaluated to determine the hydraulic influence the off-site operations have on the test area. Following this review, the facility must determine the degree that adjacent operations will affect the planned pumping test and provide a discussion and course of action, if any, in the work plan.

The off-facility influences on facility groundwater levels may be compensated for by either designing the pumping test to have a constant rate high enough to mask the influence, schedule the pumping test during times the off-facility system is not in operation, work with the off-facility system to schedule operations around the planned facility pumping test, or analyze only the unimpacted observations. If the data obtained from an observation well is impacted to the point that it is determined it to be unusable, either by the facility or by HWB, the facility must reject that dataset for use in the test analysis.

Local and regional trends in water levels may be caused by recharge events from precipitation and snowmelt and may create a gradually rising water level trend that persists for months. Additionally, other trends can be due to long-term dewatering from over-pumping and consumptive use.

3.4.2 Meteorological Influences

The aquifer head data collected during all phases of long-term pumping tests will be affected by meteorological phenomena, typically changes in barometric pressure and precipitation events. Short-term (less than 24 hours) slug tests and pumping tests may not be affected by meteorological influences because the shorter test timeframe makes it less likely to encounter these effects when compared to long-term pumping tests. If there is no significant change in barometric pressure during a test, barometric compensation will likely be unnecessary. Likewise, there may be no concern regarding effects from precipitation and streamflow recharge events on a test aquifer if there are no precipitation events immediately preceding and during an aquifer test. In some cases, these influences may be negated by creating large drawdowns that mask minor water level fluctuations. However, if distant observations wells are part of the aquifer test plan, the small magnitude of the drawdown at those far reaches may be concealed by the effects of barometric pressure changes (Toll and Rasmussen, 2007).

3.4.2.1 Precipitation and Recharge

A rise in aquifer water levels due to recharge from precipitation, snowmelt and periods of high runoff may be difficult to correct. To avoid meteorological impacts to aquifer test data, the test should be planned and conducted during climatologically favorable times when “fair” weather (dry high pressure) predominate. Changes in water level due to weather from precipitation, snowmelt, runoff, stream flow, evapotranspiration and drought may be evaluated during the background trend analyses discussed in Section 5.1.4. If it is found that weather has significantly impacted test data and the test data cannot be corrected, the test may not be accepted. Consequently, the work plan should provide how the facility will avoid conducting the test during unfavorable weather conditions, how the facility will document weather during the test, and what steps the facility will take to assess the impacts in cases where meteorological influences could not be avoided during a test. In this process, the work plan must include the evaluation of long-term (minimum of one week) background hydrographs of all wells slated to be included in the test. The HWB recommends a one-month background evaluation. The background evaluation may show that a recharge event is occurring that may affect the test water level data. Conceivably, effects from precipitation and streamflow recharge would more likely affect shallow aquifers that are hydraulically connected to local streams and have a thin permeable vadose zone.

3.4.2.2 Barometric Pressure Changes

Atmospheric conditions constantly change. As weather patterns change from high barometric pressure to low, and vice versa, groundwater levels in open standpipe wells screened below the water table respond immediately in an inverse manner. When measured in wells, such groundwater level fluctuations may render the data unusable for aquifer test analysis without compensation, especially for data collected in observations wells situated far from the test well.

In unconfined aquifers, the water table does not respond in the same manner as the water level in the well due to the delay, or lag, of the barometric pressure change manifesting at the water table. This lag is due to the resistance to air movement and the air storage capacity of the materials in the vadose zone when there is a change in pressure (Weeks, 1979). Because the barometric pressure change reaches the water surface in the well instantaneously but is delayed in reaching the water table surface of an unconfined aquifer, a pressure imbalance between the well and aquifer occurs and results in a water level fluctuation (Weeks, 1979). In unconfined aquifers and vadose zones consisting of incompressible material, the barometric pressure change at the water table will be negligible and the imbalance more pronounced.

In confined aquifers, the response to barometric pressure changes is instantaneous in both the aquifer and wells screened therein (Spane, 1999). However, the magnitude of the change in the aquifer is dependent upon the degree of confinement, rigidity of the aquifer matrix, and the specific weight of water (Spane, 1999). While unconfined aquifers and confined aquifers respond differently, both exhibit similar patterns regarding response to barometric pressure changes, which is mostly due to the direct barometric influence on the water level in the wells not the aquifer. Consequently, influence on well water levels from barometric pressure changes must be considered while planning an aquifer test. In most situations, barometric pressure changes constitute the most common and pervasive influences on measured water levels used in aquifer test analyses. The aquifer test work plan must provide a plan to evaluate and compensate for barometric pressure changes (Section 5.4).

3.4.3 Climate

Climatological considerations typically involve documenting predictable seasonal influences on groundwater levels from weather patterns, evapotranspiration, and streamflow, as well as longer-term effects like drought. The facility must use the known climate to propose a target timeframe to conduct a test, preferably when weather patterns are favorable and when there is little change in aquifer recharge and storage from precipitation, snowmelt, streamflow/runoff, and evapotranspiration.

3.4.4 Earth Tides and Loading

Regular, low-magnitude, semidiurnal fluctuations in water levels in wells located at great distances from oceans are attributed to earth tides. Earth tides result from the gravimetric attraction exerted on the earth’s crust by the moon and to a lesser extent by the sun and Jupiter. However, only the earth tides created by the moon are of any concern to water level correction for aquifer testing requirements. Almost always, while earth tide effects are commonly noticeable on high-quality head data collected at frequent intervals, correction for them for aquifer testing purpose is rarely required if the drawdown in all wells exceed about 0.5 feet in a confined aquifer. At lesser drawdowns, earth tides are noticeable in confined aquifers and data with such low drawdown may require correction for proper analysis. Head measurements in unconfined aquifers are not as affected, so earth tide effects can almost always be ignored.

The elastic properties of a confined aquifer result in changes in hydrostatic pressure when changes in loading occur. Some of the best examples are exhibited by wells located adjacent to railroads where passing trains produce measurable fluctuation in groundwater levels (Ferris et al., 1962). Correction for loading events is difficult and it is best to avoid the occurrence by conducting shorter tests or to disregard the affected data in analysis. However, in New Mexico, loading from ocean tides should not be a concern. Loading from the movement of locomotives and other very large equipment should not be an issue if such events do not occur or are not present. The facility should note in the work plan whether active rail lines, railyards or other phenomena that cause loading are present at the site and provide discussions on the course of action if they are present.

3.4.5 Geological

The impact on groundwater levels from seismic events, like earthquakes, is well documented and can render data acquired during an aquifer test difficult if not impossible to interpret. When an aquifer is affected by an earthquake, an abrupt increase in water pressure is experienced by the shockwave (and aftershocks) followed by an abrupt decrease in water pressure as the imposed stress is removed, causing water levels in wells to first rise than fall, respectively (Ferris et al., 1962). Cases have been recorded, however, where the water level did not return to its initial position presumably due to permanent rearrangement of the grains of material composing the aquifer (Ferris et al., 1962). There is no recommended correction for such an occurrence during an aquifer test.

3.4.6 Water Rights

Water rights may impact pumping tests because these tests remove water from the test aquifer that may constitute consumptive use. While water rights considerations are beyond the purpose of this Guideline, a limitation on pumping volumes will be a consideration for a facility to include in the work plan. Prior to developing an aquifer test work plan that involves a pumping test, the facility shall coordinate with NMOSE regarding the amount of water that can be pumped during the test. This requirement is of course not applicable to aquifer test plans that involve slug tests.

4 TEST REQUIREMENTS

Based on the results for test design criteria outlined in Section 3, the work plan must propose the data acquisition requirements, test data reduction requirements, and test equipment requirements discussed in this section. The workplan must also include the test methods and procedures described in Section 5 to ensure proper execution of the test objectives.

4.1 Data Acquisition Plan

The site conditions, aquifer conditions, and the data required for collection during each test shall be considered to select the equipment, methods, and procedures needed to accomplish test objectives. Four main data sets are to be collected during aquifer testing: heads (pressures and/or water levels), barometric pressure, pumping rate, and water quality. Electronically and manually collected data will be acquired during each phase of aquifer test activities, and shall include:

- Electronically collected downhole pressure data using pressure transducers with dataloggers or a DAS installed in all wells approved for monitoring.
- Manually collected water level data using electronic or steel tapes or sounders in all wells approved for monitoring.
- Electronically and/or manually collected pumping rate and volume data from wells being pumped.
- Electronically recorded barometric pressure data from commercially available barometers at the site (e.g., BaroTROLL® or Baro-Diver®) or from a meteorological station with a similar elevation within 20 miles of the test site.
- Manually and electronically collected water quality data including temperature, pH, specific gravity, and specific conductance of fluid produced during pumping, bailing, and/or swabbing; and
- Manually collected data on equipment and instrument configurations in the wells and at the surface.

Other technical data to be collected during the aquifer test are to be documented on the field forms provided in Appendix A. A logbook shall be maintained to document site observations including weather, the presence and movement of heavy equipment in the test area, serial numbers, calibrations, condition of all test equipment to be used, water quality measurements, and any comments.

4.1.1 Logbooks

Logbooks will be used to document all activities and decisions made during the testing activities. Specific information to be recorded in the logbooks includes:

- a statement of the objectives and description of work to be performed at each well.
- a list, with sample signatures and initials, of all personnel authorized to enter information into the logbook.
- weather conditions through the course of the day (e.g., temperature, clear, overcast, partly sunny, partly cloudy, precipitation type and amount, dry, wind speed and direction, storms, high pressure,

low pressure).

- a written account of all activities associated with each well.
- a list of all equipment used at each well, including make, model, and operating system (if applicable).
- a description of standards used for on-site instrument calibration and calibration results.
- traceable references to calibration information for instruments calibrated elsewhere.
- a sketch, showing all dimensions, of each downhole equipment configuration.
- tubing or pipe tallies and other equipment measurements.
- manually collected water-level measurements.
- manually collected water-quality data concerning the specific conductance, specific gravity, pH, and temperature of fluid produced during pumping, bailing and/or swabbing.
- entries that provide the names, start times, completion times of all data files created with the, as well as tables showing the configuration information (pressure transducer serial number, pressure rating calibration coefficients, etc.) entered into the DAS to initiate each data file; and
- discussion of the information and/or observations leading to decisions to initiate, terminate, or modify activities.

All entries in the logbooks will be signed or initialed and dated by the person making the entry. Continuous blocks of entries by the same individual do not all need to be initialed and dated, but the first entry on every page must always be initialed and dated.

Manually collected water-level measurements, pumping rate discharge measurements, and water-quality measurements are to be recorded on specially prepared forms, such as the example forms provided in Appendix A, instead of in the logbooks to provide a more efficient means of data collection and tracking. Any such forms will be identified in the logbook and submitted with the logbook.

4.1.2 Head and Barometric Data

Head measurements constitute a critical data set collected during any aquifer test. Head, whether measured as pressure or water level, will be measured in each test and observation well included in the proposed pumping test during the background phase, the pumping phase, and the recovery phase. Pressure transducers provide the most precise and accurate measurements and are the easiest to use after initial setup. However, the facility must use pressure transducers that are specified for 0.01-psi accuracy. Use of electronic water level indicator tapes and sounders, with measurements recorded to the nearest 0.01 foot, are acceptable and provide good checks on the data acquired using pressure transducers.

Pressure data should be recorded at the highest frequency the device allows for the first 100 seconds of any aquifer test (including the start of recovery periods). After that, the recording interval may be gradually increased to every 1 minute for the balance of the test. During recovery tests, the recording interval can be increased to every 5 minutes. The reasons for the continuing high frequency of measurements are: 1) to identify and characterize any fluctuations in the pumping rate and 2) to allow calculation of an accurate pressure derivative. Confirmatory manual water-level measurements may be made during the pumping and recovery phases of all pumping tests on the schedule provided below (modified from ASTM D 4050):

Time After Pumping Started or Stopped	Time Intervals
0 to 3 minutes	30 seconds
3 to 15 minutes	1 minute
15 to 60 minutes	5 minutes
60 to 120 minutes	10 minutes
2 hours to 3 hours	20 minutes
3 hours to 15 hours	60 minutes
15 hours to termination	120 minutes

Collecting head and barometric data simultaneously is an important consideration when requiring barometric compensation because it provides much more efficient post-processing. Barometric data collected at less frequent intervals than heads, such as those obtained from meteorological stations, will require interpolation of barometric data between each record to correspond to each head data point. During the background monitoring, head and barometric measurements should be made on identical schedules up to the initiation of the pumping phase of the test. The work plan must include the proposed frequencies for electronically and manually measured data.

Water level measurements should be collected before installation and after removal of downhole equipment from wells, and to check the calibration of pressure transducers to be installed in the wells before testing begins (Freeman et al., 2004). The facility shall record this information on forms to verify equipment calibration. All measurements will be documented on forms (Appendix A) and in logbooks as part of the test records (Section 4.1.1).

4.1.3 Pumping Rate

Along with head data, pumping rate data constitute the most essential data acquisition requirement during all pumping tests. The facility must measure and record the pumping rate from the test well and adjust the pump as necessary to keep the rate to within five percent of the planned rate provided in the HWB-approved work plan. When employing electronic dataloggers to record heads (Section 4.1.2), the use of a DAS enables the facility to record effectively continuous pumping rate measurements. Regardless of the recording method, the work plan shall provide a measurement schedule to record the pumping rate and must record the time (since test initiation and clock) and discharge rates (pre- and post) of any adjustments to the pumping rate. Early after test initiation, the pumping rate will continually drop as the water level in the test well drops if adjustments are not made to the pump speed or restricting valves. For this reason, the use of a DAS and associated flow-control equipment (Section 4.2.1.6) is required for all pumping tests, especially for APTs and step-drawdown tests due to the duration and numerous pumping rate changes that are required for the test type, respectively. The HWB may consider approval of a pumping test work plan that does not incorporate the use of a DAS/VFD to regulate, measure, and record the pumping rate if the facility has satisfactorily detailed in the work plan how it will achieve these requirements in an equally consistent manner. However, facilities that plan to employ long-term APTs and/or step-drawdown tests that have had issues with maintaining constant pumping rates at the site will be required to use a DAS/VFD. This requirement is not applicable to slug tests.

While it is critical to keep each reading within the five percent criterion, an adjustment conducted and recorded properly may prevent the need to restart the test because modern test analysis software (Section 6.1.8) accounts for the rate changes when an accurate log of the pumping rates is made and imported into the software. Otherwise, the data will not be accepted and the test will need to be reconducted. A slow, gradual, and continual decrease of the flow rate during the pumping phase is unacceptable (Osborne, 1993). This is neglecting to properly control the pumping rate and the use of the data will not be approved by HWB. Use of the DAS with a VFD in all pumping tests will rectify this problem (Sections 4.2.1.4 and 4.2.1.6). All measurements will be documented on field forms (Appendix A) and in logbooks as part of the test records (Section 4.1.1).

4.1.4 Water-Quality Measurements

Water-quality measurements are optional but recommended in the case of contaminated aquifers or brackish water aquifers. During the pumping phase of each pumping test, the specific conductance, temperature, and pH of the produced water will be measured by the DAS or by manually read instruments on a frequency equivalent to the start, middle, and end of the pumping phase. Other parameters that may be added include turbidity, dissolved oxygen, oxidation-reduction potential, sulfates, nitrates, chlorides, and other parameters of concern based on the aquifer water type and contaminants present. Specific gravity, if required by the HWB due to fluid density concerns, will be measured manually at least three times per day during pumping tests. The same suite of measurements may also be performed on water bailed and/or swabbed from the wells prior to slug tests or drill stem tests (DSTs). Except for specific gravity, these data will be considered qualitative in nature and will not be used for interpretation, but only to indicate relative changes in the quality of the fluid produced. Measurements will be documented in logbooks as part of the test records (Section 4.1.1).

4.1.5 Records

Records may consist of bound logbooks, loose-leaf pages, forms, printouts, or information stored on electronic media including:

- logbooks.
- all forms containing manually collected data.
- procedures used.
- calibration records for all controlled equipment.
- equipment-specification sheets or information.
- electronic data files collected by pressure transducer dataloggers and/or the DAS, with a log listing the files and defining their contents.
- a log of all groundwater quality samples collected.
- copies of all permits obtained.
- reports (e.g., geophysical and survey) provided by contractors.

Records resulting from work conducted under this Guidance, including forms and data stored on electronic media, will be included in a follow-up aquifer testing report to be submitted to the HWB.

4.2 Equipment and Applications

Equipment required to fulfil the data acquisition plan (Section 4.1) during aquifer testing will consist of equipment employed at the land surface and installed downhole in the wells. Equipment can consist of either "off-the-shelf" items ordered directly from qualified suppliers or standard equipment provided by qualified service companies. No specially designed equipment is deemed necessary because all methods implemented are to be standard methods. All equipment used will follow the supplier’s operation and calibration specifications. The test equipment used for the data-collection activities must:

- provide quality data to support test objectives.
- function according to design specifications.
- be calibrated, as appropriate, according to industry standards.

Selection of the proper equipment is crucial to ensure that high-quality data are obtained.

4.2.1 Surface Equipment

This section describes the equipment needed at the surface to conduct an aquifer test.

4.2.1.1 Solid Slug Test

Conducting a slug test using the solid slug method requires a solid cylindrical slug weighted for full and instantaneous submergence, a rope, cable, or wire to insert and remove the solid slug from the water in the test well, and head measuring equipment discussed in Section 4.2.1.3. Pressure transducers should be used to collect head data and are discussed in the downhole equipment section (Section 4.2.2.3). The solid slug is typically constructed of relatively inert material with a diameter and length that will fit in the well without disturbing the transducer and will create a displacement of water in the test well of at least six inches. Additional slugs with larger diameters and/or lengths should also be used to incrementally increase the water displacement at least two additional times. The slug dimensions should be designed to displace between 0.5 and 3 feet, to prevent a significant increase in the saturated thickness of the aquifer (in the case of an unconfined aquifer), disturbing the transducer, creating non-laminar flow, or affecting the speed at which one can raise or lower the slug (Cunningham and Schalk, 2011). High-K aquifers (1 to 100 ft/d) may require a larger displacement so that the recovery signal remains above the resolution limit of the transducer long enough to provide interpretable data (Cunningham and Schalk, 2011). This usually can be generated with a slug diameter about one inch less than the well diameter and a length of 3 feet or more (Cunningham and Schalk, 2011). Theoretical displacement volumes to construct adequate slugs for desired specific water-level changes are provided in “Conducting an Instantaneous Change in Head (Slug) Test with a Mechanical Slug and Submersible Pressure Transducer—GWPD 17” (Cunningham and Schalk, 2011).

4.2.1.2 Pneumatic Slug-Testing Wellhead Assembly

A special wellhead assembly is needed to conduct slug tests using the pneumatic method. The wellhead assembly seals off the wellbore from the atmosphere so that the pressure inside the wellbore can be precisely controlled. The wellhead assembly must allow a pressure transducer to be placed inside the well below the water level. With the wellbore isolated from the atmosphere, gas (N_2 or compressed air) pressure is applied to the wellbore via incorporated gas injection connections on the wellhead assembly. The application of a predetermined pressure depresses the water level in the well. As the water level is depressed, the applied gas pressure and the pressure transducer are monitored. When the test leader determines that the groundwater system has re-equilibrated to the applied stress, the applied pressure is instantly relieved by venting the gas through the incorporated vent port to initiate the slug test. Slug magnitude can be adjusted as desired with the only limitation being that the water level cannot be depressed below the top of the well screen. Pneumatic slug-testing wellhead assemblies are available commercially from several suppliers.

4.2.1.3 Water-Level Tapes and Sounders

Manually collected water levels will be made using an electric water-level tape or sounder. A steel tape is acceptable in shallow groundwater conditions (less than 100 feet in depth). However, any water-level tape or sounder to be used must be of sufficient length to accommodate the depth to water during static conditions and during the anticipated maximum drawdown conditions. The electronic water level tapes, sounder and steel tapes shall be in factory specification condition with no kinks, bends, twists, cuts, stretching or other distortions and alterations that may impact the factory length or contain severely abraded surfaces that may expose internal wiring, and shall contain all measurement markings in a visible condition easy for the user to quickly read. The indicators (e.g., alarm and light) shall be in fully functioning condition to factory specifications. A new battery shall be installed prior to commencing long-term tests. The weight, usually in the probe of electronic tapes or at the end of steel tapes and sounders must be unaltered from manufacturer specifications. Enough water-level tapes, sounders, and personnel to make timely water level measurements in all wells spread across site must be supplied. Equipment shall adhere to the requirements prescribed by “GWPD 1” and “GWPD 4“of the *Groundwater technical procedures of the U.S. Geological Survey* (Cunningham and Schaulk, 2011) and manufacturer instructions. Air lines are not recommended for water level measurements. If a sealed production well is to be used and is fitted with an air line, the equipment shall adhere to the requirements prescribed by “GWPD 13“of the *Groundwater technical procedures of the U.S. Geological Survey* (Cunningham and Schaulk, 2011).

4.2.1.4 Data-Acquisition System

A data-acquisition system (DAS) typically consists of control panels and a computer system that scan different types of gauges at a specified rate. A DAS scanning an electronic flow meter can also be used to control a variable-frequency drive (VFD) to maintain a constant pumping rate. The control panels, computer system, and all hardware components may be developed using off-the-shelf items or be purchased as manufactured units (for example Campbell Scientific, Inc.’s Granite™ series or Red Lion Sixnet® series). The control panel(s) houses the programmable logic controller, data acquisition input/output (I/O), water quality sensors (if used), and the power supplies for most of the instrumentation. The control panel(s) can also contain the VFD, motor starter, and circuit protection devices for the downhole pump. The DAS provides pump control using a proportional-integral-derivative controller that uses the flow-rate measurement from the flow meter as input and sends an output command signal to the VFD to adjust the rate as necessary. The DAS should scale the raw analog or digital signals from the gauges to their engineering unit equivalents (e.g., psi, gpm) using the entered calibration coefficients and display the engineering units on the human-machine interface software running on the system computer.

The DAS provides data acquisition and flow-rate adjustments on a near continual basis and is the preferred way to operate the pumping phase of any single- or multi-well pumping test. A DAS should be used to collect the primary pressure and flow rate data for any pumping test and must be used at facilities that have encountered difficulties in maintaining a constant rate via continual manual adjustment of the pump discharge valve.

4.2.1.5 Barometer

Barometric pressure will be monitored at the test location during all pumping tests using a specialized pressure transducer (e.g., BaroTROLL® or Baro-Diver®) as described in Section 4.1.2. These instruments are readily available, cost-effective, and provide the flexibility for the user to synchronize collection of barometric information with water-levels measurements. The barometer may be placed within the well casing but is not to be submerged below the water level in a well. It is recommended that only one barometer be used for each pumping test and that it be located on site. If necessary, downloading barometric information from a publicly accessible meteorological station can be accepted, but the user will have no control over the data acquisition frequency.

4.2.1.6 Flow Meters and Flow Control Equipment

A digital electronic flow meter, such as a magnetic-inductive flow meter, connected to the DAS shall be used to measure the flow rate during all pumping tests. Digital electronic flow meters typically provide a direct readout of the flow rate on an LCD display and can be scanned by a DAS on any desired frequency. An electronic flow meter is best when used with a DAS and is the preferred equipment for all facilities. Facilities experiencing issues with maintaining constant pumping rates due to the site conditions will be required to use a digital electronic flow meter and DAS system. The DAS will measure the output signal from the flow meter and control a variable speed pump motor (or variable frequency drive (VFD)) to maintain a consistent flow rate throughout the testing period. The flow-rate output from the flow meter will be used as the process variable to set the control variable, which consists of the variable speed pump. The user-selected set point will be set manually at the controller or remotely via the DAS. The design control range for flow rate is variable and dependent upon the conditions encountered or anticipated. Proper implementation of the DAS-VFD unit provides automated control and recording of the pumping rate, thus negating the need for continual manual adjustments to the pump to maintain a constant pumping rate.

Electronic flow meters have no moving parts, unlike mechanical flow meters that have impellers. Instead, the electronic flow meter uses a sensor to convert the movement of water past the sensor into an electronic signal. Digital electronic flow meters are factory calibrated and because there are no moving parts, do not typically require calibration due to mechanical wear. However, the meter should be checked before use that it is measuring flow accurately using manufacturer’s instructions, if applicable.

A magnetic flow meter cannot be used for pure water with an electrical conductivity less than 1 µS/cm. In such a case, the facility may choose to use another type of digital electronic flow meter if a DAS system is required or use a standard mechanical flow meter. Note that a magnetic flow meter cannot be used where external electromagnetic interference is present.

The work plan may include a proposal to use other types of digital flow meters other than the magnetic flow meter. In addition, consideration will be given for the use of a mechanical flow meter without a DAS-VFD system if the work plan discusses how the equipment will properly regulate flow to achieve and maintain a constant flow rate, and also discusses the requirement for a detailed and accurate log of frequent (at least every 10 minutes) flow rate measurements, including all rate adjustments, be completed (per Section 4.1.3).

A totalizing mechanical flow meter may be used as a backup for the digital flow meter to measure the cumulative discharge during the pumping period. If necessary, the data from the totalizing flow meter can be used to calculate the average pumping rate by observing the volume of water discharged through the meter over a given period. The performance of the mechanical flow meter shall be verified by timing the filling of a container of known volume in a specific period. These checks may be documented in the logbook for the corresponding pumping activity (Section 4.1.1).

4.2.1.7 Bailing and Swabbing Equipment

In wells in which a packer is installed on a tubing or pipe string with an in-line shut-in tool, bailing or swabbing equipment will be used to remove fluid from the tubing above the shut-in tool (Section 4.2.2.2) to conduct slug tests and/or DSTs, as needed (Section 5.1.1). The bailing and swabbing equipment will consist of a swabbing assembly with artificial and/or natural rubber tubing wipers (swab cups) or downhole bailers supplied and operated by the contractor responsible for installing and removing equipment from the well.

4.2.1.8 Water-Quality Measurements

HWB is not requiring measurements and recording of water quality parameters. However, water quality monitoring may be included in the work plan and are subject to approval. The specific conductance and pH will be measured with common commercially available meters (For example YSI, Horiba, or Hach brand sensors with measurement sensitivity of +/- .025 pH and conductance sensitivity of +/- 5% of full scale). If required, specific gravity will be measured with a laboratory-grade hydrometer. All meters are to be in factory-specified operating condition, calibrated in the field daily as appropriate, and documented in a field logbook (Section 4.1.1).

4.2.1.9 Power Source

The power source to operate the test pump will likely be determined on the availability of power at the test site. The preferred source would be the local electrical grid. More likely, diesel- or gasoline-powered generators may be used to generate electricity for the test equipment and pump. If a generator is used, it will be operated in accordance with the instructions provided by the manufacturer. Operation of generators is not a quality-affecting activity and, therefore, documentation of activities associated with the generators is not mandatory. It is also appropriate that all DAS and computer equipment be powered through an Uninterruptible Power Supply (UPS) which provides for the continued collection of data in the event the primary power source fails.

4.2.1.10 Storage Tanks

All IDW produced from the wells during test activities will be containerized at the well pad in appropriate storage tanks, lined pits, or other suitable structures or devices until after data acquisition is complete and equipment is removed from the site. It is essential that reentry of produced water into the test aquifer is prevented as it will likely interfere with the quality of the data acquired during the test. Such interference may result in required retesting to employ proper containerization of all produced water. The IDW will be properly disposed following testing and removal of test equipment.

In the case where the IDW is contaminated per accordance with the NMAC, the IDW will be handled as a hazardous waste and must be adequately treated before disposal. It shall be assumed that the IDW is contaminated if the test aquifer has known contamination, as defined by the NMAC. Obtaining proper disposition permits through NMED will be required before discharging the IDW. While water storage is not a quality-affecting activity, documentation of activities associated with the storage amounts should be compared to recorded pumping rates and durations to verify the average pumping rate of the test. In the case that onsite IDW containerization, treatment, and disposition is not possible or cost-effective for the facility, the HWB prefers that the facility conduct slug tests in lieu of pumping tests because slug tests generate no IDW and containerization and treatment of IDW can be avoided.

HWB may consider use of a lined discharge canal, piping or hose to direct the water away from the test zone instead of containment on a case-by-case basis. This will be considered in cases where the expected quantity of produced water is unrealistic for containment and the IDW is uncontaminated, or the contaminant(s) in the IDW are treated onsite as it is pumped from the aquifer. The work plan must describe how the discharged water will be directed away from the test site and whether a lined canal or a network of pipes and/or hoses will be used. The work plan must include specifics regarding the material that will be used to line the canal, the piping, and hosing as well as the length the discharge water is directed through.

4.2.2 Downhole Equipment

This section provides guidance on the necessary equipment to be installed downhole, although it may be operated from the surface, and may consist of inflatable packers and air lines, a shut-in tool, pressure transducers, a submersible pump, pump column including the discharge pipe or tubing, electrical cables, and a drop pipe for well access from the surface. The depths of all equipment installed in a well will be measured and documented relative to a known permanent datum, such as a survey marker established on the well pad. The establishment of a permanent datum should, at a minimum, meet the procedures provided in the US. Geologic Survey GWPD 3—*Establishing a permanent measuring point and other reference marks*. A secondary datum, such as the top of the well casing, may be used as a reference point for depths provided that the elevation of the secondary datum relative to that of the primary datum is known and documented. The lengths of all tubing or pipe joints and other pieces of equipment installed in the well will be measured to the nearest 0.01 ft and documented in the logbook in accordance with Section 4.1.1.

Due to the inherent variability in test-tool configurations that will be necessary to successfully complete hydraulic testing in all wells, no standard configuration is provided in this Guidance. Each test-tool configuration will be documented in the work plan and in the field as as-built diagrams to be submitted as part of a final report for HWB review. The placement of the test tool within the borehole will be determined by the facility in conjunction with their contractors experienced at setting up aquifer testing equipment. After the well has recovered to at least 95 percent of static from the disturbance caused by test equipment installation, an appropriate aquifer test(s) will be performed in accordance with the procedures provided in the HWB-approved work plan.

The type and configuration of test tools will vary from well to well based on the following:

- the type of aquifer test to be performed, e.g., slug test, single-well pumping test, APT.
- the objectives of the testing (formation(s) or parameters of interest).
- the well configuration (single-interval completion or dual-interval completion).

All test equipment will be removed from the well, and the well will be configured for long-term monitoring upon completion of the aquifer test(s).

4.2.2.1 Inflatable Packers

Inflatable packers are expandable plugs used to isolate sections in a well or borehole and are manufactured by several companies including QSP Packers, LLC, Baski, Inc., TAM, Inflatable Packers International, and Aardvark Packers. In a screened well, the packer must be set immediately above the well screen and be completely submerged below the water level in the well. In the case of a well with two screened intervals in series, two packers should be used to straddle the screened interval associated with the formation of interest.

Packers are inserted into a well on a pipe or tubing column hereafter referred to as a tubing string. The tubing string has a reduced inside diameter (ID) relative to the well casing that acts to reduce wellbore storage. The packer should have at least one feedthrough that allows a transducer located above the packer to be connected to a ¼-inch plastic or stainless-steel tube passing through the packer to the interval below. Compressed nitrogen or compressed air is used to inflate the packers through flexible plastic air lines. The air lines extend from the packer to the surface where the compressed gas is applied and must be rated for pressures much higher than the projected inflation pressure to be applied to the packer. Inflation pressures are extremely important to create a sufficient seal to prevent leaking of air and water between the packer and the well casing, and may be provided by the manufacturer, such as the QSP calculation formula at http://qsppackers.com/navbar/info.html.

Typically, the applied pressures are determined in the field by an experienced contractor. In general, packer inflation pressures will be the sum of:

- the water pressure above the packer (submergence or hydrostatic pressure),
- the pressure required to stretch the rubber element out to the borehole wall or casing, and
- the pressure required to seat the packer firmly enough against the borehole wall or casing to prevent any movement caused by the differential pressure across the packer.

The facility shall use an experienced contractor familiar with the selected packer equipment to ensure that the applied packer pressure is sufficient to achieve a proper seal while not over inflating, which can burst the packer bladder. It should be noted that the deeper the packer is set in the well, the greater the inflation pressure required to offset downhole static pressures.

The development of air leaks is common after the packer system is first assembled in the field. The facility should have the contractor test for leaks and proper packer operation before installing the packer downhole. The check can consist of assembling the packer, air line, and associated hardware to inflate the packer in a pipe of the same ID as the well ID. Upon inflating the packer in the pipe, the components are checked with soapy water for air leaks and for packer seal development along the pipe wall.

The packers to be used will have uninflated diameters consistent with the diameter of the casing in each well. It should also be noted that when a packer is inflated down well, the packer contracts in length. This may lead to an inadequate seal. Each packer should have a minimum seal length of at least one-half meter (ASTM D 4630).

Pumping tests conducted in wells that have a multiple-screen design (screens placed in series) (Section 3.1.1) will require the use of packers to reconfigure the wellbore in such a way as to allow the pressure to be monitored in multiple intervals simultaneously within the same borehole.

4.2.2.2 Shut-in Tool

A shut-in tool (SIT) may be used to control access to the packer-isolated zones in the wells in which aquifer tests are performed. The SIT may be either of the rotating ball-valve type (e.g., Inflatable Packers International’s downhole shut-in valve (DHSIV)) or a sliding-sleeve shut-in tool (e.g., Baski’s APV) that consists of concentric sections of pipe with circular ports passing through the wall of the pipe. In the open position, the ports on the two sections line up, allowing fluid to pass from the tool string to the well. When one of the sections slides vertically relative to the other, the ports no longer line up (closed position), and the fluid cannot pass from the tool to the well. A DHSIV can be placed in the tubing string above the packer whereas an APV must be below the packer in the test interval and provide the only connection between the test interval and the tubing string. Both types of SIT are controlled from the surface. Gas or hydraulic pressure is applied to a piston through a control line run alongside the tool string to rotate the ball valve or open or close the sleeve. Separate pistons and control lines are used to open and close the sleeve. No tubing movement or weight change to the tubing above the SIT is required to operate it, thus minimizing tool-induced pressure disturbances in the test zone.

4.2.2.3 Pressure Transducers

Pressure transducers are used to measure water (or air) pressure during aquifer tests. The two types of pressure transducers most frequently used in groundwater studies are strain-gage and vibrating wire transducers, with strain-gage transducers being the most common (Freeman et al., 2004). Some transducers are programmable and have built-in memory to record data during a test, whereas others require scanning by a DAS. Most commercially available pressure transducers are calibrated to operate between zero- and 120-degrees Fahrenheit and measure temperature to provide a temperature-corrected measurement (Freeman et al., 2004). Unless the facility can demonstrate that the groundwater is of uniform temperature throughout a pumping test and is within the calibration temperature range for the selected pressure transducer, temperature-corrected pressure transducers that also measure temperature and are calibrated to the range of groundwater temperatures in the test aquifer must be used.

Programmable strain-gage pressure transducers frequently used in groundwater studies include the In-situ Level TROLL®, Seametrics PT2X, and the Solinst Levelogger®. These devices typically have different pressure ranges within which they can operate, usually from 5 psi to 1000 psi, to accommodate different depths of submersion beneath the water level in the well or piezometer. The devices communicate using a Modbus® RTU (RS485) and SDI-12 4 to 20 mA signal through a communication cable to the surface where they can be downloaded and/or connected directly to a DAS.

Pressure transducers that are directly linked to a DAS, which is programmed to collect and store the data at the test well, do not require an onboard programmable datalogger. Such devices are available from Geokon, Druck, Keller, and Omega, among others. In-situ Level TROLLs® may also be connected directly to a DAS. By being linked to a DAS, these pressure transducers provide access to the data in real time to determine when intervention is necessary and for ongoing real-time analysis as the test proceeds. Programmable transducers with onboard datalogger memory are best suited where no intervention is anticipated such as installation in observation wells and piezometers as part of an APT.

Transducers can be either vented or non-vented. Vented pressure transducers are coupled with a specialized cable that contains a small diameter vent tube within the insulating sheath that transmits the variations in atmospheric pressure from the surface to the pressure transducer sensor. Thus, they measure only the pressure exerted by the water column and not the atmospheric pressure. Non-vented transducers measure the total pressure applied on the pressure transducer sensor which includes the hydrostatic pressure from the water column above the sensor and the atmospheric pressure. Because non-vented pressure transducers record total pressure, they require a greater pressure rating than vented transducers, which slightly reduces their accuracy. Manufacturers of vented pressure transducers may state that these devices provide an automatic barometrically compensated water level, but in fact they assume a barometric efficiency of 100 percent. Virtually all aquifers have barometric efficiencies between 20 and 70 percent (Todd and Mays, 2005), which means that measurements made with both vented and non-vented transducers require barometric corrections (see Section 5.4).

Deployment of multiple pressure transducers during an aquifer test requires clock synchronization of all devices to one time reference. This is a crucial step to take when deploying pressure transducers specifically if the units are programmed to start automatically using a set schedule. Another thing to consider when employing pressure transducers is to install the devices using equipment and hardware so that the device does not move or shift in any way, such as sliding further down into the well or being moved by pumping turbulence. Any movement of the pressure transducer will affect the measured water level recorded at that time. Common practice in wells without packers is to insert the pressure transducer into a protective sleeve or pipe, usually a one-inch ID PVC pipe to right above the pump. In observation wells, this will not likely be necessary. However, properly fixing the pressure transducer in all wells at the well head is another critical requirement in use of the equipment.

Information pertaining to the type, manufacturer, serial number, calibration check, installation depth, communication/suspension cable serial number, and other installation conditions for each pressure transducer used in an aquifer test study shall be documented in a field logbook, field forms, or other records (Section 4.1.1).

4.2.2.4 Submersible Pumps

In most cases, an electrically powered submersible pump will be required to conduct pumping tests, especially APTs, because they provide constant pumping rate and are the most reliable. Pump failure during the pumping phase of a test may result in retesting. In cases that a submersible pump cannot be employed to operate the pumping test, the facility must provide a sound rationale in the work plan to justify use of another pump technology (Section 3.2).

The submersible pump must allow variable motor speeds controllable by a VFD (Section 4.2.1.6). This is necessary because the VFD receives information from the DAS to automatically control the pumping rate at the predetermined constant rate. The pump capacity shall exceed the planned pumping rate of the test well by 20 percent (Osborne, 1993) to prevent the pump from being operated at maximum capacity at any point during the pumping phase (Section 3.2), especially if the pumping phase is extended based on real-time analysis of test data (Section 5.5).

There are numerous manufacturers of submersible pumps and an overwhelming number of models to accommodate various hydraulic conditions of pumping wells. Selection of the submersible pump will primarily be based on the diameter of the test well it is to be inserted within, the planned pumping rate, the depth to static water level in the test well, the projected drawdown in the well at the conclusion of the pumping phase, and the ability of the pump to be controlled by a VFD. The work plan must provide the pump selection rationale, pump curves of the selected pump, and a discussion that cavitation of the pump will not occur during the pumping phase.

The submersible pump will be installed with one or more in-line check valve(s) positioned above the pump to permit filling of the pipe or tubing column with water at the start of pumping to ensure immediate flow control and regulation, and to prevent water in the pipe or tubing column from draining back through the pump when the pump is turned off. The pump intake will be installed in the well typically just above the top of the test well screen on a pipe or tubing column and beneath a sufficient column of water to avoid cavitation. Setting the pump within or below the test well screen (in the sump) is not recommended and can cause cascading water through the screen, loss of vapor pressure, cavitation, air entrapment, and pump motor overheating. When the interval to be pumped is below or between packers, the pump will need to be installed in a shroud that is in line with the tubing string connected to the packer that also acts as the discharge pipe. The installation depth and configuration will be documented in the applicable logbook (Section 4.1.1).

5 FIELD TESTING APPROACH AND CONCEPTS

The following sections discuss the different hydraulic test types that can be performed in wells and also provide some general considerations for selection and execution of each test type. These sections as well as the rest of the Guidance are intended to provide adequate material to develop a suitable aquifer test work plan for submittal to the HWB for approval prior to conducting an aquifer test.

5.1 Slug Tests

Slug tests constitute the simplest field testing approach of the aquifer test types covered in the Guidance and can be initiated with a mechanical solid slug, the pneumatic air slug method, using a shut-in tool, or other method approved in the HWB work plan. Butler (2019) provides a comprehensive overview of all aspects of slug testing. In general, the solid slug test method is more suitable for moderate to low-K aquifers whereas the pneumatic slug test method is suitable for most aquifer K conditions (although it cannot be used if the well screen crosses the water table) and is recommended for high-K aquifers. If a shut-in tool is a component of the tool string, slug tests in low-K aquifers can be converted to drillstem tests (DSTs). Equipment requirements are more involved for pneumatic slug tests (Section 4.2.1.2) due to the wellhead assembly whereas mechanical slug test equipment requirements involve using a solid cylinder suspended on a rope or wire and equipment to measure heads (Section 4.2.1.1).

Slug tests and DSTs will generally have to be performed when:

- low yield/high drawdown conditions occur in wells incapable of sustaining adequate pumping rates to conduct pumping tests, and
- in highly contaminated zones where treatment of produced water would be required but proper disposition of the water is not feasible.

Procedures to conduct a slug test using the solid slug method, pneumatic slug tests, and slug tests conducted using an SIT and their conversion to drillstem tests are discussed in the sections below.

Data-acquisition rates will be set as fast as possible at the start of each test event (slug/flow or buildup) and will then be systematically decreased throughout the test to provide a reasonably uniform distribution of data with respect to the logarithm of elapsed time. If deemed appropriate to employ the use of a DAS to monitor slug-testing activities, all pertinent information will be documented in the logbook.

During slug test and DST activities, pressure-response data will be evaluated on a real-time basis by the test leader to determine that the objectives of the test are being met and that the test proceeds in the most efficient and effective manner. Standard type curve and diagnostic derivative techniques described in Hvorslev (1951), Cooper et al. (1967), Ramey et al. (1975), Bouwer and Rice (1976), Sageev (1986), Ostrowski and Kloska (1989), Peres et al. (1989), Yang and Gates (1997), and Butler (2019), among others, may be employed to assess both the progress of the test and to determine the flow regime of the system being tested.

5.1.1 Solid Slug Tests

Conducting a slug test using the solid slug method involves removing a submerged solid cylindrical slug from the water in the test well as quickly as possible and monitoring the resulting head recovery. The equipment needed for a solid slug test is discussed in Section 4.2.1.1. Pressure transducers should be used to collect the head data and are discussed in Section 4.2.2.3. The slug should be sized to displace between 0.5 and 3 feet to prevent a significant increase in the saturated thickness of the aquifer (in the case of an unconfined aquifer), disturbing the transducer, creating non-laminar flow, or affecting the speed at which one can raise or lower the slug (Cunningham and Schalk, 2011). Additional slugs with larger diameters and/or lengths should also be used to incrementally increase the water displacement at least two additional times. High-K aquifers (1 to 100 ft/d) may require a larger displacement so that the recovery signal remains above the resolution limit of the transducer long enough to provide interpretable data (Cunningham and Schalk, 2011). This usually can be generated with a slug diameter about one inch less than the well diameter and a length of 3 feet or more (Cunningham and Schalk, 2011).

5.1.2 Pneumatic Slug Tests

A pneumatic slug test is simply a slug test in which air pressure applied to the wellbore is used to depress the water level using equipment described in Section 4.2.1.2. The water level will decline until it is in equilibrium with the air pressure in the well. This equilibration is monitored using a pressure transducer in the water column and a pressure gauge or transducer monitoring the air column in the wellbore. After equilibrium is re-established, the pneumatic pressure is instantaneously released, thereby initiating recovery of the water level to initial conditions. Analysis of this recovery to initial conditions will allow estimation of hydraulic parameters. Testing may be terminated after the rate of change in the water level recovery is less than 0.01 feet per minute (Cunningham and Schalk, 2011), 98 percent pressure recovery has occurred, or after the collected data are adequate for analyses.

After the pressure disturbance caused by the first pneumatic slug has recovered to within 98 percent, a second pneumatic slug test will be performed in the well. The second test will be a duplicate of the first test, but with either half or double the initial pressure differential established during the first test. This stepped-up pressure can be repeated for a third time to provide good diagnostic information on the test quality and representativeness of formation K around the test well screen.

Pneumatic slug tests cannot be performed in wells with screened intervals that intercept the water table and/or with a filter pack that extends into the vadose zone as the pressurization of the well will be lost to the unsaturated zone. In this case, other slug test methods should be considered.

5.1.3 Slug and Drillstem Tests Using a Shut-In Tool

A drillstem test (DST) is simply a slug test that is shut-in before complete water-level recovery has occurred, after which recovery continues in the test interval isolated from the test tubing and atmosphere (Karasaki, 1990). The slug portion of a DST is referred to as a flow period and the shut-in portion is referred to as a build-up period. The advantages of a DST relative to a slug test are that it takes less time to complete and provides two data sets that can be analyzed instead of one. The disadvantage of a DST relative to a slug test is that the flow-period data set is less definitive than a full slug data set.

For a DST to be possible, a packer must be set on the tubing or pipe column in the test well casing above the perforations or screen with an SIT in the tubing column immediately above the packer. The packer shall seal a portion of the borehole wall or casing at least 0.5 meters in length. The SIT will be in the open position when the test equipment is installed in the well (Section 4.2.2.2). Once at the desired depth, the packer will be inflated, after which the SIT will be closed.

A pressure transducer will be strapped to the pipe column at a depth below the stabilized formation water surface calculated to keep the transducer within its calibrated range during the test. The pressure transducer will be connected to the formation of interest using a feedthrough line passing through the packer or other configuration as deemed appropriate. The depths of all equipment in the well will be carefully measured and documented in the logbook (Section 4.1.1).

With the SIT closed, the tubing will be bailed and/or swabbed to remove some of the water from above the SIT. The removal of water from the tubing (effectively under-pressuring the tubing relative to the formation) precedes what is referred to as a slug-withdrawal test. After bailing and/or swabbing, the water level in the tubing will be measured using a water-level sounder to determine the magnitude of the slug to be applied. This type of test can also be accomplished by adding water to the tubing (effectively over-pressuring the tubing relative to the formation) rather than removing water from the tubing. This is referred to as a slug-injection test and may be performed if the circumstances are deemed appropriate by HWB.

The pressure in the formation of interest below the packer will be allowed to stabilize until the rate of change is <0.5 psi/day or the test leader determines the test can begin. The SIT will then be opened to initiate a slug test. The test leader will evaluate the test data in real time to determine if the test should be continued as a slug test or converted to a DST. The following guidelines can be used to determine when a slug test should be converted to a DST:

- If 50% of the initial slug has dissipated after 3 hours, the test will remain a slug test.
- If 50% of the initial slug dissipates between 3 and 24 hours, the shut-in valve will be closed and the test will be converted to a DST when 80% of the slug has dissipated.
- If 50% of the initial slug has not dissipated after 24 hours, the shut-in valve will be closed, and the test will be converted to a DST whenever 50% dissipation occurs.

Slug tests and DST buildup periods should ideally continue until at least 98% pressure recovery has occurred. For a slug test, the SIT will then be closed, and the tubing bailed and/or swabbed to create a pressure differential approximately half of that created for the first slug test. For a slug test converted to a DST at 80% slug dissipation, the tubing will also be bailed and/or swabbed to create a pressure differential approximately half of that created for the first test. No bailing and/or swabbing will be required for a test converted to a DST at 50% slug dissipation. After the pressure disturbance caused by bailing and/or swabbing has dissipated, the SIT will be opened to begin a second slug test or DST. The second test will be an exact duplicate of the first test, but with half of the initial pressure differential. Testing may be terminated at any time after 98%

pressure recovery has occurred or after the test leader has determined that the available data are adequate for analyses.

5.2 Single-Well Pumping Tests

Constant-rate tests and step-drawdown tests are the two types of single-well pumping tests that can be conducted. The work plan must justify the decision to use one method over the other, the reasoning for the selected method in lieu of conducting an APT, and the duration and pumping rate of the pumping test. It is crucial to achieve and maintain a constant pumping rate regardless of whether the proposed pumping test conducted is constant-rate or step-drawdown. The work plan must consider the underlying assumptions of all pumping tests (Theis, 1935) when documenting the planning and designing of the test.

A second pressure transducer should be used in a pumping well during any pumping test to provide a backup data set in the event the primary transducer fails for any reason. Also, if pumping is performed below a packer, the pressure in the annulus above the packer should be monitored by a transducer to confirm that the packer did not allow bypass during the test.

5.2.1 Step-Drawdown Tests

The step-drawdown test is based on the measured drawdown in a well created by pumping that well at different constant rates over specific time intervals. The step-drawdown test can be used to evaluate well efficiency, the degree of development, formation and well loss components, to select a pumping rate for a later constant-rate test, to determine the specific capacity of the well, and to estimate aquifer transmissivity. This information will allow a determination of the optimal pump settings (depth and pumping rate) in the well to conduct a constant rate test and/or to use for continual extraction. The step-drawdown procedure should be conducted with a minimum of four, 60-minute duration constant-rate steps that are conducted sequentially at incrementally higher flow rates. It is important to run the initial step long enough to demonstrate that wellbore storage effects have dissipated (see Section 6.3.1). Each of the remaining three steps should be run for a length of time identical to the initial step.

The remaining pumping rates should be determined by multiplying the maximum design rate by 0.50, 0.75, and 1.25. Use of a DAS (Section 4.2.1.4) for step drawdown tests is crucial due to the use of multiple rates and the relatively short duration of each step. It is important that a constant rate is quickly established after changing to the subsequent step. However, in the case that a DAS cannot be used, head measurements made in the pumped well during drawdown produced from each pumping step and during recovery following completion of the final pumping step shall be measured at the frequency provided in Section 4.1.2.

Recovery should be measured immediately upon termination of pumping of the last step and measured until the water level has returned to within 95 percent of the initial, pre-pumping static water level or until twice the total pumping duration has elapsed, whichever is longer. Measurement frequency during recovery should also conform to the specifications above. The pump should not be removed until the water level has returned to 95 percent of the pre-pumping static water level.

5.2.2 Constant-Rate Single-Well Pumping Tests

Although much more straightforward than conducting an APT, the setup for the constant-rate single-well pumping test is more involved compared to other single-well tests. The design considerations and equipment required to conduct a single-well test are outlined in Section 3 and Section 4.2, respectively.

Like an APT, the test well should fully penetrate the test aquifer and be of suitable construction (Section 3.1) and have adequate yield to conduct the test. The pumping test must be conducted so that the theoretical assumptions of non-steady radial flow to a pumping well (Theis, 1935) are shown to be satisfied. This requires implementation of a proper constant pumping rate throughout the duration of the pumping phase as described in Section 4.1.3 and using the equipment described in Section 4.2.1.6 to accomplish this requirement. If partial penetration cannot be avoided, methods of data analysis will be restricted to those that adjust for this less-than ideal condition.

The common rule of thumb regarding the duration for the constant-rate single-well pumping test is a minimum of 24 hours for confined aquifers and 72 hours for unconfined aquifers to evaluate for delayed yield. However, real-time analysis of pressure responses measured within the test well must be performed to determine when to terminate the pumping phase of the test. More specifically, it should be determined that IARF has been established using the derivative method (Section 6.3.1) before terminating the test. Recovery should then be monitored for twice the duration of the pumping period.

The simplicity of the single-well test over the APT is the shorter duration and that no observation well other than the test well is used. The decreased test duration will likely result in cost savings and encountering less test interferences described in Section 3.4. This test is like running a short APT and may be used for planning a subsequent APT, especially if the tested well will be used as the test well for the APT.

The single-well pumping test duration allows the facility to plan the test during a time where weather and other interferences are more easily avoided when compared to an APT duration. Some of the common interferences discussed in Section 3.4 can be avoided if planned correctly.

The phases involved in conducting a single-well pumping test are described below with respect to APTs.

5.3 Multi-Well Aquifer Performance Tests

Constant-rate, multi-well interference tests are performed to obtain transient head response data from observation wells spread over an area up to several square miles. They differ from the single-well pumping tests described in the previous section primarily in terms of duration and the use of observations wells for additional data acquisition. The testing procedures are otherwise the same. An APT typically lasts from several days to over a month to allow distant observation wells time to respond. In addition to providing data for analysis of the individual wells' responses, multi-well interference tests also provide large-scale transient data that can be used in calibration and history matching of groundwater flow models. Like single-well constant-rate pumping tests, an APT consists of three phases: the background pre-pumping phase, the pumping phase, and the recovery post-test phase. The use of real-time derivative analysis is essential during the pumping phase and recovery phase.

5.3.1 Pre-Pumping “Background” Phase

The water level within the test well, each observation well and piezometer shall be at its “normal” static level prior to the test. Multiple interferences can cause “non normal” water levels as discussed in Section 3.4. Head measurements should be made at a frequency between one and 10 minute intervals using a downhole pressure transducer prior to initiating pumping. The pre-pumping phase of the test shall occur over a minimum seven-day period to observe background trends, barometric pressure influences, and to allow for sufficient stabilization of the hydraulic conditions in the test aquifer. Measurements of atmospheric pressure at land surface should be made at the same frequency as the head measurements recorded by the pressure transducers to facilitate subsequent barometric compensation. In settings where tidal influences may affect the pumping test results, measurements should be made at a frequency sufficient to correct the pumping test data for any observed tidal influences. It is best to plan the test so that displacement of water in all monitored wells is at least an order of magnitude greater than barometric and tidal changes in water levels. However, if this is not achievable, compensation may be required so that all head changes analyzed are the result of test pumping and recovery responses.

All incidences and amounts of precipitation measured and recorded during the entire pre-pumping phase and throughout the subsequent pumping and recovery phases must be entered in the logbook and on applicable forms (Section 4.1.1) to document the occurrence for consideration during data analysis (Section 6). If a significant precipitation event occurs during the pre-pumping phase that impacts heads, it is imperative to extend the duration of the pre-pumping phase until the hydraulic conditions in the test aquifer have stabilized back to static.

During the pre-pumping phase, the pump will be turned on briefly to perform several checks of the system to:

- ensure the submersible pump is operating properly at the design rate.
- ensure all the surface and downhole electronic equipment is operating properly.
- fill the tubing or pipe string with water to ensure that:
    - the check valve(s) above the pump is (are) holding,
    - there is water filling the surface discharge lines to ensure that both the mechanical and the electronic flow meters will register flow rates immediately upon initiation of the formal pumping test.

When all necessary checks have been made, the pumping will be terminated, and the system will be allowed to return to pre-test water-level trends prior to the initiation of the formal pumping test.

5.3.2 Pumping Phase

Following completion of the pre-pumping phase of the constant rate pumping test, the facility shall start the pumping phase at a constant rate. The best method for data acquisition and maintenance of a constant rate throughout the duration of the pumping phase is using a DAS (Section 4.2.1.4) with an electronic flow meter and VFD (Section 4.2.1.6). However, if manual methods are included the HWB approved work plan, drawdown measurements in the production and observation wells must be recorded according to the schedule provided in Section 4.1.2. The time intervals provided in Section 4.1.2 are minimum frequencies, and more frequent measurements will assist with pumping test analysis and interpretation.

The pumping phase shall proceed for a minimum of 24 hours in confined aquifers and 72 hours in unconfined aquifers where delayed yield may be encountered. It is preferred that the facility conduct the pumping phase until real-time analysis of the data provided by the DAS indicates that infinite-acting radial flow conditions have been reached at the pumping well and any observation wells or that other conditions (e.g., leakage, delayed yield, partial-penetration effects) are sufficiently well defined for analysis. It should be noted that this may take from days to weeks to achieve.

In some cases, a qualitative assessment of any hydraulic connection between the formation being tested and water-bearing formations above and/or below the formation being tested will be made. Should a hydraulic connection between water-bearing formations be identified through head responses to test pumping, the design and duration of the test may be modified in real-time to maximize the information obtained or additional testing may be scheduled at that location with modified test objectives. Pumping time may vary from 1–10 days depending on the local transmissivity of the formation of interest and/or the observed head response(s). Real-time analysis of the head data from the pumping and monitoring wells will be used by the facility to establish the time when the pump may be turned off.

Adjustments to downhole equipment that may create a change in the heads being recorded in each well should be avoided during the entire test. In the case that adjustments are required, the facility must record the time, the action, and the result of the equipment adjustment in a log book (Section 4.1.1) and in the aquifer test report.

After an adequate duration of the pumping phase has been achieved, the facility will proceed with the recovery phase of the pumping test.

5.3.3 Recovery Phase

Head measurements obtained during the recovery phase are of equal or greater importance than those collected during the pumping phase because unlike the pumping phase where variations in discharge rate can affect the observations, the recovery phase is not subject to induced variations and can provide more reliable information. Head measurements made during the recovery phase of the aquifer after the pump has been turned off should be taken at the same frequency as the drawdown measurements during the pumping phase (Section 4.1.2). If an SIT is used, it should be closed immediately before the pump is turned off, isolating the test interval from the riser pipe. A check valve must be used to prevent backflow of water in the riser pipe into the well, which could result in unreliable recovery data. Failure to install a functioning check valve and ensuring that the threads in the pump column piping do not leak may invalidate the recovery phase of the test (unless an SIT is used). During the recovery period, the pressure in the shut-in flow line will be measured, when possible, to verify that the check valve is not leaking. Additionally, all downhole equipment must remain in place and untouched until after the recovery phase is completed.

Real-time analysis of the head data from the pumping and monitoring wells will be used by the facility to establish the time when recovery monitoring will be terminated. Recovery monitoring will typically continue for a period that is at least twice that of the pumping duration.

5.4 Barometric Pressure Influences

Barometric pressure applies a load to the land surface as well as to the water surface in open wells (Toll and Rasmussen, 2007). Barometric pressure influence on measured heads in a facility's wells is highly site-specific and requires specific empirical knowledge. In the case that barometric pressure changes are significant during an aquifer test, compensation will be required for all head data collected during the test. While the facility must evaluate all the head data collected during all three phases of the test with concurrently collected barometric pressure for barometric compensation, it is first imperative that the facility engage in an empirical study on the effects that barometric pressure changes have on the heads in the wells to be included in the aquifer test.

Each well to be involved in the aquifer test should be instrumented with a pressure transducer programmed to take readings every hour while barometric pressure measurements are made at the same times. Measurements should be made over a period of 2-4 weeks (Toll and Rasmussen, 2007). At the end of this period, the head and barometric pressure data should be plotted, using the same units (e.g., psi or feet of water), in terms of *change* in head and barometric pressure from the initial values at a common time. When barometric pressure increases, groundwater levels decrease and vice versa (Rasmussen and Crawford, 1997), so that an inverse relationship and trend should be apparent in the plot.

The barometric efficiency (α) can be calculated using (Rasmussen and Crawford, 1997):

$$\alpha = \Delta \mathrm{W}/\Delta B$$

where:

$\Delta \mathrm{W}$ is the change in head due only to barometric pressure changes, and
ΔB is the barometric pressure change

Aquifer barometric efficiencies typically range from 20 and 70 percent (Todd and Mays, 2005). For head measurements made with vented transducers or by measuring water levels, a simple barometric compensation can be made using (Gonthier, 2007):

$$h(t)corr = h(t)uncorr - \alpha(B_0 - B(t))$$

where:

h(t)corr is the head, at time *t*, corrected for barometric pressure
h(t)uncorr is the uncorrected head, at time *t*
α is the barometric efficiency
(B_0– $B(t)$) is the barometric pressure *B(t)*, at time *t*, referenced to a barometric pressure datum B_0.

For head measurements made with non-vented transducers, the α term in the head-correction equation is replaced with (1-α) (Spane, 2002). More sophisticated barometric compensations that take the time lag of the response into account are described by Rasmussen and Crawford (1997), Spane (2002), and Toll and Rasmussen (2007), but this level of sophistication is not typically necessary.

If the use of an alternative compensation method to correct for barometric effects is presented, the method must be detailed in the work plan. The online application BETCO-2 (https://groundwater.app/app.php?app=betco2) can be used to remove barometric (and Earth tide) influences on measured heads in wells (Toll and Rasmussen, 2007).

5.5 On-Site Data Evaluation

During the field activities, the facility will evaluate the data in real time. The data will be diagnosed for any tool failure and/or procedure-induced effect that may affect the data quality. The facility will take immediate action (if required) to make any necessary changes to the equipment configuration or the procedures to assure the data quality is consistent with the objectives of these activities. Data associated with testing activities collected by facility contractors will be checked for accuracy and adequacy by the facility and documented in the logbook.This on-site real-time data evaluation will be documented in the logbook (Section 4.1.1).

During all aquifer testing activities, pressure-response data will be evaluated on a real-time basis by the facility to determine that the objectives of the test are being met and that the test proceeds in the most efficient and effective manner. Log-log diagnostic plots of the pressure change and pressure derivative (e.g., Ehlig-Economides, 1988; Bourdet et al., 1989; Ehlig-Economides et al., 1990; Horne, 1995; Renard et al., 2009) will be the primary method used to evaluate the progress of pumping tests as described in Section 6.1.2. Flow dimension diagnostic plots (Beauheim et al., 2004) may be used to provide information on how the flow regime is changing (e.g., when partial-penetration effects start to appear). Standard straight-line techniques may be employed to estimate T from sections of the data that the log-log derivative plot shows (by a stabilized derivative) were exhibiting infinite-acting radial flow (IARF).

Modifications to the test procedures in the work plan may be required during testing activities. If at any time the facility determines that an activity objective cannot be accomplished due to time constraints, problems concerning the performance of the equipment, or unsuitability of initial conditions, the test may be terminated, and all real-time evaluation of data will be recorded in the logbook (Section 4.1.1).

6 DATA DIAGNOSTICS AND ANALYSES

Head data collected from all aquifer tests shall be plotted with precipitation amounts, barometric pressure changes, and pump on/off times (if appropriate) in the form of a hydrograph for each well included in the study. This should be incorporated into a report submitted to HWB along with the analyses of the data.

Diagnostics shall be performed on the data sets that will be used to obtain aquifer parameters and to eliminate subjectiveness in “curve fitting” the solutions to the data. The original aquifer test analysis methods presented below considered only confined aquifers. However, these solutions have been modified to include options for unconfined and leaky confined aquifers. A good primer for applying the proper solution to data is illustrated in a flowchart provided by ASTM International (ASTM D4043).

6.1 Aquifer Test Analysis Software

Modern software has made manual type-curve methods of data analysis obsolete. It allows evaluation of multiple possible solutions with considerably less effort than manual approaches. Commercially available software that employs analytical solutions to interpret aquifer-test data includes AQTESOLV from HydroSOLVE, Inc. and AquiferTest from Waterloo Hydrogeologic. Numerous analytical solutions for both slug tests and pumping tests are available in these well-test codes, covering conditions such as wellbore storage, skin, partial penetration, leakage, and delayed yield. Analytical solutions should provide sufficient analysis for most situations and should provide, at a minimum, an initial evaluation in complex geological settings. However, in complex geological settings, such as those in which aquifer geometry varies, or where testing conditions are complex (e.g., multiple wells pumping at variable rates), analytical solutions may be inadequate. In this case, the facility should consider more sophisticated aquifer-test codes such as Saphir from KAPPA Engineering. Saphir provides data processing, diagnostics, and both analytical and numerical models to evaluate and analyze aquifer-test data. While most facilities would not need a code such as Saphir, facilities with complex geology or testing conditions could benefit from its use.

6.2 Slug Tests

Slug tests generally have a smaller radius of investigation than pumping tests because of their shorter duration. For partially penetrating wells, slug test results may, particularly at early time and/or where the ratio of vertical to horizontal hydraulic conductivity is low, represent only the screened portion of the aquifer (Lohman, 1972). Consequently, results from slug testing may not be representative of the entire aquifer thickness. Slug test data should undergo pre-analysis diagnostics to identify an appropriate interpretation model and prevent misinterpretation of the data that will result in unrepresentative results.

6.2.1 Diagnostics

Slug tests may be influenced by the presence of a near-wellbore “skin” of either higher (negative) or lower (positive) hydraulic conductivity than the surrounding undisturbed formation. Diagnostic methods to determine the presence and nature of a skin, including diagnostic derivative techniques, are described in

Ramey et al. (1975), Sageev (1986), Bouwer (1989), Ostrowski and Kloska (1989), Peres et al. (1989), Yang and Gates (1997), and Butler (2019). The facility should always use at least one of these diagnostic tools when analyzing slug test data.

6.2.2 Analysis

Two types of responses may result from conducting a slug test: overdamped and underdamped. The most common response is the overdamped response, which typically results in a linear or curvilinear pattern on a semi-log plot. This response typically lasts for several minutes in high-K formations to days in low-K formations after initiation of the test. Commonly used analytical solutions include Bouwer-Rice (1976) and Hvorslev (1951) for both confined and unconfined conditions and Cooper-Bredehoeft-Papadopulos (1967) and Ramey et al. (1975) for confined conditions. The Cooper-Bredehoeft-Papadopulos (1967) method assumes the absence of a skin, whereas Ramey et al. (1975) present a similar solution that allows for the presence of a skin, both positive and negative. Sageev (1986), Ostrowski and Kloska (1989), and Yang and Gates (1997) all build on the Ramey et al. (1975) solution.

The second and less common response is the underdamped response, which exhibits a characteristic oscillation in the data followed by a smoothing toward static. This response should be anticipated in high-K formations and may extend to only a few seconds after the test is initiated. Common solutions for the underdamped response include Butler (2019), Butler-Zhan (2004), and McElwee-Zenner (1998) for confined conditions and Springer-Gelhar (1991) for unconfined conditions. If high K is suspected, the facility should use the pneumatic slug test method discussed in Section 5.1.2.

In slug test analysis, it is common to normalize the data with respect to the initial slug magnitude before analysis to compare multiple datasets simultaneously, such as comparing slug in and slug out data, or to assess the effects of varying initial displacements.

6.3 Pumping Tests

Most analytical solutions applied to data obtained from pumping tests are based to some degree on the Theis Equation (Theis, 1935). The Theis Equation solves for drawdown at any point at any time in an aquifer due to groundwater withdrawal at a constant rate from a pumping well under idealized conditions. Many researchers have developed analytical solutions that are modifications or variations of the Theis Equation to account for specific conditions not considered by Theis, including:

1. Wellbore storage and skin (Agarwal et al., 1970; Gringarten et al., 1979)
2. Partial penetration (Hantush, 1961; Weeks, 1969)
3. Leakage from confining beds (Neuman and Witherspoon, 1972)
4. Delayed yield from an aquifer being dewatered (Neuman, 1972, 1975)
5. Anisotropy (Hantush, 1966; Grimestad, 1995)
6. Double porosity (Gringarten,1984; Moench, 1984)
7. Variable-rate pumping (Hantush, 1964; Trabuchi et al., 2018).
8. Addition of derivatives (Bourdet et al., 1989)

Most of these methods are included in modern well-test analysis software (Section 6.1). Use of diagnostic plots with derivatives is essential to determine what characteristics the pumping-test data are showing and to select an appropriate analysis model.

6.3.1 Diagnostics

The standard diagnostic plot for a pumping test is a log-log plot of the pressure change and derivative data from the pumping well (and observation well(s) if available) (Renard et al., 2009). The final report submitted after completion of the aquifer test must include the application of pressure derivative analysis must be made to demonstrate what aquifer characteristics were observed and how they were treated in analysis. By applying the derivative analysis to all pumping-test data, subjectiveness of fitting type curves to data is eliminated and the facility will be guided to the proper section of the test data to determine aquifer properties.

The pressure derivative is simply the first derivative of the plotted data (drawdown or recovery) with respect to log time and is easily calculated and plotted using commercially available software such as AQTESOLV (Section 6.1). Derivative analysis is mandatory for all drawdown data to provide a non-subjective identification of the drawdown data that reflect infinite-acting radial flow (IARF) and are therefore suitable for estimation of T. The derivative analysis provides information on the factors affecting the response with time, such as an initial unit slope on a log-log plot reflecting wellbore storage, followed by a hump that reflects skin effects, followed by the stabilized (constant derivative) period reflecting IARF, followed, in some cases, by deviations reflecting such factors as leakage, delayed yield, and/or boundaries. Partial-penetration effects can also be recognized in the pressure derivative. The stabilized (i.e., constant) derivative representing IARF is mathematically equivalent to the straight-line portion of the data on a semilog drawdown or recovery plot that can be used to calculate transmissivity and represents the period when the *u* value in the Theis well function *W(u)* is sufficiently small for semilog approximations to be valid. Ideally, a test should be run long enough for the stabilized derivative to persist over at least one log cycle of time. Transmissivity can be calculated directly from the value of the stabilized derivative (d) by (Renard et al., 2009):

$$T = \frac{Q}{4\pi d}$$

Log-log plots including the pressure derivative must also be prepared for all observation wells. The early-time response at an observation well will not show the initial unit slope indicative of wellbore storage observed for the pumping well but will have the shape of the line-source solution underlying Theis curves. The derivative will stabilize to a constant value when IARF applies to the observation well and only data from this period can be used in straight-line analyses.

To prepare a diagnostic plot for recovery data, superposition must be applied following the method of Agarwal (1980) or Bourdet et al. (1989) to produce a derivative that can be analyzed in the same way as a drawdown derivative.

The features observed in the pressure derivative, combined with knowledge of the local geological environment, should then guide the selection of the analysis model. For instance, the delayed yield derivative response is similar to the double-porosity derivative response in fractured aquifers—knowledge of the local geology should allow selection of the appropriate model. The analysis model selected should be no more complex than is indicated by the derivative.

6.3.2 Analysis

Pumping-test analysis typically involves what are known as type-curve methods, for which data are plotted in a log-log format, and straight-line methods, for which data are plotted in a semilog format with time and/or distance represented on the log axis. Both types of methods are included in modern well-test analysis software (Section 6.1).

6.3.2.1 Type-Curve Methods

Type-curve methods involve fitting the log-log data plot, including derivative data, to similarly plotted “type curves” representing analytically derived solutions for specified aquifer conditions. The coordinates of a “match point” taken at an arbitrary point on both plots with the data and type curve aligned can be used to infer hydraulic properties by substitution into the appropriate equations. Type-curve methods are available for leaky and nonleaky confined aquifers, unconfined aquifers with and without delayed yield, wells with wellbore storage and skin, and double-porosity aquifers.

6.3.2.2 Straight-Line Methods

Straight-line methods involve plotting drawdown or head on a linear y-axis versus elapsed time (or a superposition time function) or radial distance on a log x-axis. When the necessary conditions are met (discussed below), the data will plot on a straight line that can be used to estimate hydraulic properties.

For drawdown data, the method of Jacob (Cooper and Jacob, 1946) is typically used. For data from the pumping well or an observation well, drawdown is plotted against the log of elapsed time. At sufficient time for IARF to be established, the data will plot in a straight line that can be used to calculate T (and S in the case of an observation well). For data from multiple observation wells, the drawdown at a common time from all wells is plotted against the log of their radial distance from the pumping well. Provided that the time is sufficient for IARF to have been established at all the observation wells, the data should plot in a straight line that can be used to calculate T and S so long as at least one of the two following conditions is met:

1. The observation wells all lie on a line drawn from the pumping well
2. The aquifer is isotropic.

If the distance-drawdown data do not fall on a straight line, this is an indication that the aquifer is anisotropic or heterogeneous.

For recovery data, the Theis (1935) recovery method is typically used. In this case, recovery (or “residual drawdown”) data are plotted against the log of the time function *t/t′*, where:

t = time since pumping started

t' = time since pumping stopped

Elapsed time increases to the left on a Theis recovery plot using this time function. After the time at which the derivative indicates IARF has been reached, the data should plot on a straight line and the slope of this line, expressed as head change over one log cycle, is used to calculate T.

In the petroleum industry, the Theis recovery method is known as the Horner (1951) method. The only difference between the two is that in the Horner method, the y-axis is expressed as head rather than residual drawdown. The static formation head is then indicated by the head value obtained by extrapolating the straight line to the time function value of 1, representing infinite time. Whereas the recovery method of Theis (1935) applies only to the recovery following pumping at a single constant rate, the Horner (1951) method can be extended to the case of recovery following variable-rate pumping. The Horner time function divides the numerator in the Theis time function into two pieces, and is expressed as:

$$Horner\ time = \frac{t_p + \Delta t}{\Delta t}$$

where:

t_p = duration of pumping period
Δt = time since pumping stopped

For variable-rate pumping, a modified pumping duration is calculated as:

$$t_p{}^{*} = \frac{Q}{q_f}$$

where:

Q = total volume pumped
q_f = final pumping rate

The modified pumping duration is then used to calculate the Horner time.

The critical point that applies to all straight-line analyses is that flow must be in IARF for the data used in analysis to be valid, and this must be demonstrated by a derivative plot.

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8 APPENDIX A – FORMS

Pumping Test Data Collection Sheet

Date:	Site:	Well No.:
Type of Test:	Conducted By:	Well Name:
Observation Wells?	Weather:	Reference Pt.:
Distance of observation well (r) from pumped well (ft):		Ref. Pt. Elevation (MSL):
Equipment:		Page: of
Static Water Level (as measured from reference point):		

Time	**Time (t) since pumping began (min)**	**Depth to Water Level (ft)**	**Drawdown (ft)**	**t/r^2**	**Pumping Rate (Q) (gpm)**	**Comments**

Recovery Data Collection Sheet

Date:	Site:	Well No.:
Type of Test:	Conducted By:	Well Name:
Observation Wells?	Weather:	Reference Pt.:
Distance of observation well (r) from pumped well (ft):		Ref. Pt. Elevation (MSL):
Equipment:		Page: of
Static Water Level (as measured from reference point):		

Time	**Time (t) since pumping began (mins)**	**Time (t’) since pumping stopped (mins)**	**Depth to Water Level (ft)**	**t/t’**	**Residual Drawdown (ft)**	**Comments**