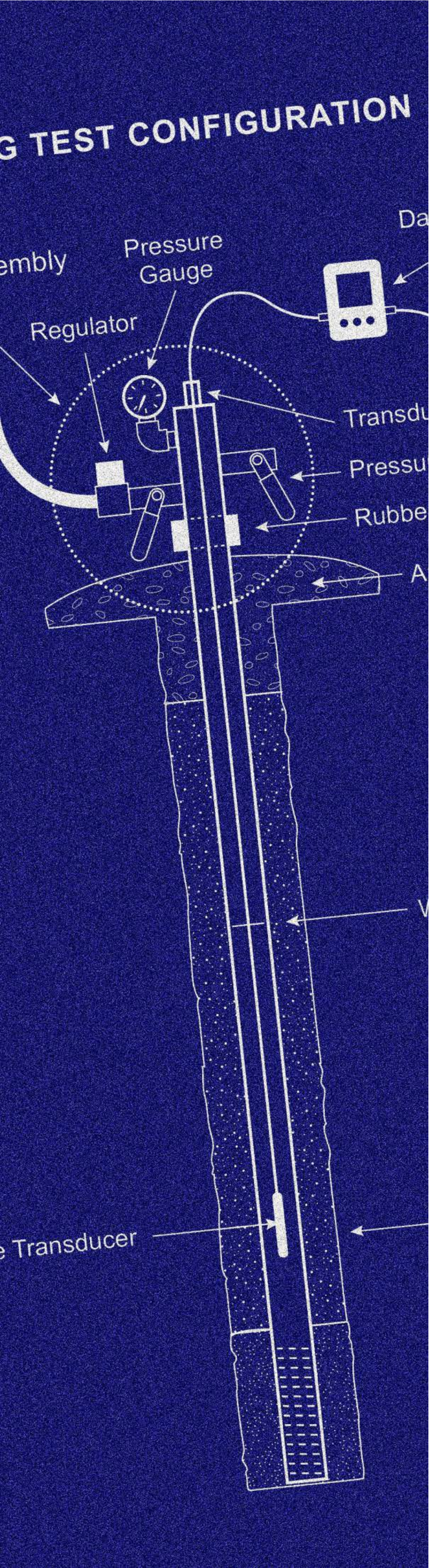

DEPARTMENT OF TOXIC SUBSTANCES CONTROL

CALIFORNIA ENVIRONMENTAL PROTECTION AGENCY

AQUIFER TESTING AT CONTAMINATED SITES

Final June 2015

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The California Environmental Protection Agency

Department of Toxic Substances Control
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Air Resources Board
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FOREWORD

The California Environmental Protection Agency (CalEPA) is charged with the responsibility of protecting public health and the environment. Within CalEPA, the Department of Toxic Substances Control (DTSC) has the responsibility of managing the state's hazardous waste and site cleanup programs. The State Water Resources Control (SWRCB) and the nine Regional Water Quality Control Boards (RWQCB's), also part of CalEPA, have the responsibility for coordination and control of water quality, including the protection of the beneficial uses of the waters of the state. Any unauthorized release of a substance, hazardous or not, that degrades or threatens to degrade water quality may require corrective action to protect the beneficial use of the waters of the state.

To aid in characterizing, remediating, and closing hazardous wastes/substances release sites (jointly referred to as contaminated sites in this document), DTSC has developed guidance documents for use by its staff and by other governmental agencies, responsible parties, and their contractors.
The Geological Services Branch (GSB) within DTSC provides geologic assistance, training, and guidance to fellow staff within the department.
This document has been prepared by GSB staff to provide guidance for the design, performance and reporting of aquifer tests at contaminated sites.

Guidance documents are posted at DTSC's website. For a general overview, please consult: *Guidelines for Planning and Implementing Groundwater Characterization of Contaminated Sites* (CalEPA, 2012) and *Preliminary Endangerment Assessment Guidance Manual (A guidance manual for evaluating hazardous substance release sites)* (CalEPA, 2013). Other CalEPA guidance documents pertinent to site investigation are listed in *10.0 References*.

This document supersedes the document, released by CalEPA in July 1995:

> *Aquifer Testing for Hydrogeologic Characterization,*
> *Guidance Manual for Groundwater Investigations.*

Comments and suggestions for improvement of *Aquifer Testing at Contaminated Sites* should be submitted to:

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This revised guidance relies heavily on the work of the authors of the original 1995 guidance document: Steve Belluomini, Bill Owen, Diane Nork, and John Woodling. Their contributions continue to be appreciated.

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DISCLAIMERS

This guidance document is intended to provide general information to assist with conducting aquifer tests. This guidance document is not legally binding.
The word “should” and other similar terms used in this guidance document are intended as general recommendations or suggestions that might be generally applicable or appropriate and should not be taken as providing legal, technical, financial, or other advice regarding a specific situation or set of circumstances.

This guidance document is not a rule, and it does not create new liabilities or limit or expand obligations under any federal, state, tribal, or local law. It is not intended to and does not create any substantive or procedural rights for any person at law or in equity.

This guidance document discusses other CalEPA guidance documents which may address the exercise of its enforcement discretion on a site-specific basis where appropriate. This guidance document does not address all the circumstances in which CalEPA may choose to exercise enforcement discretion with respect to a party under Resource Conservation and Recovery Act (RCRA) or CERCLA, nor does it cover all of the statutory or other protections that may be available to a party at contaminated or formerly contaminated property.
This guidance document does not modify or supersede any existing CalEPA guidance document or affect CalEPA’s enforcement discretion in any way.

Mention of trade names or commercial products does not constitute CalEPA endorsement or recommendation for use.

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ACRONYMS AND ABBREVIATIONS

ASTM	American Society of Testing and Materials
CalEPA	California Environmental Protection Agency
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act
cm	centimeter
CSM	Conceptual Site Model
DQO	Data Quality Objective
DTSC	Department of Toxic Substances Control
ft	foot
gpd	gallons per day
IDW	Investigation Derived Water
K	Hydraulic Conductivity
GSB	Geological Services Branch
QA/QC	Quality Assurance/Quality Control
RCRA	Resource Conservation and Recovery Act
RWQCB	Regional Water Quality Control Board
S	Storativity
SI	Système International
SWRCB	State Water Resources Control Board
Sy	Specific Yield
T	Transmissivity

1.0 INTRODUCTION

1.1 Purpose

This document provides guidelines for the application of aquifer tests in the characterization of contaminated sites. The purposes of this document are:

- To aid in the design and performance of aquifer tests;
- To provide recommendations for the evaluation of aquifer test data;
- To provide recommended quality assurance and quality control (QA/QC) procedures; and
- To present a standardized approach for the presentation of results.

1.2 Application

Aquifer[1] tests are investigative tools used to assess aquifer hydraulic characteristics that control groundwater flow and influence contaminant transport. These characteristics are used: to calculate groundwater velocities; to design groundwater cleanup remedies; and to model groundwater flow and contaminant transport.

This guidance does not address all conditions that may be present at contaminated sites. Instead, it is meant to provide stakeholders with a technically sound, general approach that will expedite regulatory review and approval of aquifer test work plans and associated reports.

1.3 Limitations

The recommendations presented here will assist stakeholders in obtaining usable data for making scientifically- and technically-supported interpretations. This document contains guidelines for conducting and interpreting aquifer tests at contaminated sites in California. It does not provide specific operating procedures for conducting aquifer tests or for interpreting the results. The licensed, qualified, professional in charge of the field investigation should specify methods, instruments, and operating procedures in an appropriate work plan, and document any significant departures from the work plan that were necessary during the course of the field investigation in the aquifer test report.

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[1] The term " 'aquifer" is technically constrained to water-bearing formations that are potential water resources. In this guidance "'aquifer'" refers to any water-bearing geologic formation

2.0 AQUIFER TESTS—GENERAL CONSIDERATIONS

Aquifer tests are used to assess the hydraulic characteristics of aquifers (i.e., water-bearing zones) and confining units in the subsurface. Slug tests measure local values of transmissivity. Aquifer pumping tests, in addition to transmissivity, can be used to calculate storativity (also known as storage coefficient) and identify potential boundary conditions (e.g., faults, streams, etc.) within the aquifer.

2.1 Conceptual Site Model

Establishing a conceptual site model (CSM) for the groundwater system at a site is a crucial element in the design, implementation, and interpretation of an aquifer test.

The CSM describes the current understanding of site hydrogeologic conditions that govern groundwater flow and contaminant transport. At a minimum, the following basic site information should be collected and reviewed in the development of the CSM (Figure 1):

Figure 1 - Conceptual Site Model

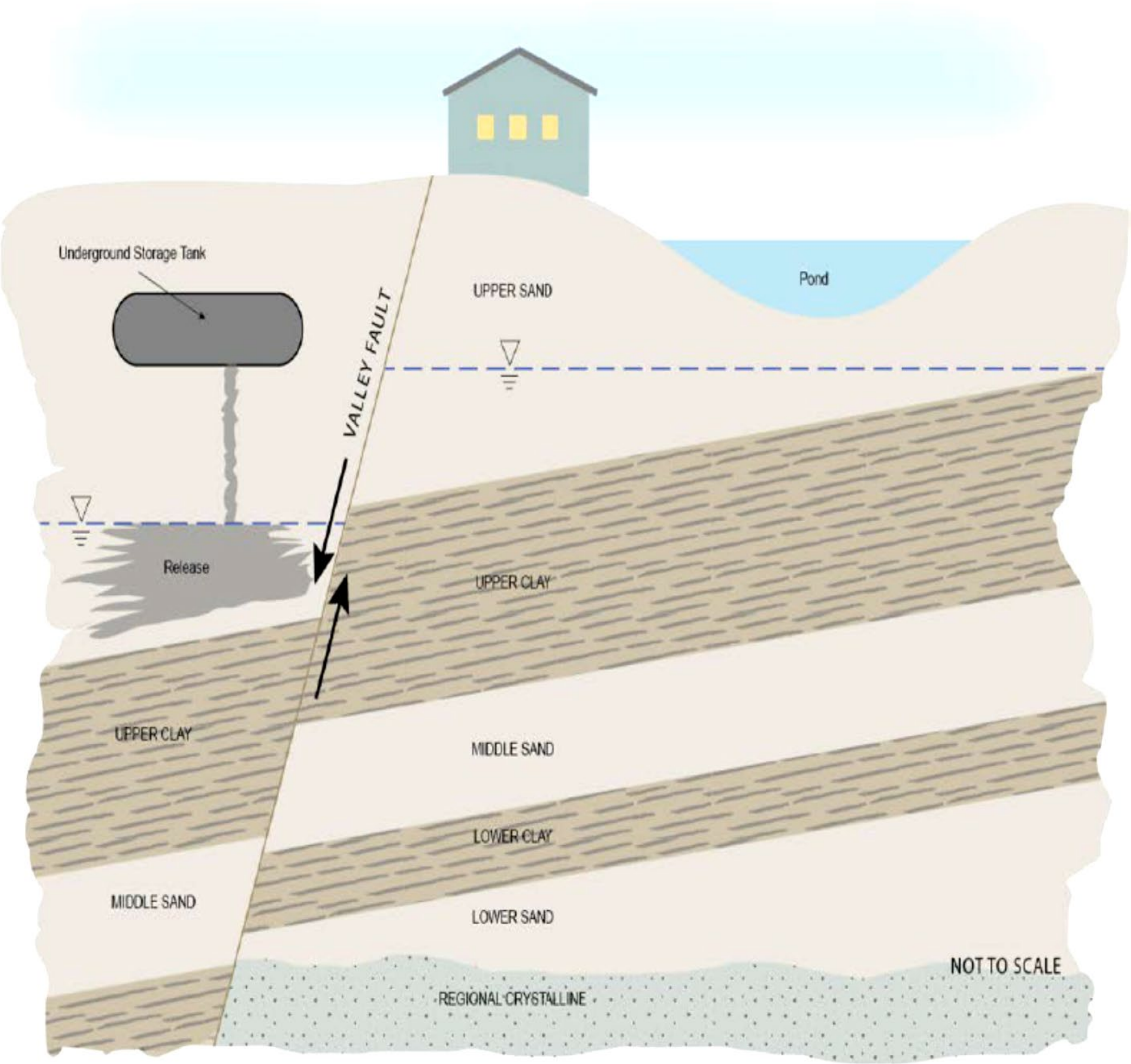

Figure 1: Conceptual Site Model

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- Geological structures, such as folds and faults and formational/facies changes;
- Geologic setting such as history of formation and major tectonic stresses;
- Topographic features such as: lakes, streams, bays, hills, depressions, and wetlands;
- Bedding orientation;
- Depth, thicknesses, and composition of water-bearing units;
- Depth, thickness, and composition of confining units;
- Groundwater elevations for each water-bearing unit;
- Groundwater flow directions and gradients;
- Water quality of the water-bearing units; and,
- Location of nearby pumping wells or recharge/collection ponds.

2.2 Data Quality Objectives

The data quality objectives (DQO's) process guides the design and implementation of the aquifer tests. The first step in the DQO process involves stating the problem and identifying decisions that need to be made to solve the problem. These steps guide the aquifer test by identifying which aquifer characteristics need to be determined and by specifying the appropriate type, quantity, and quality of data to be collected.

Specific DQO's relate to: acquiring in-situ measurements of hydraulic properties (e.g., transmissivity and storativity); identifying hydraulic boundaries; identifying preferential flow or contaminant pathways; assessing the nature of the anisotropy and heterogeneity of the groundwater system; identifying the occurrence and permeability of confining units; and assessing factors affecting well efficiency. The DQO process for contaminated sites is described in California Environmental Agency (CalEPA) guidance (CalEPA, 2012).

2.3 Work Plan

Prior to conducting any site characterization activities, a work plan describing the proposed activities should be submitted to DTSC for approval before implementation. The aquifer test work plan should include the CSM and the DQO's that are the basis for the aquifer test. The work plan should contain a comprehensive discussion of the aquifer test design, the implementation of the test, and the proposed approach to evaluating the test data. Figures and tables which illustrate and support the CSM should be included in the work plan. Figures which show the locations of the proposed pumping and observation wells in plan view and cross-section along with important site features that may impact the test should also be included in the work plan (Figure 2). Additional elements of a work plan are discussed throughout this guidance.

Figure 2 - Simple Site Map and Cross Section

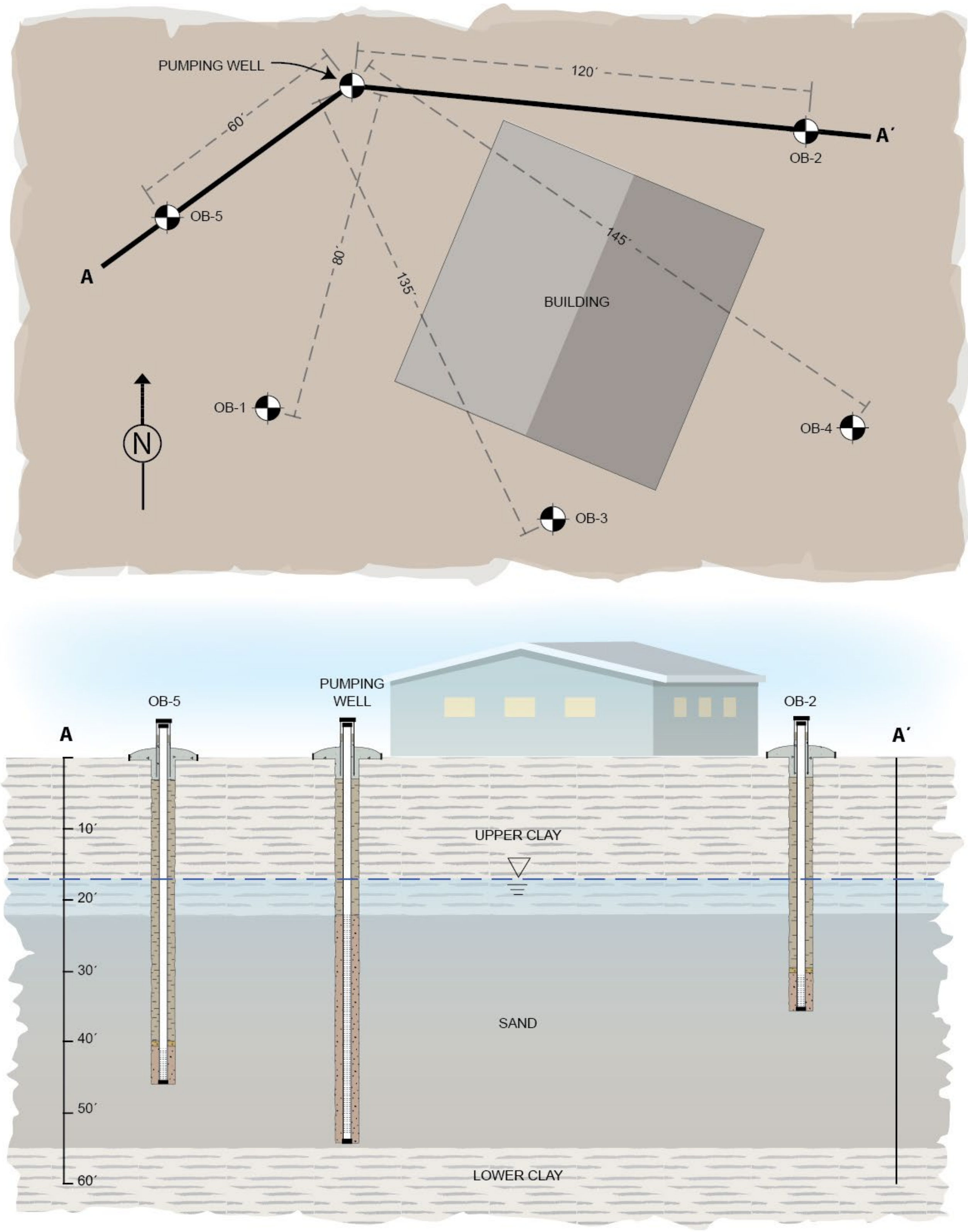

Figure 2: Simple Site Map and Cross-Section

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3.0 TYPES OF AQUIFER TESTS[2]

There are two broad categories of aquifer testing addressed by this guidance: aquifer pumping tests and slug tests.

3.1 Aquifer Pumping Tests

Aquifer pumping tests consists of pumping water out of a well and measuring the changes in water levels in the pumping well and/or observations wells. Aquifer pumping tests can involve either a single well or multiple wells.

There are three types of the aquifer pumping tests:

- Constant rate test, where the pumping rate is constant;
- Step-drawdown test, where the pumping rate is increased in several "steps" during the course of the test; and,
- Constant head test, where the pumping rate is varied to maintain a constant groundwater elevation (i.e. head) in the pumping well.

Information regarding aquifer pumping tests is contained in Sections 4 through 6 of this guidance. Recovery tests can be conducted in conjunction with the constant rate test (see Section 5.1.3).

3.2 Slug Tests

A slug test is a test in which a sudden rise or fall in the water level is created in a single well and the subsequent water level response (displacement or change from static) is measured over time in the well. Slug tests are frequently designated as rising-head or falling-head tests to describe water level recovery in the well following test initiation.

Information regarding slug tests is contained in Sections 7 to 9 of this guidance.

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[2] For this guidance, the term "aquifer tests" refers to the various test methods to collect data regarding the aquifer. In several publications, this term "aquifer test" is limited to tests using a pumping well to stress the aquifer with observation wells to monitor drawdown over time.

4.0 DESIGN OF AQUIFER PUMPING TESTS

An aquifer pumping test consists of pumping water from a well and observing water level changes in the pumping well and surrounding observation wells. When the pumping is done and the pump is shut off, water levels continue to be monitored as they return to pre-test conditions.

Pumping a well causes water levels to decline in one or more nearby wells (called “observation wells”). Water level declines (called “drawdown”) are measured at specific timed intervals in the pumped well and in observation wells using automated sensors (e.g., pressure transducers) or manual water level sounders. Pumping rates, timed intervals, and drawdowns are used to calculate the hydraulic properties of the aquifer: transmissivity (T), hydraulic conductivity (K), and storativity (S) or specific yield (S_y). In addition, aquifer pumping tests can be designed to assess the possible influence of hydrologic boundaries, aquifer heterogeneities, and groundwater flow anisotropy. Calculation of hydraulic parameters requires the selection of a mathematical model of flow that is consistent with the CSM.

4.1 Configuration and Logistics of the Aquifer Pumping Test

The well configuration and design of the aquifer pumping test affect the quality of data obtained during the test and the reliability of the data analysis. The practical restrictions of the test site as well as the constraints imposed by assumptions of the equations used for data analysis should be assessed.

At a minimum, the following considerations should be incorporated into the aquifer test design:

- The representativeness of the hydrogeologic conditions of the aquifer test area with respect to the area of interest, if different in location and/or scale;
- Nearby pumping/injection, railroads, highways, or other areas or conditions that could produce irregular water level fluctuations in wells;
- Suspected or known hydrogeologic boundaries such as faults, streams, springs, etc;
- Any suspected anisotropy or heterogeneity in the aquifer based on site-specific data or geologic history (e.g., depositional, tectonic, etc.);

- The hydraulic gradient of the water table or piezometric surface in the test area;
- The management of pumped water to prevent recharging the zones being pumped; and
- The nature and extent of contamination. Selection of pumping rates, test duration, and locations of pumping and observation wells should minimize the potential spreading of contaminants during the test.

4.2 The Pumping Well

The following guidelines represent considerations for wells used as pumping wells during an aquifer pumping test were modified from Kruseman and de Ridder (2000) and Sterrett (2007).

4.2.1 Well Diameter

The casing diameter of the pumping well should accommodate an appropriately-sized pump and be large enough to allow for adequate well development.

Generally, pumping wells that are smaller than four inches in diameter can be difficult to use as aquifer test pumping wells. This is because smaller wells are more difficult to develop, produce less water, have lower well efficiency, and can have a strong skin effect (i.e., changes in the permeability in and near the well boring due to drilling activities).

4.2.2 Well Depth and Screen Length

Optimally, pumping and observation wells should be screened across the entire thickness of the aquifer and would then be referred to as “fully-penetrating” wells. However, due to site specific conditions, this is often not practical.

If fully-penetrating wells cannot be used, the design, implementation, and evaluation of the aquifer test must take into account using partially-penetrating wells (i.e., wells not fully screened across the aquifer). Wells in areas of contamination should be designed and constructed to minimize the potential for the well to act as a conduit and facilitate the spreading of contaminants.

4.2.3 Screen Slot and Filter Pack Size

The screen slot size and filter pack material should be designed to maximize the hydraulic communication between the pumping well and the aquifer and to minimize skin effect. Screen materials should be able to resist pumping stresses without deformation. In competent bedrock, a screen and filter pack may not be necessary.

The rationale for well construction and design, along with a proposed well construction diagram should be included in the aquifer test work plan.

Well construction diagrams for new or existing wells proposed to be used as pumping or observations wells during the aquifer pumping test should be included in the aquifer test work plan and report.

Detailed discussion on design and construction of pumping wells can be found in Sterrett (2007).

4.2.4 Pumping Rate

Aquifer properties are measured by stressing the aquifer through withdrawing water and measuring the resultant water level response over time. The maximum practical pumping rate is typically selected based on step-drawdown tests conducted before the constant rate aquifer pumping test begins.

Step-Drawdown Test

- A step-drawdown test, using at least three successively greater pumping rates, should be performed before commencement of the constant rate test in order to establish an optimum pumping rate for testing hydraulic properties of the aquifer (and confining beds, where applicable).
- The duration of pumping for the step-drawdown test should be the same for each step.
- To prevent dewatering the well during the step-drawdown test, water levels should be monitored carefully throughout the test. This is particularly true in the presence of vertically and/or laterally constrained formations which may dewater rapidly.

Groundwater elevation versus time should be plotted on the same data plot for all pumping steps and should be presented in the aquifer test report. A discussion in the report should explain how the step-drawdown test results support the selected pumping rate for the constant rate test.

Further information on step-drawdown tests are available in Kasenow (1996), Batu (1998), Kruseman and de Ridder (2000), and Sterrett (2007).

Other Considerations

- To check whether the selected pumping rate for the constant rate test should produce measurable drawdown at observation wells, drawdown can be calculated for the pumping wells and observation wells using estimates of transmissivity (T) and storativity (S) from the step-drawdown test.
- Sufficient time should be allowed for water levels to return to static conditions after the step-drawdown test: usually a minimum of 24 hours. The time necessary for the recovery of water levels should be recorded.
- The pumping rate, when possible, should be significant enough to cause drawdown at observation wells that can be clearly distinguished from variations in water levels influenced by external factors (e.g., barometric pressure, earth tides, regional pumping effects, and evapotranspiration).

4.2.5 Pump Operation

At a minimum, the pump should be operated pursuant to the following recommendations.

- The pump and power supply should be capable of operating continuously at the specified constant and/or variable discharge rate(s) for the expected duration of the aquifer test. The discharge rate(s) should include a factor of safety to prevent premature termination of the test by unexpected excessive drawdown during the test.

- Prior to the start of the test, a range of conditions should be considered that may affect the response of the aquifer. Aquifer conditions that may require unscheduled adjustments to the pumping rate and duration include: spatial changes in the aquifer properties and the presence of previously unidentified boundaries.
- The pump must have an operable check valve that prevents water from flowing back into the well and corrupting water level recovery data after pumping is stopped. Recovery data can also be compromised if the pump is removed before groundwater water level recovery is complete.

4.2.6 Management and Disposal of Pumped Water

Aquifer tests at contaminated sites entail handling and storing large volumes of potentially contaminated water (i.e., investigation-derived waste, or IDW). Before aquifer testing begins, the volume of water expected to be extracted during the test should be calculated, based on a reasonable estimate of the pumping rates and the durations of both the step-drawdown test and the constant rate test. This volume can be used to requisition appropriate containers for IDW.

IDW must be analyzed prior to transportation to an appropriate disposal facility, including a publicly-owned treatment works, if applicable.

The work plan should describe how IDW will be managed in accordance with applicable laws and regulations.

4.3 Observation Wells

An important task in the design of the aquifer pumping test is determining the number, design, and locations of observation wells.

4.3.1 Number of Observation Wells

The appropriate number of observation wells for an aquifer test varies with the complexity of the hydrogeology at the site and the specific DQO's for the aquifer pumping tests. A minimum of three observation wells should be used for monitoring drawdown throughout the duration of the aquifer test.

Additional wells will likely be needed to assess: anisotropy, heterogeneity, boundary conditions, response in adjacent water-bearing zones, or other geologic or hydrogeologic conditions.

An additional observation well located outside the anticipated area of influence of the aquifer pumping test is recommended to monitor baseline/background water level fluctuations and any fluctuations due to unanticipated events which may affect the quality of the data collected. Data collected from this type of baseline well can be used to correct the data collected at other observations wells, from external influences.

4.3.2 Distance of the Observation Wells from the Pumping Well

A rationale for observation well locations should be included in the aquifer test work plan. Observation wells may be situated to assess aquifer hydraulics, confining unit hydraulics, or both. At a minimum, the following parameters should be considered before determining the placement of observation wells:

- Hydrostratigraphy or bedrock structure of the hydraulically influenced formations;
- The predicted radius of influence during the aquifer pumping test based upon estimated transmissivity and storativity;
- Vertical and lateral heterogeneities; and
- Principal directions of anisotropy, if known.

If anisotropy is suspected, observation wells should be located to assess its effects. A discussion addressing the placement of observation wells with respect to the pumping well, directions of anisotropy, and other features should be included in the work plan and in the aquifer test report.

If the pumping well or observations wells are partially-penetrating, observation wells should be located at a distance greater than 1.5 to 2 times the aquifer thickness from the pumping well. The effects of the partial penetration have been shown to be negligible at these distances (Butler, 1957).

4.3.3 Design and Construction of the Observation Wells

Observation wells must be designed, constructed, and developed to respond efficiently to the water level changes that occur during an aquifer test. Acceptable construction and development techniques for environmental monitoring wells are described in *Well Design and Construction for Monitoring Groundwater at Contaminated Site*s (CalEPA, 2014). The following guidelines represent minimum requirements for wells used as observation wells during an aquifer test.

Observation Well Diameters

The diameters of observation wells should be large enough to accommodate the water level monitoring devices to be used throughout the aquifer test. Well diameters should also be large enough for the wells to be adequately developed, ensuring hydraulic communication with the aquifer.

Lengths and Locations of Well Screens

The observation wells should have screened intervals of approximately the same length and at the same depth as the pumping well. Wells at contaminated sites may need to be constructed with shallow, partially- penetrating well screens to minimize or avoid vertical flow within the well and potential cross-contamination between zones.

If the test evaluates different hydraulic zones, the work plan and aquifer test report should clearly discuss the intent of the test with respect to each zone and specify how each zone will be monitored during the test. Justifications for the lengths and locations of screens are critical elements of the aquifer test design and should be included in the work plan and the aquifer test report. The justifications should involve: geologic cross-sections, lithologic logs, and well construction diagrams for observation wells.

The work plan and aquifer test report should contain a map and cross- section indicating the locations of observation wells with respect to the pumping well (Figure 2). Well construction diagrams for new or existing wells proposed to be used as observations wells during the aquifer pumping test should also be included in the aquifer test work plan and report. A table showing well construction details (e.g., total depths, screened intervals, etc.) and distances from the pumping well should be included.

5.0 PERFORMING AQUIFER PUMPING TESTS

The properties of the aquifer are estimated by evaluating the aquifer's response, in the form of water level changes, to the stress applied by pumping. Therefore, water levels and pumping rates are critical data needed for determination of aquifer properties.

5.1 Water Level Measurements

5.1.1 Water Level Measurements Before the Aquifer Test

Water level data should be collected before the aquifer pumping test to identify any trends in the water level data resulting from cyclic variations caused by barometric pressure, transpiration, earth tides, and nearby pumping. Understanding these trends will assist in data analysis. Ideally, an aquifer test should be conducted when background/baseline water level trends are understood and are expected to remain relatively constant. The aquifer test report should address the nature, magnitude, and frequency of any water level trends found during the aquifer test (Kruseman and de Ridder, 2000).

For sites in tidally-influenced aquifers, a representative tide cycle should be recorded for the water body itself and for the zones of interest that are affected by tides.

To identify these cyclic and noncyclic trends, the guidelines below should be followed.

- Water levels in each zone of interest should be measured and recorded for at least two days before starting the pumping phase of the aquifer test.
- Barometric pressure should be monitored and recorded for at least two days before the test starts and during the pumping phase of the aquifer test.
- Discharge rates of nearby pumping wells should be recorded for at least two days (preferably one or more weeks) before starting the pumping phase of the aquifer test.

- In the aquifer test report, water level data and barometric data should be presented in tabular form and on charts, accompanied by a discussion describing barometric pressure effects on water levels. Similarly, effects of nearby pumping wells on water levels should be evaluated and discussed.

5.1.2 Water Level Measurements During the Aquifer Test

Water level measurements must be taken continuously during an aquifer test and should be measured and recorded as accurately as practicable. The use of water level pressure transducers and automated data recorders are highly recommended. A one-minute minimum frequency for water level measurements is typical and more frequent measurements may be warranted at the beginning of the aquifer pumping test and at the beginning of the recovery phase of the test. Water level transducers and data recorders must be synchronized so that each measurement can be referenced to the exact time pumping started (Sterrett, 2007). Copies of all field data sheets or transducer records should be provided in the aquifer test report.

The reporting of water level measurements should include the following:

- Date and time the aquifer test began;
- Initial and final water levels for the pumping phase;
- Time since pumping started (in minutes);
- Measured depths to water; and
- Any unusual events (e.g., stopping of the pump, changes in discharge rate, changing weather patterns, passage of a train, or operation of heavy machinery).

For aquifer pumping tests with multiple observation wells, electronic water level records should be accompanied by a manually-measured record to verify the proper function of electronic water level measurement and recording systems. This may not be possible for single-well tests with transducers in the sounding tube, because of the difficulty of measuring water levels affected by the operation of the pumping well.

A description of all water level measuring devices (e.g., manufacturers and models) should be noted in the aquifer test report. Operators' names should be included in field notes. If various devices yield different water levels for simultaneous measurements in the same well, a discussion addressing the discrepancy should be provided in the report.

Whenever transducers are used to monitor water levels, transducers with appropriate ranges (with safety factors) should be selected, in accordance with manufacturer's recommendations. A discussion should be provided in the work plan and aquifer test report describing the technical specifications of the transducer(s) for measuring the appropriate pressure ranges (when converted to feet or meters of water).

Transducers should be field-calibrated to manual water level measurements before the aquifer test begins.
Periodic re-calibration should be performed during pumping, if possible, to monitor electronic drift. Calibration should be checked after the recovery phase of the test, to check for and, if necessary, document any drift or transducer malfunction.
In addition, it is advisable to test the stability of transducers prior to using them by placing the units in a container of water for a period of at least one day. The work plan and aquifer test report should contain a description of transducer calibration procedures and the results should be included in the aquifer test report. See Section 8.3 for additional discussion regarding calibration of transducers.

Two types of transducers are available: non-vented and vented. Non-vented transducers measure the pressure due to both hydraulic head and barometric pressure. Data from non-vented transducers, therefore, need to be corrected for barometric pressure prior to data analysis. Vented transducers have a vented tube from the transducer to the surface which cancels out the barometric pressure leaving only the pressure associated with hydraulic head being recorded. Vent tubes must be kept clean and dry throughout the test.

5.1.3 Water Level Measurements During the Recovery Phase of the Aquifer Test

After the pumping phase of the aquifer test is complete, water levels in the pumped well and observation wells will begin to rise: this is the recovery phase of the aquifer test.
Water levels should be monitored during the recovery phase of the aquifer test with the same frequency used during the pumping phase, with an increased frequency of measurements at the beginning of the recovery test. At a minimum, the following information should be provided in tabular form for the recovery test:

- Date and time the pumping phase ended, and the recovery phase began;
- Recorded water levels for the recovery phase;
- Time since pumping stopped (in minutes);
- Measured water levels;
- Residual drawdown; and
- Descriptions and records of any noteworthy occurrences.

Calculation of hydraulic properties based on the analysis of recovery data should be used in conjunction with calculations obtained from the pumping phase of the test. It should be noted that data from both the pumping and recovery phases should be plotted together on the same plot.

Recovery data can be more reliable than data from the pumping phase because recovery data are not affected by irregular fluctuations in the pumping rate, turbulence in the pumping well, and pumping wellbore storage effects.

As with the early portions of the pumping phase in which water levels drop rapidly, water levels rise rapidly during early portions of the recovery phase and are followed by a decreasing rate of water level rise.

Therefore, as stated above, it is important to collect water level data at higher frequencies during the initial portions of the recovery phase (Kruseman and de Ridder, 2000).

5.2 Discharge Rate Measurements

The analytical methods for constant-rate aquifer tests assume a constant discharge rate is held during the test. As stated above in Section 4.2.5, it is important that the appropriate pump be selected to ensure that the discharge remains constant as the discharge head increases. Pump suppliers can generally suggest the best pump for the set of conditions anticipated during the test. Variations in the discharge rate are a major cause of erratic drawdown data for constant rate tests (Sterrett, 2007).

Many references discussing various means for measuring discharge rates are available (Kruseman and de Ridder, 2000 and Sterrett, 2007). Discharge rate measurement techniques generally consist of inline instantaneous flow meters, inline flow totalizers, or a container of known volume and a stop watch. The discharge rate should be measured and recorded at least once every ten minutes during the aquifer test to confirm that the rate is relatively constant for a constant rate test.

Measurements should be collected when the flow rate is adjusted and, as necessary, during a constant head test or step-drawdown test. Any flow rate adjustments should be noted along with the time of adjustment and measured flow rate before and after adjustment.

Flow rate meters should be verified to be accurate in the field by recording the time required to fill a container of known size and calculating the rate. If the pump rate changes more than a significant amount during the constant rate test, the changes must be accounted for during data analysis and considered during the selection of the appropriate analytical solution. Analyzing only the recovery portion is not a substitute for not correcting the drawdown data for changes in pumping rate. The pumping and recovery phase can show slightly different responses to the stress on the aquifer and provide insight into the nature of the aquifer.

5.3 Consideration of Additional Influences

Drawdown values measured during an aquifer test may be influenced by external factors. In addition to tidal influences and barometric pressure, examples of these external influences may include: recharge to or discharge from the zones of interest, evapotranspiration, earth tides, pumping from wells in the general area, and water level fluctuations caused by heavy traffic, an earthquake or sudden, heavy precipitation.

Some external factors can be removed from water level data while other influences may be significant enough to make the aquifer pumping test data unusable. As previously recommended in Section 4.3.1, data from an observation well which is located outside the influence of the aquifer pumping test can be used to correct the aquifer test data which has been affected by external influences.

Because an aquifer test is conducted to measure the hydraulic properties of a zone (or zones) that is solely impacted by the force of pumping, the following guidelines should be adhered to in order to assess the impact of additional external factors on the data obtained during an aquifer test.

- A barometer and/or a barograph should be used to monitor barometric pressure during the aquifer test.
- If external influences are identified, the aquifer test report should contain a discussion addressing the consequent impact on hydraulic parameter calculations and, if applicable, a rationale for correcting the drawdown data for the external influences.
- The run-times and well discharge rates should be recorded for any nearby pumping wells.
- The nature and time of any weather changes should be recorded in the field and should be discussed in the aquifer test report.

Originals or copies of all field data sheets should be provided in the aquifer test report.

5.4 Duration of the Aquifer Test

Aquifer tests should last long enough to establish the types of aquifer response and to collect sufficient data to calculate transmissivity and storativity values. Ideally, aquifer tests should be continued until equilibrium is reached and no significant further drawdown occurs.

The length of an aquifer test should be based on at least the following considerations:

- Geologic composition of the zones of interest;
- Hydrogeologic nature of the zones of interest (i.e., confined or unconfined);
- Existence of a suspected or known boundary and its impact on the movement of groundwater and contaminants at the test site; and,
- Other aquifer tests performed nearby in the same aquifer zone.

In heterogeneous aquifers, high conductivity zones of limited extent may produce temporary flattening of drawdown curves that may be mistakenly interpreted as reaching equilibrium. The complexity of the hydrogeology should always be considered when evaluating the data and care should be taken not to terminate pumping prematurely.

It generally takes unconfined aquifers longer to reach steady state than confined aquifers. Therefore, aquifer tests conducted in unconfined aquifers should be run longer than confined aquifer tests. It should also be noted that unconfined aquifers produce drawdown curves with three recognized segments. These segments result in a S-shaped curve with a steep early-time segment, a flat intermediate-time segment, and a relatively steep late-time segment. The intermediate-time curve can be misinterpreted as the aquifer test approaching equilibrium if the test is not conducted long enough and the nature of the aquifer is not well understood.
When conducting an aquifer pumping test for an unconfined aquifer, these three segments should be identified in the data before pumping is ceased.

The actual length of the aquifer test necessary to define the hydraulic properties of specific zones at a particular contaminated site depends on the specific aquifer. If the aquifer pumping test does not continue long enough, the resulting limited data set may not indicate the true nature of the zones of interest (Sterrett, 2007). The length of the aquifer test should be described in the aquifer test work plan and report, and the report should describe the effect of the test length on the accuracy of the calculated aquifer parameters.

Viewing drawdown data plots during the test may be useful for identifying anomalies, heterogeneities, and hydraulic boundaries and for tracking the progress of the test.

5.5 Decontamination of Equipment

The procedures for decontaminating equipment used in aquifer tests conducted at contaminated sites should be presented in the work plan and aquifer test report.

6.0 AQUIFER PUMPING TEST DATA ANALYSIS AND INTERPRETATION

6.1 Compilation and Presentation of Data

Data presentation should clearly identify the methods and rationale used in analysis of the aquifer test data. Additionally, all data necessary to conduct an independent regulatory review and analysis should be presented in the report and should be submitted in electronic form.

6.1.1 Consistency of Units of Measurement

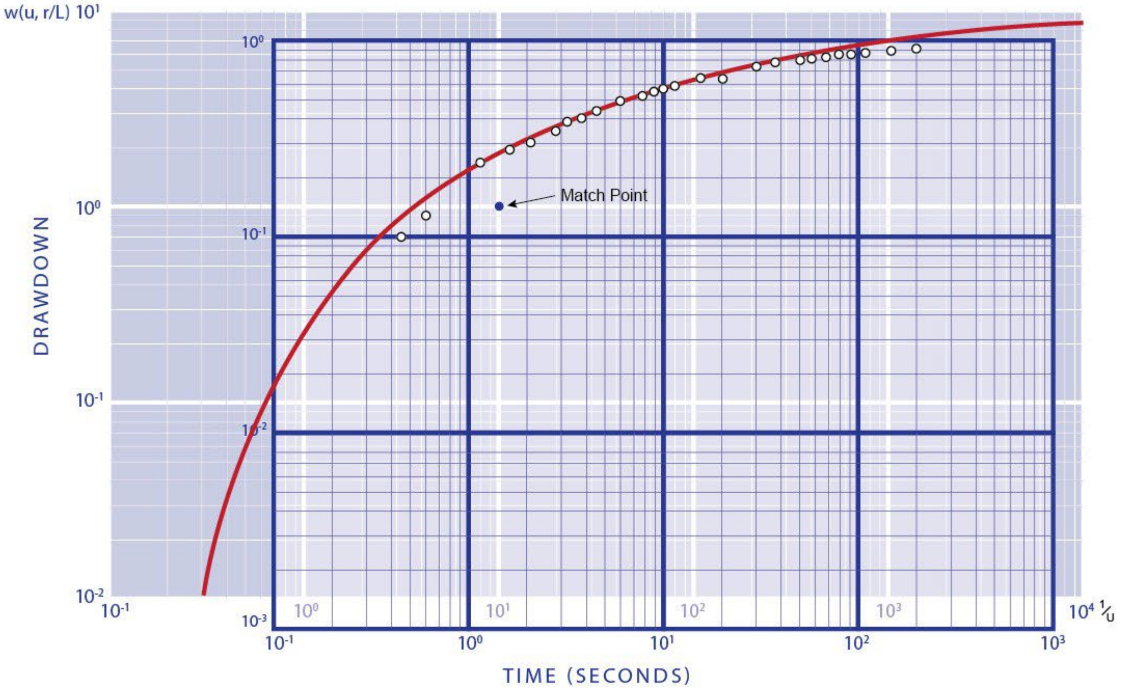
To avoid unit conversion errors: all time data should be converted to a single set of units (minutes); all water level data should be converted to values of drawdown; and, all water level and discharge rate data should be expressed in consistent English units (e.g., inch-pound) or Système International d'Unités (i.e., SI metric units). The results can be presented in a variety of customary or consistent units (gallons per day (gpd)/foot (ft), ft/day, centimeter (cm)/sec) as appropriate for the project. The significant figures presented should be consistent with the instrument precision (typically, a hundredth of a foot).

6.1.2 Presentation of Data

Time, drawdown, and distance information should be presented in the form of graphical plots. These graphical plots are necessary for any further analysis because calculation of hydraulic properties and characterization of the hydrogeologic regime is most easily interpreted through analysis of the shapes of data arrays on the plots. Whether the plots are compiled by hand or generated by computer programs, the following guidelines should be met for aquifer test data presentation.

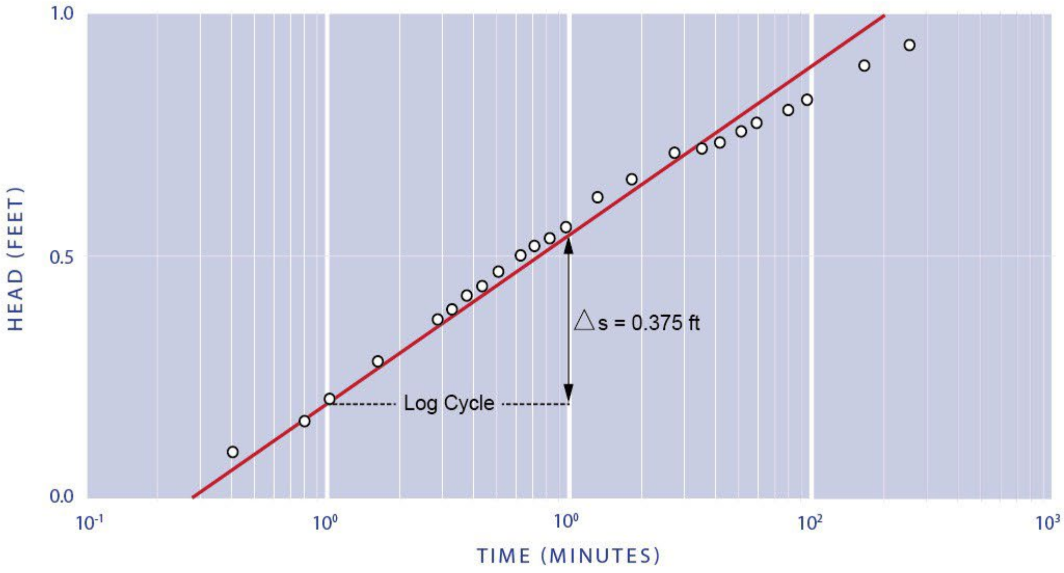
Note: Plots of drawdown versus time, depending on the data analysis methods employed, should be presented for the pumping well and for each observation well on double-logarithmic and/or semi- logarithmic paper (Figure 3).

Figure 3 – Aquifer Pumping Test Plots



Theis Curve Matching Solution

(DOUBLE LOGARITHMIC PLOT)



Cooper-Jacob Solution

(SEMI-LOGARITHMIC PLOT)

Figure 3: Aquifer Pumping Test Plots

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- The time of any adjustments in the flow rate should be noted on the graph.

- Time data (in minutes) should be depicted along the horizontal axis, and drawdown should be depicted along the vertical axis.

- For semi-logarithmic plots, drawdown should be presented along the vertical arithmetic axis.

- The horizontal scale should be the same for all data plots.

- Plots of drawdown versus distance from the pumping well should be presented. Calculations of hydraulic properties based on these plots should be used to corroborate calculations based on drawdown versus time plots.

- If drawdown data need adjustment due to external influences or because of gradual reduction in saturated thickness, separate plots depicting both adjusted and unadjusted drawdown versus time and drawdown versus distance should be presented for the appropriate wells. Any plots, graphs, or equations used to determine the magnitude of drawdown adjustment should also be presented.

- If only a portion of the data curve is being used to calculate aquifer parameters, the portion used for curve fitting should be clearly marked. For example, if the early data shows a skin effect, then the early data may be excluded from the region of the fit. If the late data show a boundary, then the fit should be made before the boundary becomes evident.

- Plots of residual drawdown versus time since pumping stopped should be presented for recovery data. If a well under-recovers or over-recovers, this information should be noted.

- Plots of discharge rate versus time should be presented.

- All plots should be clearly labeled. In the event that more than one water level measuring device was used for the same well or, if data from multiple wells are presented on the same plot, the labeling and/or color coding should enable differentiation between sets of data and should be identified in a legend. Symbols should not be so large that they obscure pertinent data.
- All data plots should be included in the aquifer test report.

6.2 Selection of Analytical Solutions

Many analytical solutions are available for interpreting aquifer pumping test data. The assumptions incorporated within each solution must be evaluated with respect to consistency with site conditions including: the type of pumping and observation wells (fully- or partially-penetrating); the pumping rate (constant versus variable); and aquifer conditions (confined or unconfined, fractured or porous).

Most analytical solutions for groundwater flow through porous media assume that flow generally conforms to the Theis assumptions, but meeting all of these assumptions is rare in practice, particularly at contaminated sites where only a portion of an aquifer is typically being studied. Breach of an individual assumption included in an analytical solution (e.g., fully-penetrating well, homogenous and isotropic media, horizontal flow to the well, instantaneous response, aquifer is infinite in extent, etc.) may not preclude its use. However, the potential effects of not satisfying an assumption must be assessed and clearly documented. The final selection of an analytical solution is, therefore, an iterative process between assessing curve fit (for various solutions) and evaluating assumptions in relation to site conditions.

Common analytical solutions for analyzing aquifer test data, along with their underlying assumptions, are as follows:

- Theim (1906): confined, steady-state solution for fully-penetrating wells;
- Theis (1935): confined, transient solution for fully-penetrating wells;
- Cooper and Jacob (1946): confined, transient solution for fully-penetrating wells;

- Hantush and Jacob (1955): confined, transient solution for fully-penetrating wells with aquitard leakage;
- Hantush (1964): confined, transient solution for partially-penetrating wells;
- Papadopulos and Cooper (1967): confined, transient solution for fully-penetrating wells with wellbore storage;
- Moench and Prickett (1972): confined and unconfined, transient solution for fully-penetrating wells; and,
- Neuman (1974): unconfined, transient solution for partially-penetrating wells.

Recent advances in computing have resulted in numerous aquifer test computer programs that include the analytical solutions listed above, along with more complex and sophisticated solutions. However, a level of familiarity with several subjects is necessary to properly analyze a pumping test dataset including: fundamentals of aquifer hydraulics; various models for groundwater flow systems and conditions and associated key features; and, aquifer testing analytical solutions.

Therefore, it is not sufficient or appropriate to input a dataset manually or via a software program into an arbitrary analytical solution and simply report the data. It is necessary that evaluation of aquifer test data be conducted by a professional geologist or engineer familiar with these subjects as well as with site conditions.

Furthermore, multiple analytical solutions may initially appear applicable to the conditions at the site and the aquifer test results. The use of diagnostic plots (e.g. Cooper-Jacob, derivative plots) during the initial evaluation of the data can be helpful in: selecting the most appropriate analytical solutions; identifying hydrogeological conditions not previously recognized (e.g., a leaky aquifer boundary condition, wellbore storage and skin effects, etc.); and selecting appropriate segments of pumping and recovery curves for analysis. A comprehensive discussion of the use of diagnostic plots is presented in Renard et. al., 2008.

It is also useful to plot drawdown at multiple observation wells on a single plot. Using the argument for the Theis solution, plotting drawdown versus the ratio of t/r^2 (where t is time and r is the distance from the pumping well) for each observation well should, under homogeneous and isotropic conditions, plot on the same curve. Deviations from a single curve provide insight into boundaries and anisotropy.

6.2.1 Documentation of Data Analysis

Data analysis methods should be identified and appropriately referenced in the aquifer test report. All assumptions and limitations of the analysis methods should be listed and their applicability to the site discussed in the report. Programs used for analysis should be referenced and all assumptions and limitations should be noted in the report. If needed for clarity, equations used for calculating hydraulic properties should also be included in the report.

For data depicted on double-logarithmic plots, the following requirements should be met.

- If a single type curve has been used to analyze the data, the type curve should be presented directly on the plot.
- If an analysis method uses a family of type curves, all curves selected to fit the data (including both early and late time responses to pumping, if applicable) should be depicted directly on the plot, and a discussion addressing the applicability of using multiple type curves should be included in the aquifer test report.
- If only a portion of the data is used, the portion selected should be identified on the plot.
- Match point values (if used) should be identified on plots.
- Diagnostic plots should be included to facilitate review.

For data depicted on semi-logarithmic plots, the following requirement should be met: The portion of the data to which a straight line is fit should be indicated on the plot.

If any boundaries are encountered by the cone of depression during the aquifer test, the aquifer test report should contain:

(1) a reference to the data plot on which the boundary's impact can be observed,

(2) identification of the type of boundary, and

(3) a discussion addressing the boundary's effect on the hydraulics at the contaminated site.

An evaluation of wellbore storage effects should be included for pumping tests.

6.2.2 Presentation of Hydraulic Property Calculations

Calculations of transmissivity, storativity, and hydraulic conductivity are the principal products of an aquifer pumping test. The guidelines included below indicate the minimum amount of information that should be presented for these calculations.

While calculations of the hydraulic properties can be presented on the plots, the resultant values should also be presented in tabular format in the aquifer test report for all zones evaluated during the aquifer test, for both the drawdown and recovery phases, and for all methods used for data analysis. Information presented in tabular format should include the following:

- Transmissivity (T) and storativity (S), including specific yield (S_y) for unconfined aquifers;
- Time at which boundaries, if any, are encountered, and an estimate of the distance to the boundary; and,
- Hydraulic conductivity (K).

It should be noted that calculation of hydraulic conductivity is based on assumptions of the aquifer thickness in the CSM. Aquifer thickness, especially when the aquifer is highly stratified, is often not clear and may be dependent on the scale of interest. As additional information is collected, assumptions for the "effective" aquifer thickness may change (e.g., dominant flow may be occurring within a narrow zone in an aquifer previously viewed as much thicker).

If an analysis method is chosen that allows for the calculation of additional hydraulic properties (such as anisotropy ratios and leakage), these values should also be included in tabular format in the aquifer test report. In the event that hydraulic property calculations are available from other multiple- or single-well aquifer tests conducted at the site, the aquifer test report should contain a discussion addressing how the most recent calculations compare with historic values, and with values from literature.

6.2.3 Summary of Results

To conceptualize how hydraulic properties are related to the overall hydrogeologic regime at a contaminated site, all relevant site characterization data, including the results of any aquifer tests, should be integrated and interpreted. Interpretation of the aquifer test data should be consistent with either the pre-test CSM, or with a revised CSM which incorporates the results from the test and which is presented in the aquifer test report.

The aquifer test report, at a minimum, should include a detailed discussion of the following points:

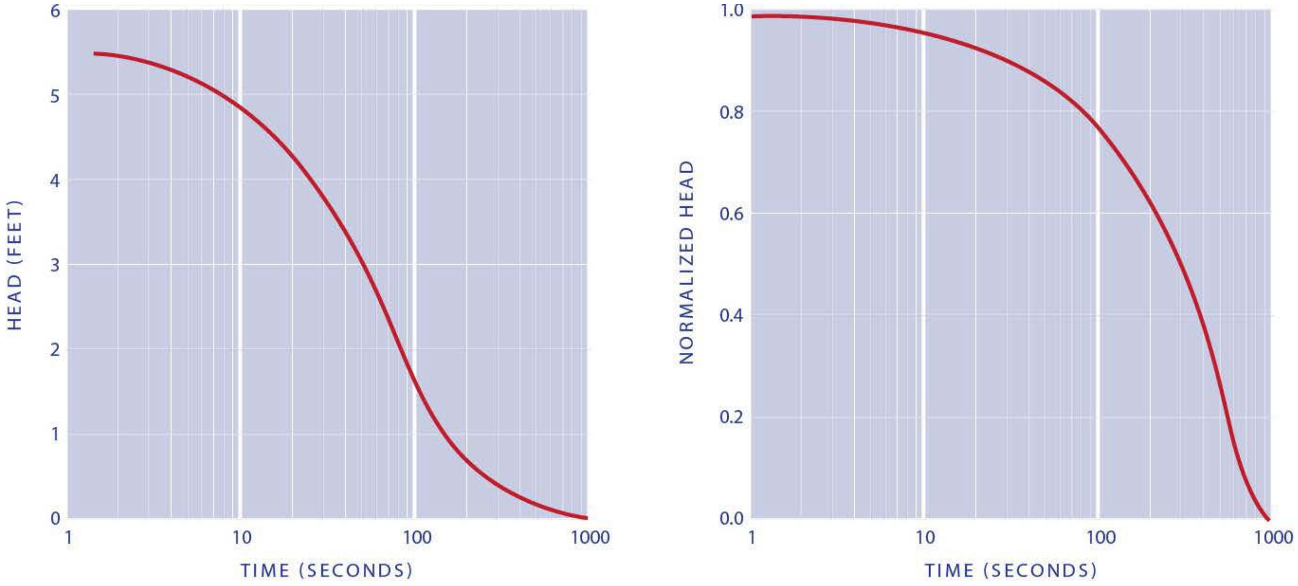
- The response of the zones of interest to the aquifer test, with an evaluation of the drawdown versus time curves as indicative of aquifer conditions (i.e., confined, unconfined, or semi-confined aquifer system, an aquitard, or a combination of these);
- Discussion of the aquifer behavior prior to and during the pumping and recovery phases;
- Determination of the probable ranges of T, S, S_y, and K and their vertical and horizontal distribution;

- Identification of remaining data gaps, if any, that need to be addressed by additional aquifer testing or other site characterization work; and,
- Discussion of the overall quality of the test data, such as identification of skin effect (suggesting that the well was not completely developed), external influences, pumping rate fluctuations, or other issues.

7.0 DESIGN OF SLUG TESTS

Slug tests are typically conducted as single well tests where the groundwater level in the well is instantaneously changed, and the subsequent water elevations are measured as equilibrium conditions return. Slug tests are conducted by displacing a known small volume of water in a well and then monitoring the return of the water level in the well to its original, pre-test level. The resulting rise or fall of water level within the well is recorded (Figure 4) and the measurements are analyzed using one or more analytical methods to derive estimates of hydraulic conductivity or transmissivity.

Figure 4 – Conventional Slug Test Raw Data and Normalized Head Plots



Idealized slug test raw data plot -- falling-head measurements plotted against log time.

Normalized head plotted against log time -- raw data are normalized by dividing head measurements by the initial induced slug displacement.

The instantaneous water level change can be achieved by several methods, including:

- The introduction and removal of a solid object of known volume;
- The application of pressure or vacuum; and,
- The introduction or removal of a known volume of water.

With all these methods, the water level displacement is the result of the addition or removal of a “slug”, whether the slug is a solid, liquid, or gas.

Slug test methods that involve lowering water levels and then measuring rising recovery are called rising-head tests, but are also referred to as slug-out, bail-out, baildown, or bailer tests. Methods that involve raising water levels and then measuring falling water levels are called falling- head or slug-in tests.

Slug tests may be run as precursors to designing a multi-well aquifer pumping test because the slug test analysis can aid in estimating anticipated discharge rates and in selecting appropriate observation well locations. Slug tests might also be used as a periodic well maintenance monitoring tool to assess if a well is fouling or clogging over time and if rehabilitation or development is warranted. Slug tests can also be used during well construction to assess if well development and construction are adequate, thus ensuring that the well has appropriate hydraulic communication with the surrounding formation.

Slug tests are relatively simple and easy to implement. Properly conducted slug tests allow for rapid and economical calculation of the hydraulic conductivity or transmissivity of the zone of interest at a single location. Slug tests offer the advantage of not having to manage the large quantities of potentially-contaminated water typically associated with conventional aquifer pumping tests and do not require the installation of neighboring observation wells. Because slug tests affect a small volume of the aquifer, they have minimal effect (compared to a large-scale aquifer pumping test) on groundwater flow and contaminant distribution, and thus minimize potential plume mixing and/or spreading (Hall, 1996). Also, slug tests may be conducted in lower hydraulic conductivity zones which may not be amenable to the prolonged pumping required for a conventional aquifer pumping test. Slug tests performed at several wells on a site can provide information regarding spatial variations in hydraulic conductivity.

However, the concept of “simple and easy” can lead to errors caused by carelessness (Butler, 2015). To counteract this potential, thorough work plan preparation and rigorous data analysis should be conducted to improve data reliability.

The hydraulic parameters calculated from a slug test are only representative of a small volume of the geologic material surrounding the well. Slug tests are also sensitive to conditions immediately adjacent to the well (e.g., well screen slot size, filter/gravel pack, clogging, skin effect, or insufficient well development).
When investigating aquifer properties, it is important that the slug test estimates the hydraulic conductivity of the formation and not the effects of the well or the well construction.

Cooper, et. al. (1967) determined that the calculation of transmissivity and hydraulic conductivity from slug test data is not particularly sensitive to the technique used for analysis. However, calculation of the storativity of the zone of interest may be reliable only to within an order of magnitude of the true value. Storativity is also affected by wellbore storage and well construction in single-well tests (Halford and Kuniansky, 2002). Therefore, storativity values calculated from slug test data can be used only as approximate indicators of the storage capability of the zone of interest and, due to this uncertainty, may be of little value for the site- specific conditions and for aquifer test DQO's. More reliable storativity values can be obtained using aquifer pumping tests.

Details for conducting slug tests in the field are described in several documents and a few have been included in the References section at the end of this guidance (e.g., Butler, 1998; ASTM, 2008; ASTM, 2013a). The trend towards smaller monitoring wells installed with direct push methods has resulted in slug tests being conducted in small-diameter wells. Direct push technology offers the potential to conduct multiple slug tests at different horizons within one boring. However, well development limitations associated with small-diameter direct push investigation techniques can reduce the quality and usefulness of slug tests.

It should be noted that when aquifer properties are being determined for the purposes of designing a groundwater extraction or injection system, aquifer pumping tests are essential as they represent larger scale system conditions better than slug tests.

7.1 Test Well and Slug

The wells in which slug tests are conducted provide a means of examining the subsurface hydrologic environment. This examination is at a much smaller scale than that which occurs with aquifer pumping tests and is representative of a smaller portion of the subsurface.

7.1.1 Skin Effect

As stated in previous sections, skin effect can affect the performance of pumping and observation wells during an aquifer pumping test and can adversely affect the results and interpretation of the test. Due to the larger scale of an aquifer pumping test in relation to the small scale of a slug test, the adverse effects associated with the skin effect can be significantly greater in a slug test. This subject is therefore addressed in further detail here.

Skin effect should be considered when selecting drilling techniques, because drilling disturbs the geologic material adjacent to the wellbore. For instance, hollow-stem augers can smear clays around the perimeter of the borehole while mud rotary drilling may plug the area around the well with drilling mud. These drilling techniques can create a low-permeability rind or skin along the borehole wall causing the permeability of the geological material near the wellbore to be reduced. Drilling techniques such as air rotary or sonic methods may create less low- permeability skin along the wellbore. Extra consideration should be given when selecting specific drilling techniques, especially when wells are to be installed with aquifer testing in mind.

If a well was not developed sufficiently to allow adequate removal of low permeability skins, then slug test data may be difficult to interpret and may yield unreliable hydraulic estimates of the aquifer. In some situations, high permeability skins may also develop, but are less problematic for slug tests (Butler, 1998). Proper well design, installation techniques and development should reduce both low- and high- permeability skin effects.

Slug tests are often conducted in wells that were initially installed as water quality monitoring wells and, because these wells are not typically designed for significant groundwater extraction, there may have been minimal effort to develop the well and minimize the borehole skin effect. Slug tests conducted in such wells may underestimate groundwater velocities and contaminant movement (Faust and Mercer, 1984).

Therefore, hydraulic conductivity estimates from slug tests should be considered lower-end estimates of the true value (Butler, 1998).

Adequate well development can be the single most important factor in a slug test program and the need for the initial or supplemental development of the test wells should be carefully considered during planning stages.

A discussion describing the development methods used at each tested well should be included in the aquifer test work plan. The aquifer test report should address the likelihood of skin effects on slug test data interpretation. Acceptable development techniques for environmental monitoring wells are described in *Well Design and Construction for Monitoring Groundwater at Contaminated Sites* (CalEPA, 2014).

There are methods to assess if well development was sufficient to minimize the effects of low-permeability skins. These methods include:

- Comparing hydraulic conductivity estimates from slug tests to estimates from other site investigation information (e.g., lithology from geologic logs, soil behavior types from cone penetrometer tests, pore pressure dissipation tests, hydraulic profiling results, or aquifer pumping test data);
- Evaluating response data plots and comparing results to best-fit curves from theoretical models;
- Evaluating at least a set of three slug test results per well, two of which are the same direction (e.g., two rising-head tests) with an initial displacement ranging from 0.2 to 2.0 meters; and,
- Conducting a short-term aquifer pumping test in an attempt to overcome skin effect (Butler, 1990).

Additionally, American Society of Testing and Materials (ASTM) (2013a) recommends performing three preliminary slug tests in quickly responding wells to assess if well development is sufficient. If the results show similar water level recovery responses and similar initial head values (H_o), then well development is considered adequate.

7.1.2 Well Screen Length

Because slug tests influence a particular zone only at the location of the screened interval and filter pack, it is important to know if the well screen fully or partially penetrates the zone of interest.

Calculation of hydraulic conductivity for a fully-penetrating well is simply achieved by dividing the transmissivity by the entire thickness of the zone. However, a partially-penetrating well yields a transmissivity value that is indicative only of that portion of the aquifer or confining bed that is penetrated by the well screen and filter pack. A discussion addressing the length of the screened interval for all wells in which slug tests are conducted at the contaminated site should be included in the aquifer test work plan and report. Justification for partially-penetrating screens should be provided and may be brief because it is understood that short- screened wells are common (and may be required) at contaminated sites. In the event that slug tests are conducted in wells with partially-penetrating screens, it should be indicated in the aquifer test report that the hydraulic properties derived from these tests are only representative of the screened interval and may not be representative of the entire zone of interest.

Of all construction parameters used as inputs to theoretical models, the screen length can introduce the most error in hydraulic conductivity estimates (Butler, 1998).
Ultimately, Butler recommends that the length of the screened interval from the well construction diagram be used (as the “effective screen length”) rather than the length of the screened interval plus the filter pack because it is doubtful that well development has adequately affected the distal ends of the filter pack, let alone the entire screened interval. If the length of the screened interval is used in the calculation, the hydraulic conductivity estimate should be considered a lower-end estimate (Butler, 1996).

7.1.3 Well Screen and Filter Pack Dimensions

Slug test analyses use both the radius of the well and the thickness of the filter pack. The dimensions of the well screen openings, filter pack thickness, grain size distribution of the filter pack, and filter pack porosity for all tested wells should be reported in the aquifer test work plan, along with well construction diagrams for all tested wells. In the event that the dimensions of the filter pack of an existing well are not known, justifications for assumptions of these dimensions should be included in the aquifer test work plan. For proposed or new wells, both the screen slot size and the filter pack should be designed on the basis of the grain size distribution of the aquifer material (CalEPA, 2014). The screen slot size and filter pack selection should allow for adequate development of the well to be tested.

The casing radius is also used in calculating hydraulic conductivity estimates from slug tests. Generally, the casing radius from a well completion diagram is used. However, when the tested well screen or filter pack intercepts the water table a modified radius may be appropriate (Bouwer, 1989). Also, for some low-yielding wells, use of the casing radius may not be appropriate. In such cases, Butler (1998) recommends comparing the initial slug displacement from actual test data with the theoretical estimate as a check to see if the casing radius selected is appropriate.

For wells with casing diameters of less than two inches, a correction should be made to take into account the influence that the transducer cable has on test results. An error in the estimated hydraulic conductivity will occur if the transducer cable volume/radius is not considered (ASTM, 2013a). Frictional losses can also result in errors when small-diameter wells are screened in permeable formations with hydraulic conductivities greater than 200 to 250 feet/day (ASTM, 2010a). Methods to correct for frictional losses should be appropriately applied (ASTM, 2013a).

7.1.4 Selection of the Slug

A solid or pneumatic slug test method is generally recommended at contaminated sites (Figure 5). For zones with low to moderate hydraulic conductivities (e.g., recovery lasting more than a couple hundred seconds), a solid, inert slug may be used to displace a known volume of water. For aquifers of high hydraulic conductivities and the well screen, filter pack, and transducer are completely submerged throughout the entire test, a pneumatic method is recommended as it can typically displace a larger volume of water and experience reduced water level measurement noise during initiation of the test. .

Figure 5 – Typical Slug Test Field Equipment

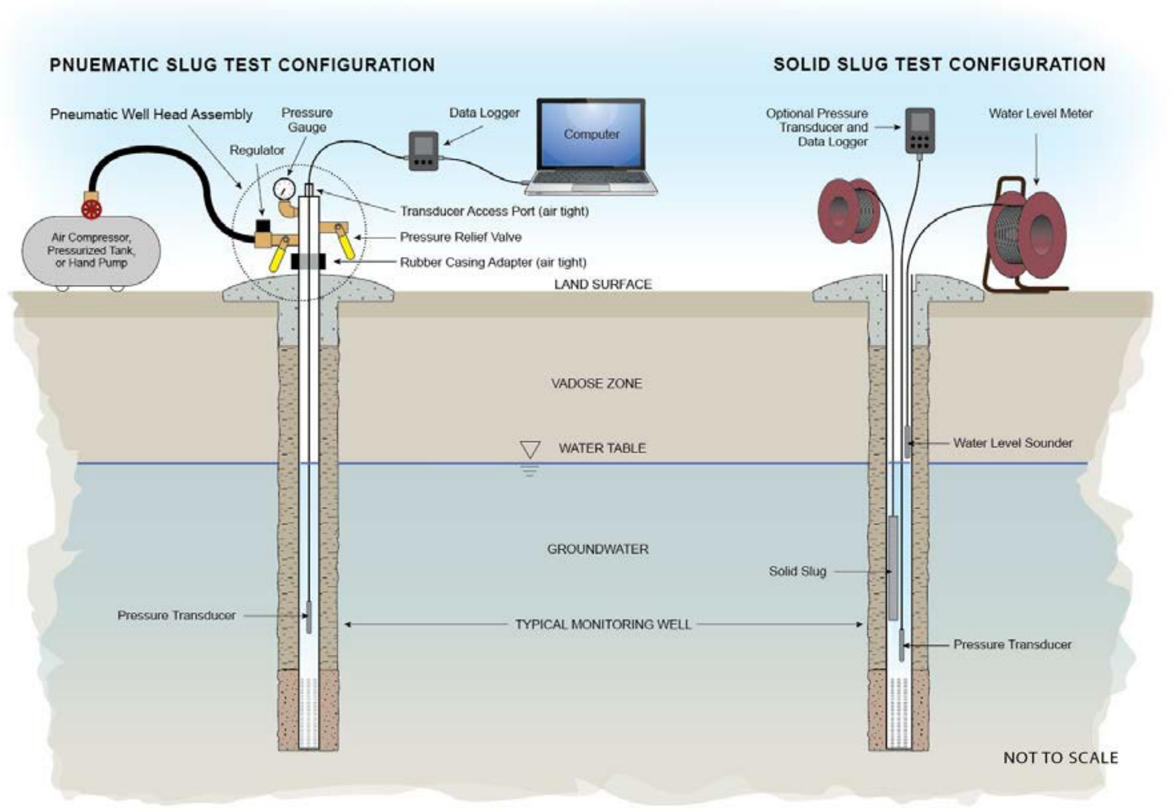


Figure 5: Typical Slug Test Field Equipment

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At contaminated sites, the addition or removal of a slug of water from wells may not be advisable for several reasons:

(1) the addition of water may impair the ability of the well to provide representative ground water quality samples for some time;

(2) the removal of contaminated water from a well requires management of IDW; and,

(3) when water is added, water draining from the sides of the well can result in non-instantaneous initiation of the slug.

For zones with very low hydraulic conductivities (e.g., 1×10^{-7} cm/sec in confining zones), a solid slug could be utilized, with transducers to record the water level response over the long duration needed for recovery to static conditions. Additional methods to shorten the duration of slug tests in low-conductivity zones focus on reducing the casing radius parameter, as it has the most impact on test duration (Butler, 1998). This can be done by using a packer system to isolate the screened interval from the larger-diameter casing by using a standpipe or shut-in test. In the standpipe method, a short casing of reduced size is inserted into a larger existing well: water level changes are now monitored in the smaller casing. The shut-in test isolates the screened zone completely: water level changes need to be corrected for the compressibility of water and test equipment displacement volumes.

Whenever possible, either a decontaminated solid slug (of appropriate size and composition) or pressure (delivered to a sealed well) should be used to conduct slug tests in wells. The following information should be documented in the aquifer test report:

- Dimensions and volume of the slug, or the magnitude of the induced pressure change;
- Composition of the slug;
- Manner in which the slug was lowered into and raised from the well;
- Assurance that the slug was fully submerged;

- Nature of the tests (i.e., falling- and/or rising-head tests);
- Manner in which the well was sealed and manner in which pressure was delivered to the well;
- Results of pre-test leak testing of pneumatic systems; and
- Assurance that a clean air source for pressurization was used (e.g., oil-less compressor, nitrogen gas, etc).

In small diameter wells, such as those installed with direct push technologies, utilizing a solid slug instead of a pneumatic method may not be advisable due to difficulties in actually measuring water levels.

Although adding water to a well for slug testing is not recommended, if done, the water should be analyzed, and results shared with the agency conducting regulatory oversight before the water is added to the well.

Chemical analytical results for the added water should be included in the aquifer test report. Subsequent groundwater quality measurements from the tested well should be examined to assess any effects from the introduction of the water. Similarly, if a vacuum (negative pressure) is used to conduct a falling-head test in a monitoring well, the potential for loss of volatile compounds exists and, if necessary, may require monitoring. If adverse effects are observed in water quality data after conducting slug tests in a manner described above, additional well purging or well development may be warranted to eliminate or minimize non-representative water quality data.

For water removed during the slug test, waste water (i.e., investigation derived water (IDW) disposal considerations described in Section 4.2.6 should be followed.

7.2 Number of Slug Tests Conducted

Since slug tests only allow for the determination of in situ hydraulic properties at a single location, multiple slug tests are necessary to assess the nature and spatial variability of a water-bearing zone. Several slug tests should be conducted in wells or piezometers in each zone of interest as it can be anticipated that hydraulic properties will vary in relationship to the scale of the heterogeneities of the geologic materials encountered.
The aquifer test work plan and report should contain a map indicating the locations of slug test wells and a rationale for the number of slug tests conducted.

More importantly, a series of slug tests are required at each well tested to assist in data assessment. Three or more slug tests at each well, two of which are in the same direction (e.g., two rising-head tests) are recommended. The initial displacement should be varied by a factor of two or more in at least two tests while the first and last test should use similar or equivalent displacements.

8.0 PERFORMANCE OF SLUG TESTS

As with aquifer pumping tests, slug test results reflect the quality of pre-test planning, well development, design and construction, and data quality control. The data collection phase of the slug test should indicate if the aquifer response is a result of its actual geologic and hydrogeologic characteristics, or if the response was masked by mechanical aberrations or human activity. Slug tests are generally monitored with pressure transducers, which automatically collect measurements at specified times. In very permeable aquifers, well recovery may take only one to several minutes, requiring many measurements be collected over a short period of time. In aquifers with lower permeability, the test may range from tens of minutes to days and manual reading with an electronic sounder may be adequate for monitoring recovery.

8.1 Water Level Measurements

Water level measurements should be obtained over the entire duration of a slug test, and pre-test water levels should also be collected. When a solid slug is introduced into a well, both falling-head and rising-head tests can be conducted by:

(1) Introducing the slug;

(2) Monitoring water levels until they have returned to pre-test levels;

(3) Removing the slug; and

(4) Once again, monitoring water levels until they have recovered to pre-test conditions.

Running the test to near completion is important as it can allow for better data interpretation. However, waiting potentially long amounts of time to attain 100% recovery to pre-test levels is generally not necessary and 95% recovery should be adequate for estimating hydraulic parameters.

8.1.1 Water Level Measurements Before Application of the Slug

The water level representative of the aquifer to be tested should be measured and recorded prior to initiation of the slug test and for a period of time that is at least as long as the expected duration of the slug test. The pre-test water level measurements should be presented on both tables and graphs in the aquifer test report.

Additional pre-test and post-test data collection is warranted if the tests are influenced by tidal activity, river fluctuations, and/or barometric pressure. These data are necessary in order to attempt to correct and remove those influences from the affected test data.

If a transducer is used to measure water levels, the slug test should not begin until the water level has equilibrated following the introduction of the transducer. Additionally, pressure transducers may take twenty minutes or more for electronics to equilibrate to ambient temperatures. Care should also be taken to ensure that:

(1) The transducer is sensitive enough to monitor anticipated responses;

(2) The transducer is located at an appropriate depth below static water level (e.g., a depth appropriate for the type of instrument selected and for the pressure rating—but, not at the base of the well where fine-grained material could adversely affect its operation);

(3) The transducer does not become tangled or encumbered during the movement of a solid slug while testing; and,

(4) The transducer cables are not exposed to sunlight because heat can cause fluctuations in transducer responses (ASTM, 2013a).

Preliminary slug tests should be conducted to ensure appropriate transducers are utilized that are capable of capturing essential initiation and recovery data. Transducers with data acquisition rates of 5 to 10 measurements per second are recommended for highly permeable formations (ASTM, 2013a). Leak tests should also be conducted while conducting preliminary pneumatic slug tests.

8.1.2 Water Level Measurements After Application of the Slug

One of the advantages of slug tests is that the tested zones of interest typically respond quickly to the slug (depending on the geologic composition of the zone); therefore, the tests can be conducted fairly rapidly. Because of the often-short test duration, many water level measurements should be taken in a very short time. Ensuring that an instantaneous water level change occurs while initiating a slug test is important for analysis of some slug test data, and therefore, is a factor to be cognizant of during testing. Consequently, transducers and data loggers are recommended for water level measurements, rather than manually operated sounders.
Pressure transducers are mandatory if a vacuum or pressure is applied as the slug mechanism and the well will be sealed during the test. Water level measurement frequencies are a function of the hydraulic conductivity of the zone being tested and increase as the hydraulic conductivity increases.
Several measurements per second (e.g., every 0.2 seconds or less) are suggested for higher hydraulic conductivities (Halford and Kuniansky, 2002). Discussion regarding recommended measurement frequencies can be found in Butler (1998) and ASTM (2008).

Water levels in lower to moderate-permeability zones respond to slug tests more slowly than water levels in high-permeability zones. Accuracy of the measurements and issues concerning electric tape water level sounder tape stretch and sounder measurement calibration are a concern. Therefore, different sounders should not be used on the same well during a test as they could actually introduce noise and error to the water level data. The serial number/make/color of the sounder should be recorded to ensure that a sounder is dedicated to a particular well during tests.

Water level measurements taken during and after application of the slug should be presented in the aquifer test report. It is recommended that data presentation should include at least the following information:

- Date and time slug test began;
- Well and zone tested;
- Initial water level and assessment of any water level trends before application of the slug;
- Frequency of water level measurements;
- Water level immediately after the application of the slug;
- Time since application of the slug (in appropriate units);
- Water levels following application of the slug;
- Final stabilized water level; and,
- Description of any unusual events (such as changing weather, passage of a train or heavy machinery, or trouble with equipment during test).

The theoretical water level displacement attributed to the known volume of the slug used in the slug test should be compared to the magnitude of the actual water level change in the well to ensure that hydraulic property calculations are based on the impact of the slug on the aquifer.

Otherwise, a water level change that is less than what could be attributed to the slug may lead to misinterpretations of the hydraulic properties of the zone of interest. If discrepancies between the actual and theoretical displacement are identified, then such discrepancies should be evaluated and corrective measures initiated as needed.

A discussion describing how the water level change in the tested well corresponds to water displacement in the zone of interest produced by the slug should be included in the aquifer test report. The discussion should also include a description of well dimensions used in hydraulic property calculations. Originals or copies of all field data sheets should be provided in the aquifer test report.

8.2 Decontamination of Slug Test Equipment

Statements related to decontamination of equipment used for aquifer pumping tests (Section 5.5) also apply to equipment used for slug tests. Equipment used throughout the duration of a slug test should be decontaminated in accordance with an approved decontamination plan contained in the aquifer test work plan. All proposed and completed slug test decontamination activities should be described in the work plan and aquifer test report, respectively.

8.3 Quality Control Checks

It is suggested that prior to completing field activities, that preliminary data analysis be conducted to determine if appropriate input parameters have been accounted for. If the preliminary assessment suggests potential error or inconclusive results, suspected slug tests should be repeated before departing from the field.

Care should be taken understanding equipment capabilities and limitations. Transducers should be periodically calibrated to ensure that data are accurate and do not drift as the transducer ages. Transducers should also be calibrated in the field prior to and after testing by verifying water level readings with another device such as an electronic sounder. For lengthier transducer tests, periodic checks with manual measurements are highly recommended. Some transducers can be adversely affected by power lines or electrical sources. The name and date of the last equipment calibration should be included in the aquifer test report for all those instruments requiring periodic maintenance and calibration. As stated in Section 5.1.2, it is advisable to test the stability of transducers prior to using them by placing the units in a container of water for a period of at least one day.

8.4 Documentation of Field Test Data and Parameters

Well and aquifer parameters (e.g., screen/casing diameter, screen length, aquifer thickness, confined/unconfined conditions) will need to be recorded and summarized to allow for easy access when applying the parameters to theoretical models during slug test data analysis. A figure and/or table should be developed to ensure all appropriate data are consistently recorded. The method of analysis should be known or anticipated prior to implementation in the field to ensure all appropriate parameters and dimensions are monitored and recorded during the test (ASTM, 2008).

9.0 SLUG TEST DATA ANALYSIS AND INTERPRETATION

A variety of slug test analysis methods are applicable to zones with hydraulic conductivities ranging from high to extremely low values (e.g., Bouwer, 1989; Bredehoeft and Papadopulos, 1980; Bouwer and Rice, 1976; and Hvorslev, 1951).

A few common analytical solutions for analyzing slug test data, along with their underlying assumptions are provided below. Additionally, corresponding ASTM citations are noted and provide basic summary information and references for each method:

- Bouwer & Rice (1976) / ASTM (2004): homogeneous, isotropic and unconfined conditions; partially or completely penetrating wells; overdamped well response.
- Cooper et. al. (1967) / ASTM (2010c): confined conditions; fully-penetrating wells; overdamped well response.
- Kipp, (1985) / ASTM (2013b): homogeneous, isotropic, and confined conditions; fully penetrating well; critically damped well response.
- Van der Kamp, 1976. ASTM (2013c): homogeneous, isotropic, and confined conditions; fully penetrating well; underdamped well response.

It is beyond the scope of these guidelines to specify how slug test data should be analyzed in any great detail. Rather, these guidelines:

(1) Stress the importance of utilizing a process to ensure selection of an appropriate analytical method, and

(2) Suggest minimum requirements for how slug test data should be compiled, presented, and summarized.

While slug tests may be easy and rapid to implement in the field, care must be taken to ensure that appropriate analytical methods are applied while deriving hydraulic conductivity estimates and interpreting response data. Factors such as aquifer type (e.g., confined, unconfined), well construction (fully-penetrating, partially-penetrating), and nature of recovery data must be considered.
A systematic decision tree can be beneficial in determining the proper analytical method to employ. Several decision trees exist with differing levels of complexity, but most begin with assessing aquifer type (e.g., see Table 1 in ASTM, 2010b; Chapter 12 in Butler, 1998; and The Midwest Geosciences Group, 2013).

For instance, The Midwest Geosciences Group (2013) stresses normalizing data plots from a series of slug test to assist in data interpretation and then highlights using a decision tree system based upon three well formation categories:

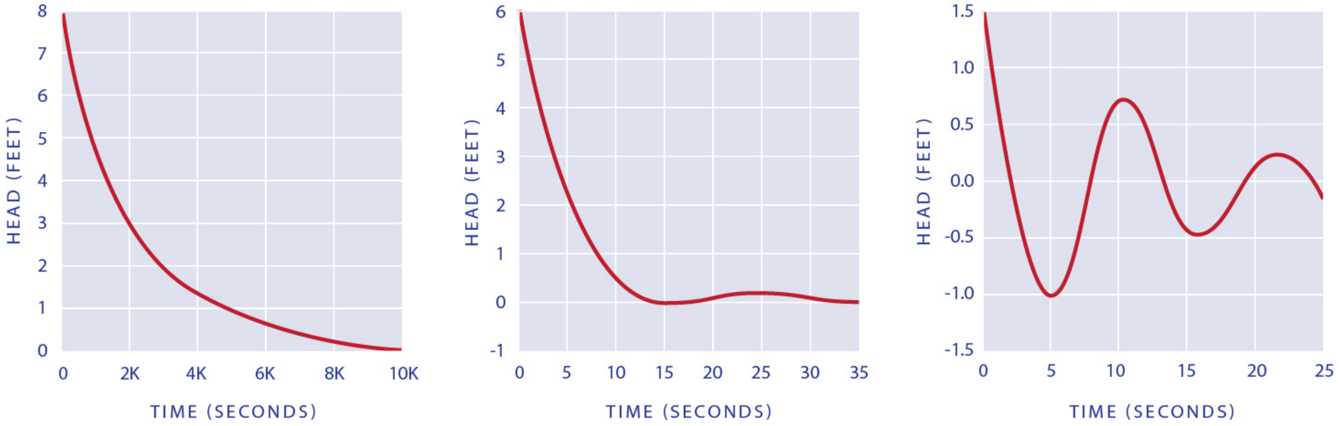
I) Confined and unconfined formations with saturated screens;

II) Wells screened across the water table; and

III) Highly permeable Category I wells.

There are a variety of analytical slug test methods as well as slug test responses (see Figure 6 for common responses). Details of these and other analytical methods are available in the literature. Selection of an appropriate method and resulting solution can be accomplished using decision trees, such as those mentioned previously in this section. Of course, the type of response data will play into the selection of the analytical method. The aquifer test report will need to clearly justify the choice of the analytical solution selected for each slug test.

Figure 6 – Range of Slug Test Responses to a Sudden Change in Head



An **OVERDAMPED WELL RESPONSE** exhibits water level recovery data that returns to pre-test levels in a roughly exponential manner over a period of time of seconds, to minutes, to hours (finer-grained units).

A **CRITICALLY DAMPED WELL RESPONSE** is transitional between under-damped and overdamped responses.

An **UNDERDAMPED WELL RESPONSE** exhibits water level recovery that oscillates after slug initiation and then the amplitude of the oscillatory response decreases/dampens with time as an exponentially decaying sinusoidal function. This may occur in highly transmissive confined aquifers or in deep wells with long water columns. The response to the slug initiation occurs over seconds and can be complete in less than a minute.

Figure 6: Range of Slug Test Responses to a Sudden Change in Head

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9.1 Compilation and Presentation of Data

All hydraulic head slug test data should be provided electronically in the aquifer test report to appropriately document the original pretest, initiation, and recovery data and to allow independent assessment of the data if so desired. The exact electronic format provided should be amenable to the agency conducting regulatory oversight.

9.1.1 Consistency of Units of Measurement

All time data should be converted to a single set of units and all water level data should be expressed in consistent English (e.g., inch-pound) or Système International d'Unités (i.e., SI metric units).

9.1.2 Presentation of Data

In addition to the data requirements noted in previous sections, hydraulic head and time information should also be presented on graphical plots. As with multiple well tests, such depiction of the data is necessary for further analysis because calculation of hydraulic properties is based on the shape of the data plot.

The following minimum requirements should be met for slug test data presentation.

- Data plots of change in hydraulic head versus time should be presented for all tested wells on an arithmetic scale, and either on double-logarithmic or semi-logarithmic scale, depending on the analysis technique employed. Time data should be depicted along the horizontal axis and change in head should be depicted along the vertical axis in all cases. Normalized data plots should also be presented to assist in data interpretation.

- All plots should be clearly labeled. All colors, symbols, and abbreviations should be explained in a legend. In the event that more than one water level measuring device was used for the same well or, if data from multiple wells are presented on the same plot, the labeling and/or color coding should enable differentiation between sets of data, and should be identified in a legend. Symbols should not be so large that they obscure pertinent data.

- All data plots should be included in the aquifer test report including identification of the portion of data to which type curves are fit.

9.1.3 Presentation of Data Analysis

Slug test data analysis methods should be identified and appropriately referenced in the aquifer test report.
All assumptions and limitations of the analysis methods should be listed and their applicability to the site discussed in the report. Programs used for analysis should be referenced and all assumptions and limitations should be noted in the report. For data analysis methods that can be used only if stringent criteria are met, appropriate calculations and a discussion indicating the validity of the method for analysis of the data should be included in the aquifer test report.

9.1.4 Slug Test Reporting

A report documenting slug test findings including information described in previous sections of this guidance should be prepared.

It is recommended that the aquifer test report include, at a minimum, a detailed discussion addressing the following points:

- Objectives of the slug tests;
- General quality of the data supported by data analysis (i.e., an evaluation of whether field activities and data analysis met the DQO's);
- Estimated ranges of T and K values (and S or S_y values, if applicable);
- Comparisons with other pump and slug test results, if other tests have been performed at the site; and,
- Identification of remaining data gaps, if any, that need to be addressed with additional aquifer testing or other site characterization work.

Conclusions regarding additional objectives (e.g., slug testing as a maintenance assessment tool) should also be provided as applicable.

10.0 REFERENCES

ASTM International (ASTM, formerly American Society of Testing and Materials), 2013a. *ASTM D7242/D7242M−06, Standard practice for field pneumatic slug (instantaneous change in head) tests to determine hydraulic properties of aquifers with direct push groundwater samplers*.

ASTM International, West Conshohocken, PA. Reapproved 2013.

ASTM, 2013b. *ASTM D5881–13, Standard test method for (analytical procedure) determining transmissivity of confined nonleaky aquifers by critically damped well response to instantaneous change in head (slug)*. ASTM International, West Conshohocken, PA.

ASTM, 2013c. *ASTM D5785−95, Standard test method for (analytical procedure) determining transmissivity of confined nonleaky aquifers by underdamped well response to instantaneous change in head (slug test)*. ASTM International, West Conshohocken, PA. Reapproved 2013.

ASTM, 2010a. *ASTM D6725−04, Standard practice for direct push installation of prepacked screen monitoring wells in unconsolidated aquifers.* ASTM International, West Conshohocken, PA. Reapproved 2010.

ASTM, 2010b. *ASTM D4043–96, Standard guide for selection of aquifer test method in determining hydraulic properties by well techniques*.

ASTM International, West Conshohocken, PA. Reapproved 2010.

ASTM, 2010c. *ASTM D4104–96, Standard test method (analytical procedure) for determining transmissivity of nonleaky confined aquifers by overdamped well response to instantaneous change in head (slug tests)*. ASTM International, West Conshohocken, PA. Reapproved 2010.

ASTM, 2008. *ASTM D4044−96, Standard test method for (field procedure) instantaneous change in head (slug) tests for determining hydraulic properties of aquifers*. ASTM International, West Conshohocken, PA. Reapproved 2008.

ASTM, 2004. *ASTM D5912–96, Standard test method for (analytical procedure) determining hydraulic conductivity of an unconfined aquifer by overdamped well response to instantaneous change in head (slug)*.

ASTM International, West Conshohocken, PA. Reapproved 2004.

Batu, V., 1998. *Aquifer Hydraulics, A Comprehensive Guide to Hydrogeologic Data Analysis*, John Wiley & Sons, Inc., Canada, 727 p.

Bouwer, H., 1989. *The Bouwer and Rice slug test - an update. Groundwater*, Vol. 27, No. 3, pp. 304-309.

Bouwer, H. and R.C. Rice, 1976. *A slug test for determining hydraulic conductivity of unconfined aquifers with completely or partially penetrating wells.* Water Resources Research, Vol. 12, No. 3, pp. 423- 428.

Bredehoeft, J.D. and S.S. Papadopulos, 1980. *A method for determining the hydraulic properties of tight formations*. *Water Resources Research*, Vol. 16, No. 1, pp. 233-238.

Butler, J.J., Jr., 2015. *Slug testing for site characterization–The six key steps*. Midwest GeoSciences Group webinar.

Butler, J.J., Jr., 1998. *The Design, Performance, and Analysis of Slug Tests.* Lewis Publishers, Boca Raton, Florida, 252 pp.

Butler, J.J., Jr., 1996. *Slug tests in site characterization: some theoretical considerations. Ground Water*, Volume 28(3), pp. 394-402.

Butler, J.J., Jr., 1990. *The role of pumping tests in site characterization: some practical consideration*. *Environmental Geoscience*, Volume 3(3), pp.154-163.

Butler, S.S., 1957. *Engineering Hydrology*. Prentice-Hall, Inc., Englewood Cliffs, New Jersey, 356 p.

California Environmental Protection Agency (CalEPA), 2014. *Well Design and Construction for Monitoring Groundwater at Contaminated Sites*. Department of Toxic Substances Control, 91 p.

CalEPA, 2013. *Preliminary Endangerment Assessment Guidance Manual (A guidance manual for evaluating hazardous substance release sites), Interim Final*. Department of Toxic Substances Control, 103 p.

CalEPA, 2012. *Guidelines for Planning and Implementing Groundwater Characterization of Contaminated Sites*. Department of Toxic Substances Control, 79 p.

Cooper, H.H. and C.E. Jacob, 1946. *A generalized graphical method for evaluating formation constants and summarizing well-field history*.

Transactions of the American Geophysical Union, Vol. 27, pp. 526-534.

Cooper, H.H., J.D. Bredehoeft, and I.S. Papadopulos, 1967. *Response of a finite-diameter well to an instantaneous charge of water*. *Water Resources Research*, Vol. 3, No. 1, pp. 263-269.

Faust, Charles R. and J.W. Mercer, 1984. *Evaluation of slug tests in wells containing finite-thickness skin*. *Water Resources Research*, Vol. 20, No. 4, pp. 504-506.

Halford, K.J. and E.L. Kuniansky, 2002. *Documentation of spreadsheets for the analysis of aquifer-test and slug-test data*. *U.S. Geological Survey Open-File Report 02-197*, Carson City, Nevada, 51 p.

Hall, Phil and Chen, Joe, 1996. *Water Well and Aquifer Test Analysis*. Water Resources Publication, LLC, Highlands Ranch, Colorado, 412 p.

Hantush, M. S. and C.E. Jacob, 1955. *Non-steady radial flow in an infinite leaky aquifer*. *American Geophysical Union Transactions*, Vol 36, No. 1, pp. 95–100.

Hantush, M. S., 1964. *Hydraulics of wells*. *Advances in Hydroscience, Vol 1*. Academic Press, Inc., New York, pp. 281–442.

Hvorslev, M.J., 1951. *Time lag and soil permeability in groundwater observations*, *U.S. Army Corps of Engineers Waterway Experimental Station Bulletin 36*, Vicksburg, MS.

Kasenow, M., 1996. *Introduction to Aquifer Analysis*, *4th Edition*. Water Resources Publications, LLC, Colorado, USA, xxx p.

Kipp, K. L., Jr., 1985. *Type curve analysis of inertial effects in the response of a well to a slug test*. *Water Resources Research*, Vol. 21, No. 9, pp. 1397–1408.

Kruseman, G.P. and N.A. de Ridder, 2000. *Analysis and Evaluation of Pumping Test Data*, *Second Edition, Publication 47*. International Institute for Land Reclamation and Improvement, Wageningen, The Netherlands, 377 p.

Midwest GeoScience Group, 2013. *Field Guide for Slug Testing and Data and Analysis*. Midwest GeoScience Group Press, 4 p.

Moench, A.F. and T.A. Prickett, 1972. *Radial flow in an infinite aquifer undergoing conversion from artesian to water table conditions*. *Water Resources Research*, Vol. 8, No. 2, pp. 494-499.

Neuman, S.P., 1974. *Effect of partial penetration in unconfined aquifers considering delayed gravity response*. *Water Resources Research*, Vol. 10, No. 2, pp. 303-312.

Papadopulos, I.S. and H.H. Cooper, 1967. *Drawdown in a well of large diameter*. *Water Resources Research*, Vol. 3, No. 1, pp. 241-244.

Renard, P., D. Glenz, and M. Mejias, 2009. *Understanding Diagnostic Plots for Well-Test Interpretation*. *Hydrogeology Journal*, 17, (3), pp. 589- 600.

Sterrett, R.J., 2007. *Groundwater and Wells*, *Third Edition*. Johnson Screens, A Weatherford Company, New Brighton, Minnesota, 812 p.

Theim, G., 1906. *Hydrologische methoden (Hydrology Methods)*. J.M. Gebhardt, Leipzig, 56 p.

Theis, C.V., 1935. *The relation between the lowering of the piezometric surface and the rate and duration of discharge of a well using ground- water storage*. *Transactions of the American Geophysical Union*, Vol. 16,

pp. 519-524.

Van der Kamp, G., 1976. *Determining aquifer transmissivity by means of well response tests: The underdamped case*. *Water Resources Research*, Vol. 21, No. 1, pp. 71-77.