Appendix E: Recommended Pumping Test Procedures

1.0 Introduction

This aquifer pumping test procedures document specifies the minimum pumping test procedures that DOH considers sufficient for demonstrating that a new source is capable of providing a safe and reliable yield of water for the water system. This pumping test procedures document was prepared to provide Group A water systems with basic information suitable to develop an approach to satisfy the source approval requirements in WAC 246-290-130 (3)(c)(iii) and (3)(d). Information is presented to enable a water system to address DOH concerns regarding the most commonly encountered aquifer conditions or hydrogeologic settings across the state. Situations involving complex hydrogeolgic settings, however, may require a high level of expertise and experience to adequately design and evaluate pumping tests for demonstrating source reliability. Stand-alone pumping test procedures specifying the minimum steps DOH consider adequate are presented at the end of this document. A discussion of the basic components of a pumping test is also provided to assist with understanding the procedures presented in this document. The intent of this document, however, is not to provide a detailed step-by-step approach for conducting or analyzing a pumping test. Numerous references provide detailed, industry-accepted information on designing the specifics of a pumping or aquifer test. A list of selected references is provided at the end of Section 5.0 of this document.

The principal objective of the pumping test is to obtain adequate information for DOH to evaluate whether a source is capable of reliably providing a safe yield of groundwater. This objective differs somewhat from the Department of Ecology's whose concern is focused on overall protection of the aquifer. In establishing water rights, the Department of Ecology evaluates withdrawals from all users and recharge to the aquifer, and considers future water needs from the aquifer.

This procedures document is not intended to evaluate the aquifer as a water resource, but rather to establish the ability of the source to meet the design pumping rate. Reliability considers the ability of the source over time to meet normal conditions of operation, without adversely affecting the water quality or quantity demands of the water system. The reliability of groundwater yield requires that the pumping test results can be projected for some time into the future. From DOH's perspective, a properly conducted pumping test is the best basis from which to judge a source's current and future reliability. A pumping test can indicate lateral flow boundaries, hydraulic continuity, constraints of fracture flow, and recharge. All of these can be important factors in establishing reliability. From the water system's perspective, the pumping test is the best method by which to size and establish the optimal depth setting of the pump, as well as, establish water system storage and operational needs. Proper pump sizing and depth selection can provide considerable savings to a water system over the lifetime of the well, through reduced power consumption and maintenance costs.

WAC 246-290-130(c)(iii) states that one acceptable approach for demonstrating source reliability is to conduct a pumping test at the maximum design rate and duration. For DOH to make a source reliability assessment, Section 7.3 and Appendix F specify the pumping test and hydraulic parameter information that should be submitted to DOH in a project report.

Those information requests pertaining to the pumping test portion of the report are summarized below:

- Measurements of the static water level prior to pumping (in the test well and observation wells, if any);
- All water level data for both the pumping and recovery phases of the pumping test;
- Graphical presentations of the data, as appropriate;
- Transmissivity, saturated thickness, and hydraulic conductivity values/calculations for the producing aquifer;
- Storage coefficient and specific yield for the producing aquifer;
- Delineation of the 6-month, 1-, 5-, and 10-year time-of-travel zones for each well;
- Identification of any hydraulic connection with surface water; and
- Conveyance of pumped water.

This document is divided into three main sections.

1. Section 2.0 discusses the rationale of DOH basic pumping test procedures, and the general approach for a water system to use when determining a pumping test protocol for obtaining DOH new source approval. This is followed by a discussion of special aquifer settings DOH has identified as having greater potential for concern regarding water quality and the ability of the aquifer to provide a reliable source of water. Section 3.0 also describes the basic pumping test requirements, provides the rationale behind their selection, and presents a flow chart for a water system to follow for selecting a pumping test.
2. Section 4.0 discusses what to do if the test is improperly conducted or goes wrong, and at what point the test would probably not produce adequate data for DOH to conduct a source reliability evaluation.
3. Section 5.0 discusses pumping test components and defines terms used throughout this document.

The stand-alone pumping test procedures for each of the basic pumping tests are provided at the end of this document. These procedures summarize the basic instructions for the step drawdown and constant rate discharge-pumping test, including specific instructions for sources with concern for saltwater intrusion.

2.0 Basic Pumping Test Approach

Various aquifer settings can be encountered when evaluating source reliability. For most settings, source reliability will be defined sufficiently by conducting one or two basic pumping tests. If necessary, adjustments can be made to the basic pumping test to address aquifer settings needing more rigorous data collection and analysis.

Under WAC 246-290-130(c)(iii), DOH requires that a minimum of two components be addressed when determining whether the source will be able to produce a reliable groundwater yield. The first component is to determine the pump size and depth setting appropriate for the aquifer and well. In most cases, this will require that a step drawdown test be conducted. The second component is to determine whether this pumping rate can be maintained for some time into the future. This test of reliability is accomplished by conducting a constant rate discharge test. Under certain conditions, a single test—either a step drawdown or constant rate test—may be adequate.

What is a step drawdown test? The step drawdown test is similar to the constant-rate discharge test in many respects. The major difference being that the step drawdown test consists of several short-duration, constant-rate discharge tests—each run at a progressively higher pumping rate. The minimum suggested *step drawdown* test consists of at least four different pumping rates, each conducted for a minimum duration of 60 minutes. It is important, however, to run the initial step long enough to establish that the effects of well storage have dissipated. The remaining steps should each be run for the same duration as the initial step.

This step drawdown test provides a range of specific capacities for the well and is therefore, the most reliable method for determining the pump size and setting. This test produces minimal aquifer information, however, and will likely not identify impermeable boundaries, recharge boundaries, interferences from other wells, or conditions of groundwater under the influence of surface water, unless these conditions exist in very close proximity to the well being tested.

In most cases, a step drawdown test would be recommended to establish the optimal pumping rate and depth for water system operation and to determine the pumping rate at which the constant rate discharge test should be conducted. As mentioned, the step drawdown test produces minimal information regarding aquifer characteristics and generally does not involve observation wells. Therefore, where information on long-term productivity is critical or lacking, a constant rate discharge test is needed.

The following paragraphs provide the basic pumping test recommendations for water systems seeking new source approval or water system expansion where an existing source is utilized. Information is also provided about DOH approaches and concerns to be addressed when the aquifer response to pumping is anticipated to differ from a "standard" setting. "Standard" applies to a wide range of conditions that could be encountered in source development. For the pumping test requirements, a standard setting is defined as one in which water quality and water reliability concerns are expected to be minimal. Within the standard setting, the results of the pumping test could indicate the presence of flow boundaries (impermeable or recharge) and that the source is in direct hydraulic connection with surface water. Encountering these conditions during a pumping test does not necessarily indicate that there are concerns from a water quality or a source reliability standpoint.

Table 1 in this Appendix has the hydraulic parameters that can be determined directly from the pumping tests or a pumping test measurement component. Some parameters may be determined in more than one manner. To determine all of the requested reporting information, however, it is necessary to collect data during all aspects of a pumping test.

A pumping test is likely necessary under either of the following situations: 1) new source approval or expansion of an existing water system, and 2) source capacity may be in question (WAC 246-290-130(c)(iii)). Table 2 presents the pumping test recommendations for the aquifer settings most likely to be encountered during development of a new source. In most cases, an initial step drawdown test is recommended. There is only one condition where the step drawdown test is not believed advisable. This condition occurs in standard aquifer settings where adequate hydrogeological information exists to establish a sustainable pumping rate. This situation could include a new source that will be used in a multiple well, paired well, or tandem well configuration.

Figure 1 is a flow chart, which can be used to establish the appropriate pumping test, and to identify those concerns to be addressed in a report sent to DOH. As an initial step, a water system would be expected to review any existing hydrogeologic information to assist in identifying any concerns which careful pumping test design could address. In many situations, including standard aquifer settings and any areas of existing water quality or quantity concerns, a water system would be expected to conduct *at a minimum*, a four-point step drawdown test. This would be followed by a minimum, 24-hour constant rate discharge test with a minimum of 4 hours of stabilized drawdown data and completed with the collection of recovery data. The constant rate discharge test would be conducted at the pump settings determined from the step drawdown test and after aquifer recovery from the test. As a general rule, the aquifer should be allowed to recover to within 95 percent of the static water level as measured prior to conducting the step drawdown test. In situations common to small water systems, where a low demand source is completed in a high productivity aquifer, it is expected that running the final step of the step drawdown test until 4 hours of stabilized drawdown data have been collected will be sufficient to establish source reliability. An example of this situation is a small water system with a source completed in a high flow aquifer where drawdown stabilization would be expected to occur quite rapidly.

Table 1: Data Provided by Pumping Test and Drawdown Measurements

Step Drawdown Test	Constant Rate Test	Recovery Data	Observation Wells Data
Well Efficiency, Pumping Rate (Q), Transmissivity (T), Specific Capacity (sc), Yield	T, sc, Hydraulic Conductivity (K), Yield	T, S	S

Definitions	Comments
Pumping Rate (Q) = gallons per minute [gpm]	None
Yield = volume/time [gpm]	None
Specific Capacity (sc) = yield/drawdown [gpm/ft]	Allows well yields to be calculated at various drawdown levels. This information is needed to determine the maximum yield of the well and can be used to examine the economics of well operation at a given yield.
Transmissivity (T) = K*b [gpd/ft], (K = hydraulic conductivity [gal/day/ft^2] and b = aquifer thickness [ft])	Transmissivity can also be calculated from the pumping test graphical solution using either the Nonequilibrium Well Equation or the Modified Nonequilibrium Equation. This value provides a measure of how much water will move through the aquifer as defined by a 1-ft wide vertical strip extending through the full, saturated thickness of the aquifer, under a hydraulic gradient of 1.
Coefficient of Storage (S) = [dimensionless], can be calculated directly from the pumping test graphical solution using either the Nonequilibrium Well Equation or the Modified Nonequilibrium Equation	This provides a measure of how much water can be pumped or drained from the aquifer per unit of aquifer storage area per unit change in head. This value can only be calculated if observation wells are incorporated into the pumping test. *If no observation wells;* for a confined aquifer, a value of $sc = 5 \times 10^{-4}$ may be used; for an unconfined aquifer, a value of $sc = 0.1$ may be assumed for calculations of well performance and interference between wells.
Well Efficiency = theoretical drawdown/actual drawdown [dimensionless], expressed as a percent	Highly inefficient wells may or may not be something that can be addressed. This information can be very valuable if additional wells are planned or can indicate that the well would benefit from further or re-development.

Table 2: Aquifer Settings and Appropriate Tests

Setting Description	Step Drawdown Test	Constant Rate Test	Recovery Data	Observation Wells
Standard Aquifer Setting				
No Expected Problems Or Concerns With Aquifer Productivity	Yes[1] (recommended)	Yes (optional)	Yes (recommended)	Should be used if available
Special Aquifer Settings (at Q established by step drawdown test)				
Low Flow Conditions	Yes	Yes	Yes	No
Fracture Flow	Yes	Yes	Yes	Should be used if available
Aquifer Of Limited Areal Extent	Yes	Yes	Yes	Should be used if available
Saltwater Intrusion Potential	Yes	Yes	Yes	Should be used if available
Multiple Wells/Tandem Wells	Not Necessary	New well only	Yes	Yes

[1] In settings of a high productivity aquifer, low demand source, and no water quality issues; to demonstrate source reliability, the final step should be run until four hours of stabilized drawdown data have been collected and well recovery should be measured. Under these circumstances only, a constant rate test is unnecessary.

How to set pumping rate (Q) for ***step drawdown*** *discharge test*:

1. Set Q as follows:
   Use the maximum design pumping rate as Q for the 3rd step. Multiply this value by 0.5, 0.75, and 1.25 to obtain Q for the 1st, 2nd and 4th steps, respectively.

How to set pumping rate (Q) for ***constant rate*** *discharge test*:

<u>Method (in order of preference)</u>

1. Conduct step drawdown test to establish optimal Q, or if step drawdown test is **not necessary**

a. use maximum design pumping rate.

b. check with other aquifer test results conducted in the area.

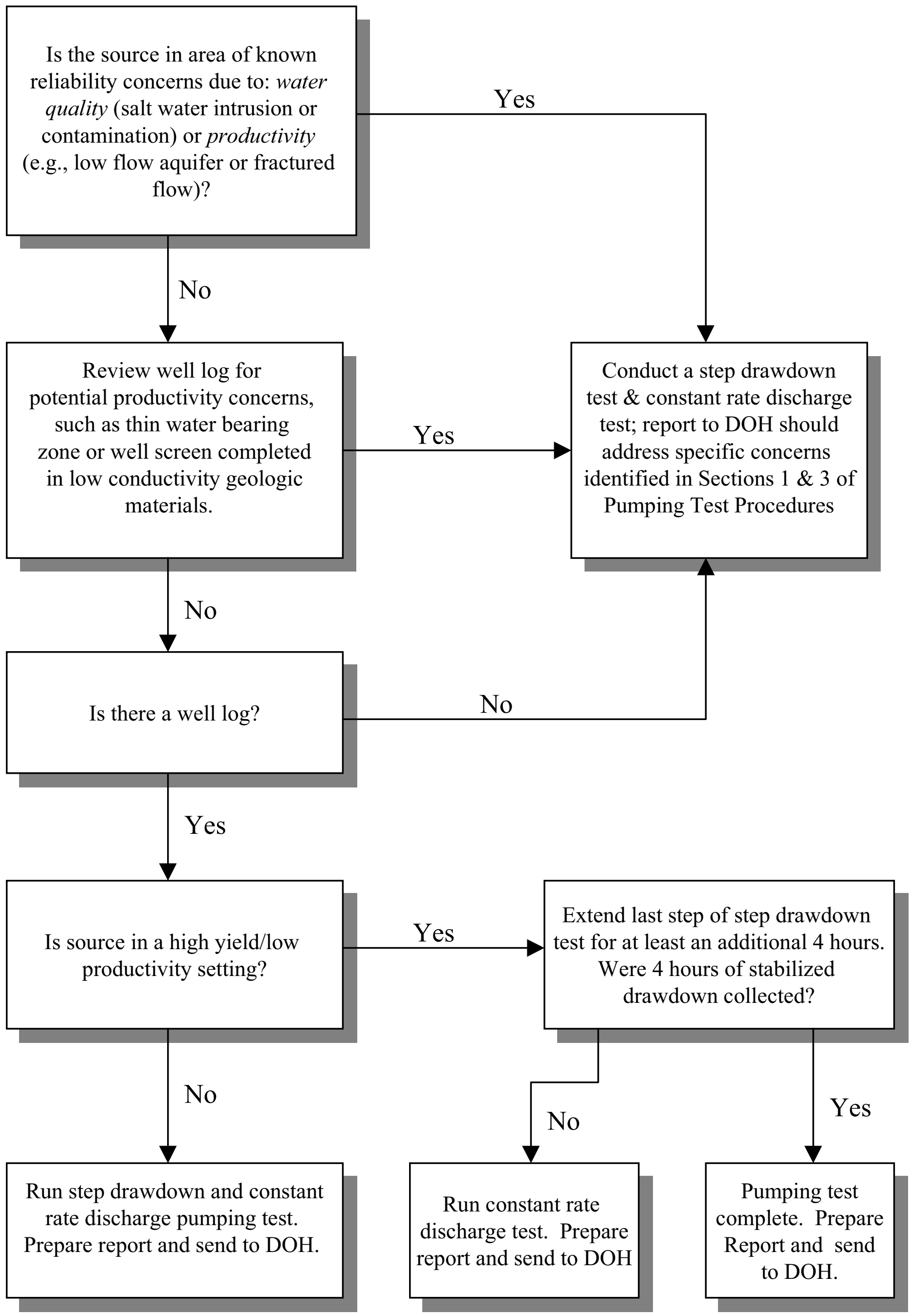

Figure 1

PUMPING TEST
PROCESS FLOW CHART

3.0 Pumping Test Concerns in Special Aquifer Settings

Several aquifer settings have been identified as having a greater potential for reliability concerns and were presented on Table 2. Reliability concerns include both water quality concerns (such as high chloride levels or other contaminants) and water quantity concerns (such as seasonal availability or aquifer continuity). Typically, these aquifer settings do not require that different types of pumping tests be conducted. However, they may require a longer test or more rigorous analysis of certain aspects of the pumping test results. Because of the greater difficulty and complexity in pumping test design and evaluation presented by these settings, consultation with an experienced hydrogeologist or engineer may be advisable. DOH information elements and concerns unique to these conditions are discussed below.

Low Flow Conditions

Low flow conditions could be encountered for wells completed in materials of low hydraulic conductivity such as silts, sandy clays or sandy silts, weathered sandstone, and other weathered consolidated materials. In these cases, the ability of the well and aquifer to produce at the required pumping rate is of concern, not necessarily the quantity of water available. Turbulent flow induced during pumping can result in a significant decrease in aquifer performance with increasing pumping rate. Therefore, a step drawdown test is recommended to determine the specific capacity, yield, and the optimal pump settings.

Because it is unlikely that boundary conditions would be encountered in low-flow conditions during the step drawdown test, a constant rate discharge test is also recommended. The maximum pump setting, as determined from the step drawdown test, should be used for the constant rate discharge test. The constant rate discharge test should be run after the static water level has stabilized at initial levels (following the step drawdown test recovery period). DOH is interested in an evaluation of aquifer stabilization and constant-rate discharge test drawdown effects to demonstrate longer-term reliability of the source. Observation wells are not necessary, even if available, because effects of pumping in low-flow conditions are typically not far reaching.

Fracture Flow

DOH concern for fractured material is based on whether the source is adequately evaluated to demonstrate that pumping requirements can be met over the long term. Typically, sources completed in bedrock composed of shale, basalt, granite or any consolidated material can have fractured flow concerns. The continuity of fractures can vary significantly within an aquifer and affect its ability to provide water in a consistent manner. This difficulty may be compounded by a lack of seasonal source reliability. Recharge may vary seasonally and cause production problems in low flow periods (low water level and low recharge). During these periods excessive drawdown may occur. Because of these concerns, each source must demonstrate an ability to provide a safe and reliable yield.

The reliability of an individual source in the aquifer does not define the reliability of other sources in this type of setting. A step drawdown test is recommended to determine the optimal pump setting for consistent yield. A constant rate discharge test is also recommended to demonstrate long-term reliability. The constant rate discharge test should be conducted at the optimal pumping rate and pump depth setting indicated by the step drawdown test results.

Restrictive conditions identified by the pumping test could include lack of stabilization, for example, drawdown continues to increase with time. This could signify that recharge does not occur within the aquifer at a rate sufficient to maintain consistent discharge at the desired pumping rate. It is also possible that the rate of drawdown decreases with time. This effect would suggest that a recharge boundary was encountered and that the source could be capable of producing a reliable yield. Observation wells should be used if available, because measurement of drawdown in these wells can provide an indication of the extensiveness and interconnectivity of the fractures. Selection of appropriate observation wells in a fractured setting, however, can be problematic and may warrant input from a hydrogeologist or engineer experienced in pumping test design.

Aquifer of Limited Areal Extent

This aquifer condition presents the same type of concerns as fracture flow. Although wells in this setting may initially be able to provide a reliable source of water, because of limited areal extent and recharge capacity, these aquifers may be unable to produce over the long term at the desired pumping rate. These aquifers are commonly made up of highly variable material, which may also show significant variation in its ability to transmit water. For this reason, a step drawdown test is recommended to determine the pump depth and settings. Again, because of the often variable nature of the geologic materials throughout the water-bearing zone, a constant rate discharge test is recommended to identify any recharge boundaries or impermeable boundaries. The characteristics of the data and their significance are similar to those presented above in the discussion for fractured flow. If available, observation wells should be used so that the coefficient of storage can be determined as accurately as possible.

Saltwater Intrusion

In addition to demonstrating that the well and aquifer are capable of producing a reliable yield of groundwater, an assessment of the potential for inducing saltwater intrusion in the pumping well or nearby wells is also requested. The pumping test recommendations are identical to those previously discussed in the special aquifer settings. Initially, the pump settings are determined by the results of a step drawdown test, which is followed with a constant rate discharge test to assess the longer-term reliability of the aquifer. Ideally, observation wells should be selected so that they are positioned between the pumping well and the saltwater body. In situations where observation wells are present but in less desirable locations, it is still recommended that those wells be used to allow calculation of storage coefficient and other hydraulic parameters data. In areas where the potential for saltwater intrusion is high, it is also important to evaluate tidal influences prior to conducting the pumping test. This is also a situation where because of the complexity of pumping test design and evaluation, input from an experienced hydrogeologist or engineer may be beneficial.

Pumping tests in potential saltwater intrusion areas differ from the other aquifer settings primarily in that, water quality tests for chloride and specific conductance are needed in both the pumped wells and observation wells at specific intervals throughout the aquifer test period. These water quality indicators are monitored in the field using instruments specific to these parameters. Water quality measurements are to be made to determine whether concentrations are increasing, potentially signifying that saltwater is being drawn towards the pumping well. Stabilization in drawdown or the presence of a recharge boundary without an associated increase in chloride levels in the pumping well or observation wells would be favorable in demonstrating source reliability.

Multiple Wells/Tandem Wells

This setting refers to two or more wells completed in the same aquifer that will be pumped either cyclically or concurrently. DOH's primary concern in this setting is whether the new well interferes with other wells pumped by the water system or with aquifer recovery. Because of the variety of water system needs addressed by adding an additional well(s), it is recommended that the purveyor contact DOH to discuss a pumping test approach prior to actually conducting the test. This is also a situation where because of the complexity of pumping test design and evaluation, input from an experienced hydrogeologist or engineer may be beneficial.

In situations where a pumping test has been conducted for an existing well and data was also collected from an observation well(s), the potential for well interference due to adding an additional well can be determined using a distance-drawdown graph and evaluating additive drawdown for all pumping wells. In many instances, conducting an additional pumping test exclusively on the new well would provide little new information beyond validating the findings of the initial pumping test, unless it was conducted at the total concurrent pumping rate. In general, an evaluation of potential well interference for either cyclical or concurrent pumping can be determined using this approach. If an observation well was not used during the pumping test the same approach can be used, however, the results will likely be less accurate in predicting well interference.

Depending upon the new maximum design pumping rate and desired yield, however, this approach alone can fall short in demonstrating the ability of the aquifer to recover under the new pumping configuration. Therefore, in settings where the new maximum design pumping rate would significantly increase the required aquifer yield, DOH may request that a constant rate pumping test be conducted using the proposed maximum design pumping rate for all wells that would be concurrently pumped. For this reason, DOH considers each source approval in a multiple well/tandem well setting to be a unique situation and DOH should be consulted during the pumping test development process.

4.0 When Problems With Pumping Tests Occur

Tables 3 and 4 provide information regarding some of the more typical problems that can occur when conducting the step drawdown and constant rate discharge pumping test, respectively. The significance of these problems varies according to how far into the test they occur and to what degree they are caused by the aquifer responding to the pumping test or are due to human error.

These potential problems are discussed in terms of, at what point would DOH question the ability of the pumping test to demonstrate source reliability. This will vary, however, depending on how much information has been obtained from the pumping test and what the information provides towards establishing source reliability. As indicated in the tables, not all problems or situations would result in a recommendation that the pumping test be repeated.

5.0 Pumping Test Components

The following components require consideration when designing a pumping test. The information presented is not intended to be a resource on all aspects of pumping tests, but rather to provide an idea of the considerations necessary to plan a pumping test and to supplement the information presented in the individual policies presented later in this procedures document.

Duration

The duration of the pumping test is specified within each of the individual pumping test methodologies provided later in this appendix. It is *very important*, regardless of whether the pumping test conducted is constant-rate or step-drawdown, that the pumping rate is held as constant as possible during each phase of a pumping test. The step-drawdown procedure should be a minimum of four, 60-minute constant rate tests, with each run using an increasingly higher flow rate. It is important to run the initial step, however, for a duration long enough to demonstrate that well storage effects have dissipated. Each of the remaining three steps should be run for a length of time identical to the initial step. The pumping test duration for the constant rate discharge test is a minimum of 24 hours.

Pumping Rate

Fluctuations in pumping rate make the test analysis very difficult and raise questions as to whether deviations in the data are actually a result of flow boundaries or other hydrogeologic features. Control of the pumping rate is often best accomplished by accurately measuring and controlling the discharge rate. Consideration should be given to the type of pump used to conduct the test. A pump driven by a gasoline engine which needs to run at full throttle in order to meet the required pumping rate, may vary significantly in pumping rate. Using a pump with a large enough capacity to meet the required pumping rate at ½ to K full throttle will produce a more constant yield. Electric pumps are generally not subject to the same rate fluctuations as gasoline powered pumps. A valve in the discharge line, ½ to ¾ open, allows for flexibility in adjusting discharge rate if necessary. The pumping rate should be monitored every 10 to 15 minutes during the first hour of pumping and throughout each phase of the step drawdown test. At later times, the pumping rate should be monitored every 2-hours and the rate maintained within 10 percent of its starting value.

Table 3: Step Drawdown Test Problems and Their Significance to Demonstrating Source Reliability

Problem	Significance	Would Repeating Pumping Test Be Advised?
Discharge rate varies during pumping by more than 10%.	Stabilize discharge rate as quickly as possible. Discharge rate fluctuations make identification of optimal yield difficult.	Probably not, if it was only one of the steps and the follow-up constant rate discharge test was conducted adequately. Collection of recovery data would also provide adequate data.
Data collection does not occur at the minimum specified intervals.	Without data collection at a sufficient frequency, it is very difficult to establish what conditions may be affecting groundwater flow.	Yes
Well is pumped dry because pump was placed too close to static water level.	For the pumping tests, the pump should be placed as far below the static water level as possible without placing it within the screened interval of the well. This allows the maximum possible drawdown and maintains some degree of well efficiency.	Yes.
Well is pumped dry because the pumping rate is unsustainable.	No additional higher rate steps are necessary and the step drawdown test is complete at this point.	Repeating the test at the same pumping rate(s) would probably be of little value. Repeating the test at a lower rate would be advisable, if lower pumping rate drawdown data was not obtained.
Drawdown does not stabilize and shows continued increase.	This is likely to be the case for the step drawdown tests. The tests are short enough that drawdown is unlikely to stabilize, unless low demand source in a highly productive aquifer.	No, the test would not need to be repeated. If a water system extended the final step and did not achieve 4 hours of stabilization, then a constant rate discharge test should be conducted.
Drawdown does not stabilize and decreases at some point through the end of the pumping test.	This may indicate a recharge boundary has been encountered and would not signify a problem. It may indicate that a surface water body has been encountered and that the source would be designated as groundwater under the influence of surface water (GWI). It may also indicate that the source is located in or adjacent to a leaky aquifer.	The pumping test does not need to be repeated. All of these conditions may have implications for source susceptibility and vulnerability, but do not necessarily suggest a problem for reliability.
Water never clears up (stays turbid) during the pumping test.	This may indicate that the well was inadequately developed or that too coarse a filter pack was placed around the well screen.	Assuming the pumping test was properly conducted, repeating the test would not be necessary. Additional well development may be necessary.
Water starts out clear, but becomes turbid during the pumping test.	This likely indicates that the well was inadequately developed. It may also indicate that groundwater of poorer quality or a surface water body was encountered within the well's area of influence and that water system modification may be necessary.	Pumping test would not need to be repeated. Water system may want to verify this problem as an ongoing concern, however, by repeating the pumping test and establishing its constancy.

Table 4: Constant Rate Discharge Test Problems and Their Significance to Demonstrating Source Reliability

Problem	Significance	Would Repeating Pumping Test Be Advised?
Discharge rate varies during pumping by more than 10%.	Stabilize discharge rate as quickly as possible. Any conditions masked by the flow rate variance may be visible in the recovery data.	Yes, if rate fluctuated frequently by more than 10% and recovery data was not collected.
Data collection does not occur at least at the minimum specified intervals.	Without data collection at sufficient frequency, it is very difficult to establish what aquifer conditions may be affecting groundwater flow.	Yes
Well is pumped dry because pump was placed too close to static water level.	For the pumping tests, the pump should be placed as far below the static water level as possible without placing it within the screened interval of the well. This allows the maximum possible drawdown and maintains some degree of well efficiency.	Yes, unless it occurred very late into the test (for example, at 24 hours or later) and it is apparent that drawdown was in the process of stabilizing. In most cases, however, the test would need to be repeated.
Well is pumped dry because the pumping rate is unsustainable.	This may reflect that either the pumping rate or duration needs to be reduced.	Depends at what point in the test the well was dewatered and the slope of the time verses drawdown curve for the data that has been collected. If pumping time was less than 18 hours, the test will probably need to be repeated.
Drawdown does not stabilize and shows continued increase.	There is no remedy, short of reducing the pumping rate until equilibrium is reached with recharge. The pumping test should be completed with collection of recovery data, as this may be a particularly key component in establishing source reliability.	This is very much a case-by-case situation. If recovery is very slow, the pumping test may need to be repeated at a lower pumping rate to demonstrate source reliability.
Water levels do not recover or exhibit limited recovery after pumping test.	This may be observed in conjunction with continuous, excessive drawdown during the pumping test. This could indicate that the aquifer has a very limited recharge area, the aquifer is of small areal extent, or of limited hydraulic continuity.	The pumping test has revealed significant limitations of the aquifer and repeating the pumping test would probably not provide new information. Conducting the pumping test at a lower rate may be necessary to determine new storage and pumping criteria.
Drawdown does not stabilize and decreases at some point through the end of the pumping test.	This may indicate a recharge boundary has been encountered and would not signify a problem. It may indicate that a surface water body has been encountered and that the source would designate as groundwater under the influence of surface water (GWI).	The pumping test does not need to be repeated.
Water never clears up (stays turbid) during the pumping test.	This may indicate that the well was inadequately developed or that too coarse a filter pack was placed around the well screen.	Assuming the pumping test was properly conducted, the test would not need to be repeated. Additional well development may be necessary.

Problem	Significance	Would Repeating Pumping Test Be Advised?
Water starts out clear, but becomes turbid during the pumping test.	Although, this may indicate that the well was inadequately developed, it probably indicates that groundwater of poorer quality or a surface water body was encountered within the well's area of influence and that water system modifications may be necessary.	Pumping test would not need to be repeated. Water system may want to verify this problem as an ongoing concern, however, by repeating the pumping test and establishing its constancy.

Observation Wells

Other wells in the vicinity and open to the same aquifer as the test well should be used as observation wells, whenever possible. The use of observation wells greatly enhances the ability to obtain more representative and accurate data during the test. Pre-test analysis of well depth and distance can determine the best wells to use for observation. If the aquifer being evaluated is confined, it may be useful to select an additional observation well completed within the overlying unconfined aquifer to determine whether there is any leakage from the overlying aquifer into the confined water system. For saltwater intrusion determinations, observation wells positioned between the pumping well and saltwater body provide the most useful information. Information collected from observation wells is desirable, however, regardless of whether well positioning is optimal.

Stream Stage

If there is a stream near the well being tested, and the conceptual model or simulation suggests a potential connection, the stage (depth and width) of that stream should be periodically monitored for changes during the pumping test period. The relative size and distance of the surface water body with respect to the proposed pumping rate should be considered when evaluating the usefulness of conducting stream stage measurements.

Pre-pumping Phase

The well to be tested should be at its "normal" static water level prior to the test. Water level measurements should be made at 24, 16, 12, 3, 2, and 1 hours prior to initiating pumping. Within the hour immediately preceding pumping, water level measurements should be taken at 20-minute intervals to establish any short-term trends in water level changes that may be occurring. Barometric measurements of atmospheric pressure (inches of mercury) should be made as well. These measurements will allow appropriate corrections to be applied to the drawdown data. In settings where tidal influences may affect the pumping test results, measurements should be made at a frequency sufficient to correct the pumping test drawdown data for any observed tidal influences.

Pumping Phase

After initiation of the pumping test (regardless of pumping test method used), drawdown measurements in the production and observation wells should be recorded according to the schedule below. The greatest numbers of measurements are made within the first 100 minutes when the water levels are changing rapidly. The time intervals given are suggested minimums; more frequent measurements can assist with pumping test analysis and interpretation.

Time After Pumping Started For Constant Rate Test And After Pump Shut Off For Recovery	Time Intervals To Measure Water Levels And Record Data
0 to 10 minutes	1 minute
10 to 60 minutes	5 minutes
60 to 240 minutes	30 minutes
240 to 600 minutes	60 minutes
600 to 1440 minutes	120 minutes

Recovery Phase

Water level measurements obtained during the recovery phase are of equal or greater importance than those collected during the pumping phase because it can confirm any disturbances to flow. In addition, unlike the pumping phase where variation in discharge rate can affect the observations, the recovery phase is not subject to induced variations and can provide more reliable information. Water level measurements made during the recovery phase of the aquifer after the pump has been turned off should be taken at the same frequency as the drawdown measurements during the pumping phase. Do not remove the pump until the test is completely done, including the recovery phase. Measurements should commence immediately upon pump shut down and continue for the same duration as the pumping phase, or until the water levels have reached 95 percent of the initial, pre-pumping static water level. A check valve should be used to prevent backflow of water in the riser pipe into the well, which could result in unreliable recovery data.

Stabilization

Stabilization is defined as less than 0.1 foot of drawdown fluctuation/hour in 4 hours of drawdown measurement.

Measurement Considerations

Water level measurements should be determined to the nearest 0.01 foot. Because of the frequency of measurement required during the initial portion of the test, electronic water level indicators marked in tenths and hundredths of a foot should be used. Data loggers and pressure transducers provide the most accurate measurements and are the easiest to use after initial setup, although, they can add considerable expense to the test.

Conveyance of Pumped Water

There is no fixed rule on how far the water produced during the pumping test should be discharged from the vicinity of the well. It is best to pipe the water outside of the area likely be influenced by the pumping test. The objective of conveying pumped water as far from the site as possible is to minimize the possibility of artificially recharging the aquifer and producing an erroneous pumping test or at least affecting the later stages of the test. This is particularly important when conducting pumping tests in shallow unconfined aquifer settings. Considerations for determining a suitable distance include:

- Is the aquifer confined? If so, less distance will be necessary.
- The duration of the pumping test: the shorter the test, the less distance necessary.
- Depth to water and nature of geologic materials overlying the water producing materials: the greater the depth to water, the less distance necessary; and, the more transmissive the aquifer materials, the greater distance necessary.
- If at all possible, do not discharge conveyed water between the pumping test well and any observation wells or any suspected flow boundaries.

References

The following is an incomplete list of references that provide information and methodologies suitable for designing and analyzing a pumping test.

American Society for Testing and Materials (ASTM). 1997. *D4043-96 Standard Guide for Selection of Aquifer Test-Method in Determining of Hydraulic Properties by Well Techniques*.

Dawson, K. J., and Istok, J. D., 1991. *Aquifer Testing, Design and Analysis of Pumping and Slug Tests*. Lewis Publishers, Inc. 121 South Main Street, Chelsea, Michigan, 48118.

Driscoll, F.G. 1986. *Groundwater and Wells*. Published by Johnson Division, St. Paul, Minnesota 55112.

U.S. Geological Survey (USGS). 1983. *Basic Ground-Water Hydrology*, Water Supply Paper 2220. United States Government Printing Office.

DOH Step Drawdown Pumping Test Procedure

Objective

To evaluate well performance and determine the specific capacity of the well, aquifer transmissivity, and yield. This information will allow a determination of the optimal pump settings (depth and pumping rate) in the well.

Elements

1. It is recommended that a qualified water professional oversee testing of the well and review data analysis and interpretations.
2. An access port to allow depth to water measurements, as described in WAC 173-160-355, must be installed and maintained, if not already present.
3. The step drawdown test should consist of a minimum of four consecutive constant rate discharge steps, with each step utilizing a higher pumping rate. Each step should be conducted for at least 60 minutes. *Some water systems may be eligible to conduct the last step of the step drawdown test according to Step 8.*
4. The step drawdown test should utilize the *maximum design pumping rate* as the third step. The remaining pumping rates should be determined by multiplying the maximum design rate by 0.50, 0.75, and 1.25.
5. Drawdown should be measured in the pumped well at least at the frequency given below:

Time After Pumping Started	Time Intervals
0 to 10 minutes	1 minute
10 to 60 minutes	5 minutes
60 to 240 minutes	30 minutes
240 to 600 minutes	60 minutes
600 to 1,440 minutes	120 minutes

6. Water samples must be collected from the source using proper sampling procedures and analyzed by an accredited laboratory (WAC 246-290-130(3)(g)), unless a constant rate discharge test will be conducted. Water samples should be taken within the last 15 minutes of pumping and must be analyzed for the following water quality parameters:

Group A Water System Type		
Community	**Nontransient Noncommunity**	**Transient Noncommunity**
Bacti/Col	Bacti/Col	Bacti/Col
IOCs	IOCs	IOCs
VOCs	VOCs	VOCs
SOCs	SOCs	--
Rad	--	--

- Bacteriological/coliform (Bacti/Col).
- Inorganic chemicals (IOCs).
- Volatile organic chemicals (VOCs).
- Radionuclide tests.
- Synthetic organic chemicals (SOCs); unless the source qualifies for a waiver, exempting the source from analysis of all or a partial list of SOCs.

7. Recovery should be measured beginning at the end of the last step and measured until the water level has returned to within 95 percent of the initial, pre-pumping static water level. Measurement frequency should conform to the specifications above. The pump should not be removed until the water level has returned to 95 percent of the pre-pumping static water level.
8. *Applicable to only some water systems*. Low water demand sources, which are completed in high productivity aquifers may continue to record drawdown measurements during the last step until stabilization occurs. Measurements should be recorded at the frequency specified in the above table. Stabilization means less than 0.1 foot of drawdown fluctuation per hour in 4 hours of drawdown measurement. The data from this final step should be used to plot the time versus drawdown graph and to determine transmissivity, storage coefficient, and hydraulic conductivity. Generally, stabilization should occur quickly in this type of aquifer setting. Water systems meeting these conditions and running the last step to stabilization do not need to also run a minimum 24-hour constant rate discharge test. In most instances, the appropriateness of this approach should be able to be identified before running the step-drawdown test by reviewing previously conducted tests in the area that are specific to the aquifer.
9. Determine the maximum pumping rate and pumping depth as established from the step drawdown test. Use these values for conducting the constant rate discharge test, if the test is applicable.
10. When the pumping test is completed and if a constant rate discharge test will not be conducted, the data should be compiled into a report and submitted to DOH. The project report guidelines for a groundwater source of supply are in Section 7.3 and Appendix F. Reporting guidelines specific to pumping tests include the following:

a. All data on pumping rates and water levels (including static water levels) from the pumping test and recovery period, and appropriate graphical presentations of the data.

b. The report should determine the following hydraulic parameters; transmissivity or coefficient of transmissibility, hydraulic conductivity or coefficient of permeability, and storativity or coefficient of storage.

c. A map and description (¼, ¼, Section Township Range) accurately indicating the well location, as well as the land surface elevation to the nearest foot above sea level. Address and parcel number should also be provided.

d. Summary, conclusions, and recommendations from the engineer or hydrogeologist regarding pump settings and source reliability

e. A well construction report (well log) for the pumping well and all observation wells.

f. Distance, to the nearest foot, from pumping well to all observation wells and a map indicating all well locations.

g. A copy of all laboratory test results.

DOH Constant Rate Discharge Pumping Test Procedure

Objective

To determine the capability of the well and aquifer to provide a reliable yield of water at the desired rate. Sources with the potential for seawater intrusion should also conduct the additional elements provided at the end of this document.

Elements

1. It is recommended that a qualified water professional (hydrogeologist or engineer) oversee testing of the well.
2. An access port to allow depth to water measurements, as described in WAC 173-160-355, must be installed and maintained, if not already present.
3. The source should be pump tested at no less than the maximum rate determined from the step drawdown test. The constant rate discharge test should not be conducted until after the water levels in the aquifer have achieved at least 95 percent recovery from the step drawdown test pre-pumping static water level conditions.

   Note: *Bailer tests, air lift tests, and slug tests are not acceptable. They do not sufficiently stress the aquifer and are too limited in areal extent.*
4. The duration of the constant rate discharge test should be a minimum of 24 hours. If, at 24 hours, four hours of stabilized drawdown have been observed, the pump may be shut off and measurements of recovery begun. If stabilized drawdown has not been observed within a total of 36 hours, the pump may be shut off and recovery measurements begun. Stabilization is defined as a drop in water level of less than or equal to 0.1 feet per hour.
5. Drawdown should be measured in the pumped well at least at the frequency given below:

Time After Pumping Started	Time Intervals
0 to 10 minutes	1 minute
10 to 60 minutes	5 minutes
60 to 240 minutes	30 minutes
240 to 600 minutes	60 minutes
600 to 1,440 minutes	120 minutes

6. Drawdown in observation wells should be measured, if such wells are available and the information is necessary. Table 2 in Appendix E provides information about aquifer settings for which collection of information from observation wells is encouraged.
7. Water samples must be collected from the source using proper sampling procedures and analyzed by an accredited laboratory (WAC 246-290-130(3)(g)), unless the samples were collected during the step drawdown pumping test. Water samples must be taken within the last 15 minutes of pumping and analyzed for the water quality parameters as follows:

Group A Water System Type		
Community	**Nontransient Noncommunity)**	**Transient Noncommunity**
Bacti/Coli	Bacti/Coli	Bacti/Coli
IOCs	IOCs	IOCs
VOCs	VOCs	VOCs
SOCs	SOCs	--
Rad	--	--

- Bacteriological/coliform (Bacti/Coli).
- Inorganic chemicals (IOCs).
- Volatile organic chemicals (VOCs).
- Radionuclide tests.
- Synthetic organic chemicals (SOCs); unless the source qualifies for a waiver, exempting the source from analysis of all or a partial list of SOCs.

8. Pumping should be followed by collection of recovery data until 95 percent recovery of the pre-pumping static water level has been achieved. Recovery measurements should be made in the same manner and at the same frequency as drawdown measurements. To facilitate accurate recovery data collection, the water system should incorporate backflow check-valve(s) that prevents water within the riser pipe from flowing back into the well when the pump is shut off.
9. When the pumping test is completed, the data should be compiled into a report and submitted to DOH. The project report guidelines for a groundwater source of supply are in Section 7.3 and Appendix F. Reporting guidelines specific to pumping tests include the following:
   a. All data on pumping rates and water levels (including static water levels) from the pumping test and recovery period, and appropriate graphical presentations of the data.
   b. The report should determine the following hydraulic parameters: transmissivity or coefficient of transmissibility, hydraulic conductivity or coefficient of permeability, and storativity or coefficient of storage
   c. A map and description (¼, ¼, Section Township Range) accurately indicating the well location, as well as the land surface elevation to the nearest foot above sea level. Address and parcel number should also be provided.
   d. Summary, conclusions, and recommendations regarding pump settings and source reliability.
   e. A well construction report (well log) for the pumping well and all observation wells.
   f. Distance, to the nearest foot, from pumping well to all observation wells and a map indicating all well locations.

g. A copy of all laboratory test results.

Additional Steps for Potential Seawater Intrusion Areas

a. For the source well (the well pumped during the aquifer test), chloride and conductivity samples should be collected at the following intervals: one sample during the initial 30 to 60 minutes, one sample during the 6th hour (360 to 420 minutes), one sample during the 12th hour (720 to 780 minutes), and one sample within the last 15 minutes of the aquifer test pumping phase.

b. For at least one observation well, two chloride and conductivity samples should be collected, one base sample prior to initiation of the aquifer test and one sample upon completion of recovery data collection. Any observation well sampled should be purged of three well casing volumes prior to sample collection. Following collection of the base sample, observation wells should be given adequate time to recover to static water level prior to initiation of the aquifer test.

Note: *It is recommended that a field test kit be used to monitor chloride levels within the pumping well during the pumping phase.*

In addition to the reporting requirements in Item 9 above, the following should also be included in the report:

1. Tidal influence on the pumping well. Data on pumping water levels, chlorides, and tidal fluctuations (corrected to point) should be plotted on a single graph with respect to time.
2. Potential for seawater intrusion into this or other seaward wells.

Pumping Test Data Collection Sheet

Water System ID:	Owner:	Well Tag No.:
DOH Source ID:	Water System Name:	Well Name:
Type of Test:	Conducted By:	Date:
Static Water Level (as measured from reference point):		County:
Observation Wells?		Well Elevation (MSL):
Distance of observation well (r) from pumped well (ft):		

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

Recovery Data Collection Sheet

Water System ID:	Owner:	Well Tag No.:
DOH Source ID:	Water System Name:	Well Name:
Type of Test:	Conducted By:	Date:
Static Water Level (as measured from reference point):		County:
Observation Wells?		Well Elevation (MSL):
Distance of observation well (r) from pumped well (ft):		

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