Aquifer Test Procedures

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Introduction

As opportunities for issuing new water rights in Washington State become more limited, changes to existing water rights and mitigation strategies are becoming more complex. Department of Ecology (Ecology) Water Resources Program hydrogeologists rely on aquifer test results, and the numerical models they inform, to better understand the occurrence, movement, and quality of groundwater. In water right decisions, aquifer test results are used to estimate potential impacts of a proposed groundwater withdrawal on senior water rights and regulated streams.

Ecology's Aquifer Test Procedures provide recommendations for conducting aquifer tests that yield useful and reliable data to support water right decisions. The procedures have been prepared for hydrogeologists and engineers that design and oversee constant-rate aquifer tests. Procedures include: aquifer test planning; data collection (including baseline data); data correction and analysis; and aquifer test reporting and data submittal.

Although the procedures presented here are intended to be widely applicable, some adaptation will be needed to address individual project objectives and the regulatory environment of a proposed groundwater withdrawal. With the exception of studies designed to address seawater intrusion concerns, the procedures are not meant to address aquifer tests asssociated with groundwater contamination investigations. Ecology recommends reviewing a proposed project with a Water Resources Program hydrogeologist before conducting any testing.

In many instances an aquifer test is performed under the authority of a preliminary permit per RCW 90.03.290 and 90.44.050. In those cases, preliminary permits issued by the Water Resources Program will not only grant authority to conduct the test, the preliminary permit will prescribe how such testing needs to occur. Conducting an aquifer test under the direction of the Water Resources Program does not guarantee approval of a water right. An aquifer test that fails to provide useful and reliable data may result in all or portions of the test being repeated.

Planning an Aquifer Test

Planning is an important component of aquifer test procedures. Without adequate planning, the time and expense of conducting an aquifer test may be wasted. This section reviews recommendations for planning an aquifer test, including development of a conceptual site model; conducting an initial step-test to determine an appropriate pumping rate; and additional discussion on aquifer test duration and observation wells. During aquifer test planning and other procedures described here, it may be helpful to review Appendix A, which provides background on hydrogeologic principles and an aquifer's response during testing.

Conceptual site model

Before initiating an aquifer test, it is important to prepare a conceptual site model that incorporates existing information and data to understand the capacity of the well and potential effects of a proposed withdrawal. The conceptual site model can be used to design an aquifer test, interpret data collected, and select an analytical model to estimate the aquifer's hydraulic properties. The conceptual site model should be updated as necessary and, at a minimum, include the following sections.

- Site characteristics – A general geographic description of the project area may include elevation and topography, precipitation, current and historical land use, and general hydrologic characteristics and catchment areas of all surface water bodies in the vicinity.
- Well characteristics – Available information for the pumping well and nearby wells (especially those that will be used as observation wells) should be reviewed. Important information includes lithology, well construction details, and the results of previous testing. Historical water use and well maintenance records may also be helpful.
- Geological setting – Information collected on the geological setting provides important context for the hydrogeological setting. This information includes both regional geology and geologic processes, as well as local geologic units and their areal extent, thickness, and material description (size, sorting, and stratification). Information on the geological setting should be sourced from reputable investigations.
- Hydrogeological setting – A description of the hydrogeological setting should include aquifer thickness and areal extent; any potential boundary conditions; recharge and discharge areas; nearby springs; depth to groundwater and generalized groundwater flow directions; and regional and/or seasonal water-level trends. Depending on the data objectives of a proposed project, previous water quality data collected may also be important. Information on the hydrogeological setting should be sourced from reputable investigations.

When gathering information for the conceptual site model, it may be helpful to use estimates of hydraulic properties to predict the results of a proposed withdrawal. This is referred to as forward modeling. When no suitable estimates of hydraulic properties exist, well test data collected from nearby well logs may be used to estimate transmissivity (Fetter, 2001). Slug test data are generally not reliable for estimating an aquifer's hydraulic properties and in some cases provide an erroneous estimate based on properties of the well's filter pack (EPA, 1993).

Initial step-drawdown test

A step-drawdown test is recommended before conducting an aquifer test to determine an appropriate pumping rate, corresponding to sustainable yield. If no step-drawdown test is conducted, the aquifer test should be conducted at a rate less than what the aquifer is known to produce. If an aquifer test is conducted at a pumping rate greater than what the aquifer can produce, it is unlikely that steady-state conditions will be encountered. Failure to reach steady-state conditions during an aquifer test may result in a need to repeat the test once the water-level has recovered to within 95% of pre-pumping conditions.

A step-drawdown test typically consists of four consecutive steps, each step having a higher pumping rate (see below). Ideally, each step should be conducted for a minimum duration of two hours, during which the water-level in the pumping well is measured. A pumping rate at which the water-level remains stable is referred to as a sustainable yield. True steady-state conditions are rarely encountered during a step-drawdown test and a factor of safety should be applied to the estimated sustainable yield. Recommended steps for a step-drawdown test are based on the maximum design rate of the well and include:

Step 1: 50% of the maximum design rate

Step 2: 75% of the maximum design rate

Step 3: The maximum design rate of the well

Step 4: 125% of the maximum design rate.

Some well operators find it helpful to calculate the specific capacity of the well following the step-drawdown test. Specific capacity is defined as the rate of discharge of a production well per unit drawdown and is calculated by dividing the pumping rate by the change in head for each step (Fetter, 2001). The general term "well efficiency" refers to an operational pumping rate of approximately 60 to 80 percent of specific capacity (Heath, 1983). Factors impacting well production and well efficiency include biofouling, fines in the well's filter pack, iron oxidation and other mineral precipitates. These conditions should be resolved with mechanical or chemical development methods before conducting an aquifer test.

Disposal of discharge water

Unless a step-drawdown test and aquifer test are conducted under the limits of a valid water right authorization, all discharge water generated during testing must be disposed of in accordance with state and local permit requirements and in a manner that will not interfere with data collection during testing. Failure to properly dispose of discharge water may result in the need to repeat the aquifer test. Ecology may require a discharge water management plan before testing to evaluate whether discharge water is likely to interfere with testing.

Aquifer test duration

In general, the drawdown portion of a constant-rate aquifer test should extend a minimum of 72 hours for unconfined conditions and 24 hours for confined conditions, and last until steady-state conditions are encountered. Ecology defines steady-state conditions as a rate of change in the pumping well of less than 0.1-foot per hour. The Washington State Department of Health defines steady-state conditions, or stabilized drawdown, as a drawdown of less than 0.5-foot for every 100 feet of water in the well for a minimum of six hours (DOH, 2019). Ecology recommends using the more conservative estimate when working with both agencies. Any questions on aquifer test duration should be discussed with a Water Resources Program hydrogeologist.

The recovery portion of a constant-rate aquifer test begins once steady-state conditions are encountered, and the pump has been shut-off, and lasts until the water-level in the pumping well has returned to within 95% of pre-pumping conditions. Aquifer test recovery data can provide valuable information on an aquifer's response to stress and, in the case of a variable pumping rate or interference during drawdown, may provide more reliable information on aquifer conditions encountered during testing.

Observation wells

To accurately estimate an aquifer's hydraulic properties, at least one observation well completed in the same aquifer as the pumping well should be monitored during drawdown and recovery. Data from an observation well are necessary to determine the storage coefficient of an aquifer. The number and placement of observation wells will depend on the conceptual site model, regulatory setting, and project objectives. If requirements for observation wells are outlined in a preliminary permit, they must be followed. Any questions on observation wells should be discussed with a Water Resources Program hydrogeologist.

Aquifer Test and Data Collection

An aquifer test is designed to exert a known stress on an aquifer so that the aquifer's response may be recorded. An aquifer's response is captured by drawdown and recovery data collected at the pumping well and all observation wells during the test. These water-level data are compared to baseline data collected before an aquifer test. This section reviews common baseline data collection, water-level measurements, and discharge rate measurements. Failure to collect useful and reliable data during an aquifer test may result in all or portions of the test being repeated.

Baseline data collection

Baseline data are important for establishing aquifer conditions before an aquifer test. The nature of baseline data collection will depend on the conceptual site model, regulatory setting, and project objectives. Recommendations on common baseline data collection are included here. In some cases, baseline data collected may indicate a need to monitor for interference during testing. Any questions on baseline data collection or potential sources of interference should be discussed with a Water Resources Program hydrogeologist before testing.

- Barometric pressure – The degree to which barometric pressure can influence water-levels in an aquifer is referred to as barometric efficiency. The barometric efficiency of an aquifer should be determined by comparing pre-test, baseline water-level data to barometric pressure data available either from a nearby weather station or a locally deployed barometric pressure transducer. If the influence of barometric pressure is significant, a barometric pressure transducer should be deployed at the pumping well during an aquifer test so data collected can be used for water-level data corrections.
- Well interference – There is a possibility that neighboring groundwater withdrawals may affect data collected during an aquifer test. To address this, nearby groundwater withdrawals should be investigated before conducting an aquifer test and, if possible, a test period selected when well interference can be avoided or minimized.
- Time of year – Ideally aquifer tests should be conducted when interference from recharge events will be minimal. Recharge can result from precipitation events, snowmelt, and reservoir operations. If a significant recharge event occurs during an aquifer test, the event should be documented in field notes. Depending on the magnitude of a recharge event, an aquifer test may need to be restarted once the water-level in the pumping well has returned to baseline conditions.
- Stream stage – If an aquifer test is conducted near a stream or river, the stage data should be reviewed in conjunction with baseline (non-pumping) groundwater-level data to determine the extent to which stream stage may affect the aquifer test. Historical and current stream stage data may be available through the USGS, Ecology's River and Stream Flow Monitoring Network, and other sources.

- Tidal influence – Depending on aquifer conditions, tidal influence may have an effect at significant distances from the salt water body. Tidal influence on an aquifer is often attenuated and delayed relative to the actual tidal event. If tidal influence is anticipated, baseline (non-pumping) water-level measurements should be compared to recorded tides, and a relationship determined for data correction.
- Water quality – If analytical testing is to occur due to potential seawater intrusion or groundwater contamination concerns, a Washington State Accredited Laboratory should be contacted in advance to obtain sample bottles and instructions for sample collection and transport under chain-of-custody procedures. To avoid sampling problems and potential source-water degradation in the test vicinity, work should be conducted in coordination with a Water Resources Program hydrogeologist and/or other applicable regulatory agencies.
- Seawater intrusion – If baseline water quality sample collection or information collected during development of the conceptual site model indicate potential seawater intrusion, consult with a Water Resources Program hydrogeologist before and during testing. To avoid potential source water degradation, an observation well located between the pumping well and saltwater body should be continuously monitored for conductivity during testing. Additionally, water quality samples for chloride and conductivity should be collected from the pumping well and observation wells at the start of pumping, midway through pumping, and near the conclusion of pumping.

Water-level measurements

Water-level measurements should be collected for at least one week before an aquifer test, in addition to during drawdown and recovery portions of the test. Baseline water-level measurements are collected to determine static (non-pumping) water levels and to evaluate any data trends that may interfere with the interpretation of aquifer test results. Water-level measurements collected during drawdown and recovery portions of an aquifer test are used to record the effect of a known stress applied to the aquifer.

Water-level measurements should be collected with a pressure transducer and e-tape (for manual measurements) at the pumping well and observation wells. The pressure transducer should be set to a minimum recording frequency of 30 seconds or be programmed using the schedule for manual water level measurements below as a minimum standard. Manual water level measurements collected with e-tape are a valuable data source for the hydrogeologist or engineer overseeing an aquifer test as they provide a field check for transducer data and a source for correction, if needed. All water-level measurements collected during testing should be made available to Ecology upon request.

Table 1: Recommended manual water-level measurement schedule

Test Duration (Drawdown or Recovery)	Measurement Interval (Pumping Well)
0 – 10 minutes	30 seconds
10 – 60 minutes	1 minute
60 – 360 minutes	30 minutes
360 – end of test	60 minutes

Table 1 applies to manual water-level measurement collection at the pumping well during both drawdown and recovery portions of an aquifer test. Manual water-level measurements should be collected at regular intervals for all observation wells. It is important to collect manual water-level measurements during testing to verify pressure transducer data and in the event of instrument malfunction or failure. Additionally, manual water-level measurements are used to create time-drawdown plots during testing for field interpretation. All manual measurements should be carefully recorded using field data sheets.

Discharge rate measurements

During the drawdown portion of an aquifer test, the discharge rate must remain within 5% of the target pumping rate. Collect regular discharge rate measurements using an operable flowmeter and record the measurements on field data sheets. Any correction to the discharge rate should be recorded in the comments. A variable pumping rate during an aquifer test may not yield useful and reliable data, and may result in all or portions of the test having to be repeated.

Data Correction and Analysis

Once an aquifer test has been completed, data correction (as applicable) and analysis can occur. Data correction reduces "noise" associated with natural fluctuations in water-level (drawdown) data, like that caused by tidal influence or barometric pressure changes. Data analysis generally refers to the review and interpretation of drawdown data and use of analytical models to estimate the hydraulic properties of aquifers, including effects of leaky confining units and boundary conditions. In this section, data correction and estimation of hydraulic properties are reviewed, along with suggestions for helpful resources.

Data Correction

If aquifer drawdown data (water levels) collected during an aquifer test have been significantly influenced by tides or changes in barometric pressure, then correction of the drawdown data should occur. Data correction will reduce "noise" associated with natural fluctuations and help during interpretation of flow regimes and identification of an appropriate analytical model used to estimate hydraulic properties. Open access worksheets for data correction, like that available with the Microsoft Excel Add-in, SeriesSEE, developed by the USGS (Halford et al., 2012), can be used to conduct data corrections.

Estimating hydraulic properties

Aquifer properties can be estimated using open-source spreadsheets or commercially available aquifer test software. Although estimating hydraulic properties of aquifers is relatively straightforward, it is critical that the analytical model selected be appropriate for aquifer conditions encountered during testing. The conceptual site model developed before the aquifer test will help with initial interpretation of aquifer conditions. Information contained in Appendix B may also be helpful, as it discusses flow regime identification using type curves of common analytical models and their derivative.

An open source spreadsheet for the analysis of aquifer test data is available from the USGS (Halford and Kuniansky, 2004). For complex flow regimes, it may be helpful to use software that has a library of analytical models that can be applied to find the best match. For a helpful guide on selecting an appropriate analytical model, see ASTM's Standard Guide for Selection of Aquifer Test Method in Determining Hydraulic Properties by Well Techniques (ASTM, 2017).

Report and Data Submittal

An aquifer test report should be prepared by the hydrogeologist or engineer that designed and oversaw testing and should follow a standard report outline. This section reviews figures, charts, and appendices that may be required with the aquifer test report, depending on the individual project objectives and regulatory environment. If an aquifer test was conducted under a preliminary permit, any reporting requirements prescribed must be followed.

Aquifer test report figures may include:

- Site and vicinity map – including the pumping well, all observation wells, nearby streams and surface water features (springs, wetlands), and where discharge water was disposed of during testing. It is generally helpful to include topographic lines, and township, range, and section on the site and vicinity map.
- Cross-section(s) depicting bulk hydrostratigraphy with reference map – including aquifers and aquitards; piezometric surface; surface water bodies; geologic structures affecting flow; and the pumping and observation wells' casing and screened interval.
- Groundwater contour maps – if sufficient data exist, a groundwater contour map can be created that depicts groundwater flow at baseline and during maximum drawdown.

Aquifer test report charts may include:

- A semi-log plot of time-drawdown data at the pumping well and all observation wells.
- A plot of distance-drawdown using at least one observation well.
- Charts of baseline data collected as well as data from other sources, for example barometric pressure data from a nearby weather station and tides from a nearby NOAA station.

Aquifer test report appendices may include:

- Copies of water well reports for the pumping well and observation wells.
- Copies of all field data sheets.
- Copies of all analytical reports and chains-of-custody for water quality samples collected.
- All uncorrected and corrected data as well as any data used for correction. These data should be provided in a digital format, be clearly labeled, and have consistent units.
- The results of previous aquifer testing or other investigations performed in support of the proposed project.

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Appendices

Appendix A. Background on Hydrogeologic Principles

Within an aquifer, groundwater flows from high to low head under a hydraulic gradient. Hydraulic conductivity is a measure of the ability of an aquifer to transmit water under the effect of a hydraulic gradient and is a function of aquifer materials. Depending on aquifer materials, hydraulic conductivity can range by 12 orders of magnitude (Table 1). Sometimes hydraulic conductivity can vary by several orders of magnitude within the same hydrogeologic unit.

Table A: Hydraulic conductivities as adapted from Domenico and Schwartz (1990)

Unconsolidated Material	Hydraulic Conductivity (m/sec)	Rock Type	Hydraulic Conductivity (m/sec)
Gravel	3×10^{-4} to 3×10^{-2}	Shale	1×10^{-13} to 2×10^{-9}
Medium Sand	9×10^{-7} to 5×10^{-4}	Weathered granite	3.3×10^{-6} to 5.2×10^{-5}
Fine Sand	2×10^{-7} to 2×10^{-4}	Permeable basalt	4×10^{-7} to 2×10^{-2}
Till	$1\times10\text{-}^{12}$ to 2×10^{-6}	Fractured rock	8×10^{-9} to 3×10^{-4}
Clay	1×10^{-11} to 4.7×10^{-9}	Basalt	2×10^{-11} to 4.2×10^{-7}

Transmissivity is a term that describes an aquifer's ability to transmit groundwater throughout its saturated thickness and is the product of an aquifer's hydraulic conductivity and the aquifer's saturated thickness. The storage coefficient of an aquifer (also referred to as storativity) is the ability of the aquifer to release groundwater from storage due to a change in head. The storage coefficient can vary widely depending on whether the aquifer is confined or unconfined.

An aquifer's response to the withdrawal of groundwater during an aquifer test depends on the transmissivity and storage coefficient of the aquifer. An unconfined aquifer releases groundwater from storage under gravity drainage and the storage coefficient typically ranges from 0.1 to 0.3 (Lohman, 1972). For a confined aquifer, groundwater is only released from storage by compaction of the mineral skeleton and expansion of water. The storage coefficient of confined aquifers typically ranges from 5×10^{-5} to 5×10^{-3} (Todd, 1980), or approximately 100 to 10,000 times less than for unconfined aquifers.

When groundwater is withdrawn from a well, the water-level declines within the well casing and neighboring aquifer and groundwater begins to flow from aquifer storage into the well. This movement of groundwater into the well creates a "cone of depression." For an unconfined aquifer, the cone of depression is expressed in the water table surface. In a confined aquifer, the cone of depression is expressed in the potentiometric surface of the aquifer, corresponding to a relative pressure head.

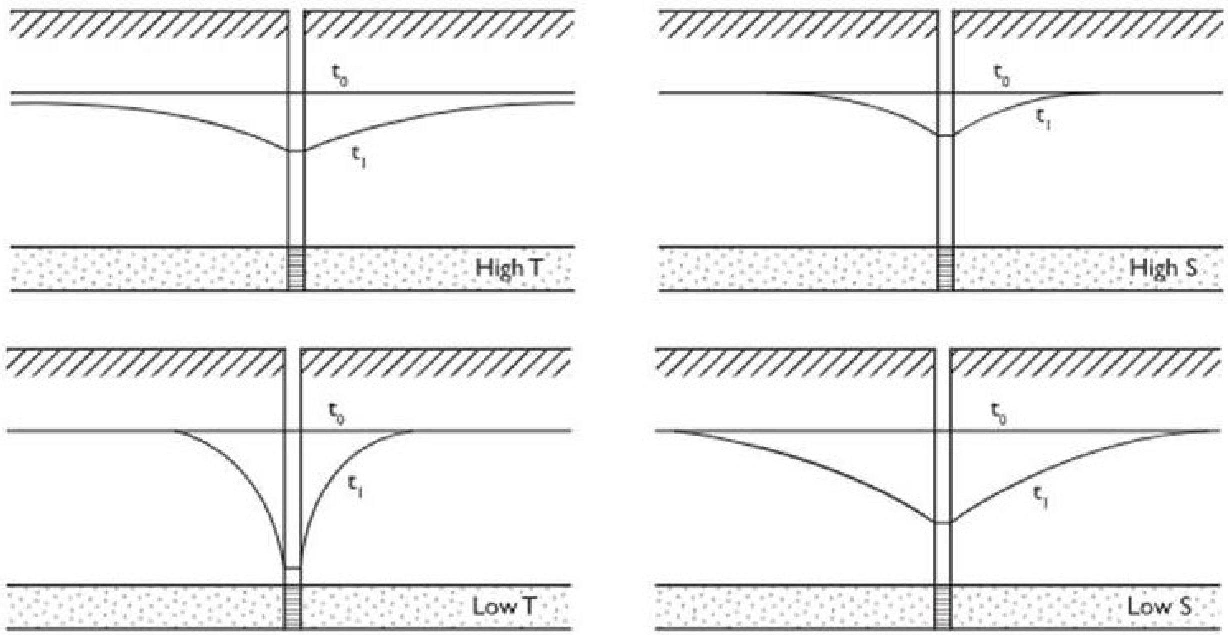

Figure A: Comparison of cones of depression as adapted from Freeze and Cherry (1979)

As shown in Figure A above, adapted from Freeze and Cherry (1979), an aquifer's response to drawdown depends on aquifer characteristics, including transmissivity (T) and the storage coefficient (S). This figure depicts baseline (non-pumping) conditions (t_0), and conditions during drawdown, when the well is being pumped (t_1).

An aquifer with high transmissivity will have a shallow cone of depression that spreads out over a large area as the aquifer quickly responds to the change in head. An aquifer with low transmissivity has a relatively small impacted area and deep cone of depression as the change in head is not readily transmitted to the surrounding aquifer and the deep cone of depression is needed to drive groundwater into the well.

An aquifer with a high storativity will have a relatively small cone of depression as groundwater is readily released from storage, or "dewatered" due to a change in head. An aquifer with low storativity will release much less groundwater from storage due to a change in head and therefore must dewater a much larger area to compensate for the groundwater withdrawal.

As groundwater continues to be withdrawn from a pumped well, the cone of depression expands until the rate of groundwater withdrawal is equal to an increase in aquifer recharge and/or a decrease in discharge. This is referred to as "steady state" conditions. During steady-state conditions, the water-level in the well is at maximum drawdown and the cone of depression is stable. Most aquifer tests are conducted until steady-state conditions are encountered.

Appendix B. Flow Regime Identification and Derivative Analysis

Following any correction(s) to aquifer test data, it may be helpful to compare time-drawdown data to theoretical models for different aquifer conditions or flow regimes (i.e., unconfined aquifer, confined and leaky aquifer, etc.). Comparison of time-drawdown data to the characteristic shape of theoretical models can help interpret the results of an aquifer test and determine which analytical model to choose when estimating hydraulic properties. A conceptual site model is useful during this step to help resolve uncertainty.

Derivative analysis can support flow regime identification by drawing attention to small changes in the rate of drawdown that may indicate a specific condition, like a no-flow boundary, that has been encountered. However, derivative analysis has the effect of amplifying noisy data and may require the initial step of data interpolation or other methods to smooth the dataset. To perform derivative analysis, the logarithmic (log) derivative of discrete drawdown (s_i) at time (t_i) values must first be calculated using the following equation, adapted from Renard et al. (2009).

$$\frac{ds}{dlnt_i} = \frac{s_i - s_{i-1}}{\ln(t_i) - \ln(t_{i-1})}$$

Then, plot the derivative with the time-drawdown data on a semi-log and log-log plot. These plots can be used to compare the dataset to theoretical models (also known as type curves). Figure B below depicts several theoretical models for common flow regimes, along with their derivatives, as adapted from Renard et al., 2009. Different flow regimes yield similar characteristics and the derivative of the respective dataset, indicating the rate of change in drawdown, can be useful to identify the dominant flow regime and if any changes, including boundary conditions were encountered.

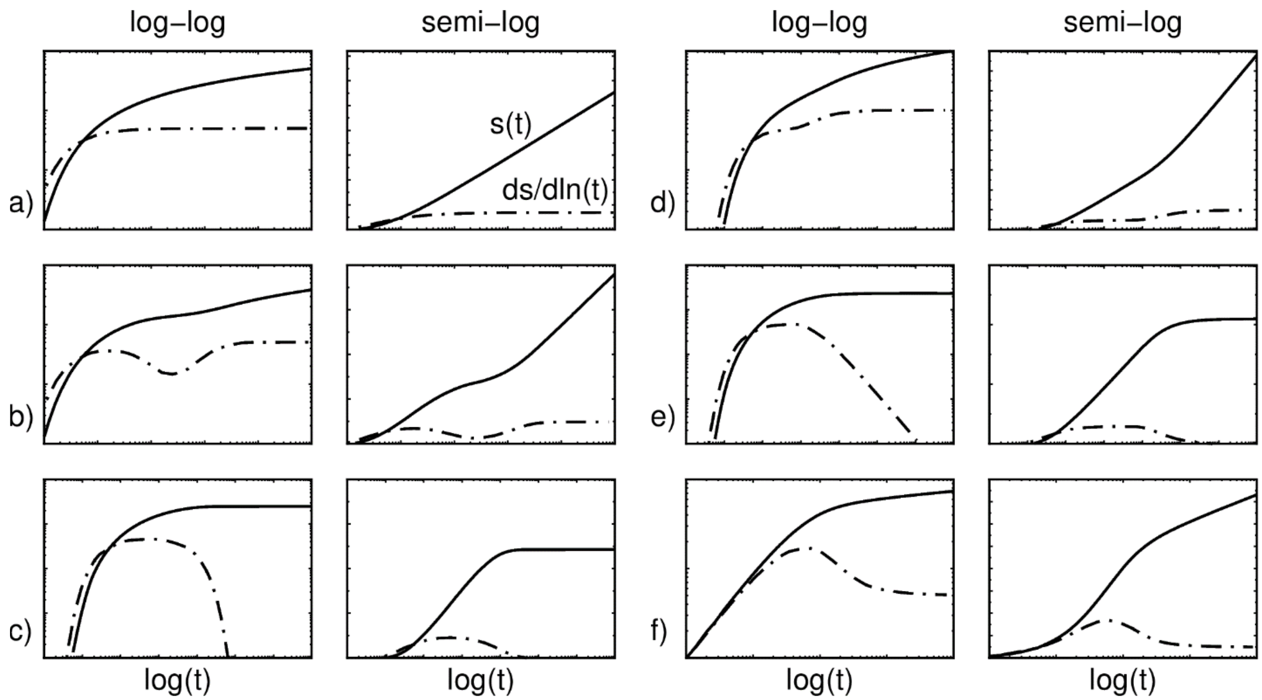

Figure B: Type curves with their derivative, as adapted from Renard et al. (2009)

The theoretical models above are for a confined aquifer (a); unconfined aquifer (b); leaky confined aquifer (c); no-flow boundary (d); constant-head boundary (e); and wellbore storage and skin effect (f). The vertical axis represents drawdown (s) and the horizontal axis represents time (t). The solid line represents the theoretical model and the dashed line, the model's derivative. See below for a discussion on the identifying characteristics of each theoretical model.

- Confined aquifer (a) – For true confined aquifer conditions, the drawdown will reach a steady rate of decline as the radius of influence expands. Because the rate of drawdown is constant, the derivative (dashed line), indicating the rate of change, is flat. This is the condition necessary to apply the Cooper-Jacob straight line approximation (Cooper and Jacob, 1946) to estimate hydraulic properties.
- Unconfined aquifer (b) – The characteristic shape of the theoretical model for unconfined aquifer conditions is dominated by delayed yield. The concept of delayed yield can be seen in mid-time where the rate of drawdown is lowered as a result of induced drainage from the unsaturated zone. Note that unconfined conditions are not the only flow regime where delayed yield is observed. In systems where there is double porosity, like that of a confined fractured aquifer, the same characteristic shape is observed (Kruseman and de Ridder, 1994).
- Leaky confined aquifer (c) – The type curve for the leaky confined aquifer represents flow within an aquifer with a semi-confining aquitard. At early time the plot appears similar to the confined aquifer, however, at mid-time the effect of leakage is visible as the drawdown

stabilizes. At late-time, the leakage is balanced by the rate of withdrawal at the pumping well, and the derivative (dashed line) drops to zero, indicating steady-state conditions.

- No-flow boundary (d); – The theoretical model presented here for a no-flow boundary assumes an infinite linear boundary to groundwater flow. The identifying characteristic of this flow regime is the inflection in the rate of drawdown when the no-flow boundary is encountered. This is best represented by the semi-log plot where the rate of drawdown appears to double based on the observed change in the derivative (dashed line).
- Constant-head boundary (e) – For the purpose of comparison, the flow regime appears identical in early time as the no-flow boundary condition discussed above. However, at the time a constant-head boundary is encountered, the rate of drawdown stabilizes. At late-time, the reduced discharge and/or increased recharge from the constant-head boundary is balanced by the rate of withdrawal and the derivative (dashed line) drops to zero, indicating steady-state conditions.
- Wellbore storage and skin effect (f) – The effects of wellbore storage and skin effect (positive) produce the same theoretical model (Renard et al., 2009). The identifying characteristic of the flow regime is the reduced rate of drawdown at mid-time before the drawdown rate stabilizes at the reduced rate in late-time. The change to a reduced rate of drawdown creates a hump shape that is dependent on the amount of wellbore storage and/or the reduced transmissivity from the positive skin effect around the well.

Additional theoretical models or type curves can be found in Renard et al. (2009). A discussion of theoretical models, boundary conditions, and the effects of partial penetration can be found in Kruseman and de Ridder (1994). Another source for theoretical models, including a catalogue of derivative plots, can be found through HydroSOLVE, Inc., makers of aquifer test interpretation software, Aqtesolv. Website: aqtesolv.com/pumping-tests/derivative-analysis.htm