PNNL-30163

Aquifer Hydraulic Testing and Characterization Plan for the Ringold Formation Unit A in the Hanford 200-ZP-1 Groundwater Operable Unit and Vicinity

September 2020

RD Mackley
ML Rockhold
R Ekre
I Demirkanli

Prepared for the U.S. Department of Energy
under Contract DE-AC05-76RL01830

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Pacific Northwest National Laboratory
Richland, Washington 99354

Summary

This document presents a plan for testing and characterizing the hydraulic properties of the Ringold Formation member of Wooded Island – unit A (Rwia) in the 200-ZP groundwater operable unit. The testing approach includes multiple field methods and associated analyses designed to investigate and understand aquifer hydraulic properties over a range of scales. Testing was designed to achieve specific testing objectives identified previously in the *200-ZP-1 Groundwater Operable Unit Ringold Formation Unit A Characterization Sampling and Analysis Plan* (Ringold A SAP).[1] The test plan provides necessary technical and operational detail for writing subsequent field test instruction documents specific to each testing location.

Hydraulic characterization activities will proceed in a phased manner focusing on areas identified to have knowledge gaps and that are critical for remedy modifications and/or selection. These activities are designed to minimize impact to pump and treat (P&T) operations and to use existing P&T injection and extraction wells as stress wells. The new Rwia monitoring wells installed for Ringold A SAP activities will also be used as observation wells. ZP-1 hydraulic testing will include slug testing in new Rwia wells, shutdown-recovery tests in multiple Rwia and composite Rwie[2]-Rwia aquifer test locations, installation of new automated water level network stations in Rwia monitoring wells, characterization of P&T and barometric responses, identifying the vertical distribution of hydraulic conductivity in the Rwia and Rwie units using electromagnetic borehole flowmeter tests, and single-well tracer testing in select Rwia monitoring wells. Slug testing to be conducted during drilling is described under the Ringold A SAP. The remaining testing activities are to be conducted after well drilling and completion and are described in this test plan.

[1] DOE/RL-2019-23. 2019. *200 ZP-1 Groundwater Operable Unit Ringold Formation Unit A Characterization Sampling and Analysis Plan (SAP)*. Rev. 0, U.S. Department of Energy, Richland Operations Office, Richland, Washington.

[2] Ringold Formation member of Wooded Island – unit E (Rwie).

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Acronyms and Abbreviations

AWLN	automated water level network
CHPRC	CH2M Hill Plateau Remediation Company
COC	contaminant of concern
CPGM	Central Plateau Groundwater Model
EBF	electromagnetic borehole flowmeter
EW	extraction well
F&T	flow and transport
FY	fiscal year
HSGFM	Hanford South Geologic Framework Model
IRF	infinite-acting radial flow
IW	injection well
KGS	Kansas Geological Survey
MNA	monitored natural attenuation
MW	monitoring well
OSP	*200-ZP-1 Operable Unit Optimization Study Plan*
OU	operable unit
P&T	pump and treat
PMP	performance monitoring plan
PNNL	Pacific Northwest National Laboratory
Ringold A SAP	*200 ZP-1 Groundwater Operable Unit Ringold Formation Unit A Characterization Sampling and Analysis Plan*, DOE/RL-2019-23, Rev. 0
Rlm	Ringold Formation member of Wooded Island – lower mud unit
ROD	*Record of Decision Hanford 200 Area 200-ZP-1 Superfund Site*, *Benton County*, *Washington*
ROI	radius of influence
Rtf	Ringold Formation member of Taylor Flat
RUM	Ringold Formation member of Wooded Island – upper mud unit
Rwia	Ringold Formation member of Wooded Island – unit A
Rwie	Ringold Formation member of Wooded Island – unit E

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1.0 Introduction

This test plan describes the approach for hydraulic testing activities to be performed for wells completed in the Ringold Formation member of Wooded Island – unit A (Rwia) in the 200-ZP-1 groundwater operable unit (OU), including existing and new monitoring wells described in the *200-ZP-1 Groundwater Operable Unit Ringold Formation Unit A Characterization Sampling and Analysis Plan* (Ringold A SAP; DOE/RL-2019-23, Rev. 0).

Figure 1.1 shows the locations for 8 (MW-A to MW-H) of the 12 new monitoring wells to be installed in the first phase of well drilling performed under the Ringold A SAP. These locations were based on the distribution and migration of the primary contaminant of concern (COC), carbon tetrachloride, hydrogeology of the 200-ZP-1 OU, and an evaluation of data gaps (DOE/RL-2019-23, Rev. 0). Four additional Rwia monitoring wells (MW-I through MW-L) will be installed during a second phase of drilling performed under the Ringold A SAP, and their locations have yet to be determined. As documented in the Ringold A SAP, these new Rwia monitoring well locations are intended to provide data for defining the nature and extent of plumes for COCs, physical and hydraulic properties, transport parameters for the Rwia, and, to a lesser extent, the Ringold Formation member of Wooded Island – unit E (Rwie) and Ringold Formation member of Wooded Island – lower mud unit (Rlm) hydrogeologic units. Additional monitoring, extraction, and injection wells are planned under the performance monitoring plan (PMP; DOE/RL-2009-115, Rev. 3) and are shown in (Figure 1.1).

The hydraulic testing data to be collected under this test plan will support flow and transport (F&T) modeling, allow for performance evaluation of the 200-ZP-1 OU remedy, and assist in making recommendations for optimizing or modifying the groundwater remedy. The current remedy at the 200-ZP-1 OU is detailed in the EPA et al. (2008) *Record of Decision Hanford 200 Area 200-ZP-1 Superfund Site, Benton County, Washington* (ROD). The remedy consists of pump and treat (P&T), hydraulic containment, and institutional controls, followed by monitored natural attenuation (MNA). The ROD states that remediation is estimated to require 125 years to achieve final cleanup levels for eight COCs, with carbon tetrachloride as the primary COC due to its high concentration relative to the cleanup level and corresponding large mass within the aquifer.

A separate investigation in the 200-ZP-1 OU was initiated in fiscal year (FY) 2020 to collect and interpret data to evaluate remedy performance enhancements and P&T configuration changes associated with P&T operations, focusing on Ringold Formation member of Wooded Island – unit E (Rwie), under an optimization study per DOE/RL-2019-38, *200-ZP-1 Operable Unit Optimization Study Plan* [hereinafter referred to as the 200-ZP-1 OU optimization study plan (OSP)]. The optimization study activities are anticipated to have minimal impact on contamination in the Rwia, except (1) in areas where the intervening low-conductivity Rlm is absent so the unconfined aquifer is continuous with the Rwie and Rwia (referred to as the composite Rwie-Rwia aquifer in this document), and (2) where some of the extraction and injection wells are screened within both Rwie and Rwia. The information resulting from the implementation of this test plan, as well as the Ringold A SAP, will be combined with results from the optimization study to help evaluate remedy performance and/or support remedy modifications.

1.1 Document Scope

The hydraulic test plan document presents the technical basis and details for the hydraulic testing methods and locations, and provides high-level information needed for work planning and creating field test instruction documents specific to each testing location (e.g., SGW-40266, Rev. 0). The field test instructions will contain the additional details and step-by-step work instructions needed to fully implement the field activities outlined here.

The aquifer hydraulic testing and characterization approach presented in this document is based on the current test objectives as identified in the Ringold A SAP, operational constraints and limitations of the 200 West P&T system, and conceptual understanding of the ZP-1 study area. As testing progresses, the results and lessons learned can be used to inform and refine the testing that is performed at other locations and in other phases of this characterization effort. Operational or logistical constraints (e.g., the P&T facility's ability to effectively implement the long-term pump tests) will be considered and factored into any modifications or revisions to the testing approach. If test objectives or conceptual site models for the ZP-1 test area change significantly during the multi-year hydraulic testing activities, the testing plan may be modified accordingly. Similarly, if testing methods outlined in this plan produce unexpected or non-ideal results during initial testing, the methods may be reevaluated, and alternatives considered prior to continuing to the next testing location/phase currently identified in the plan.

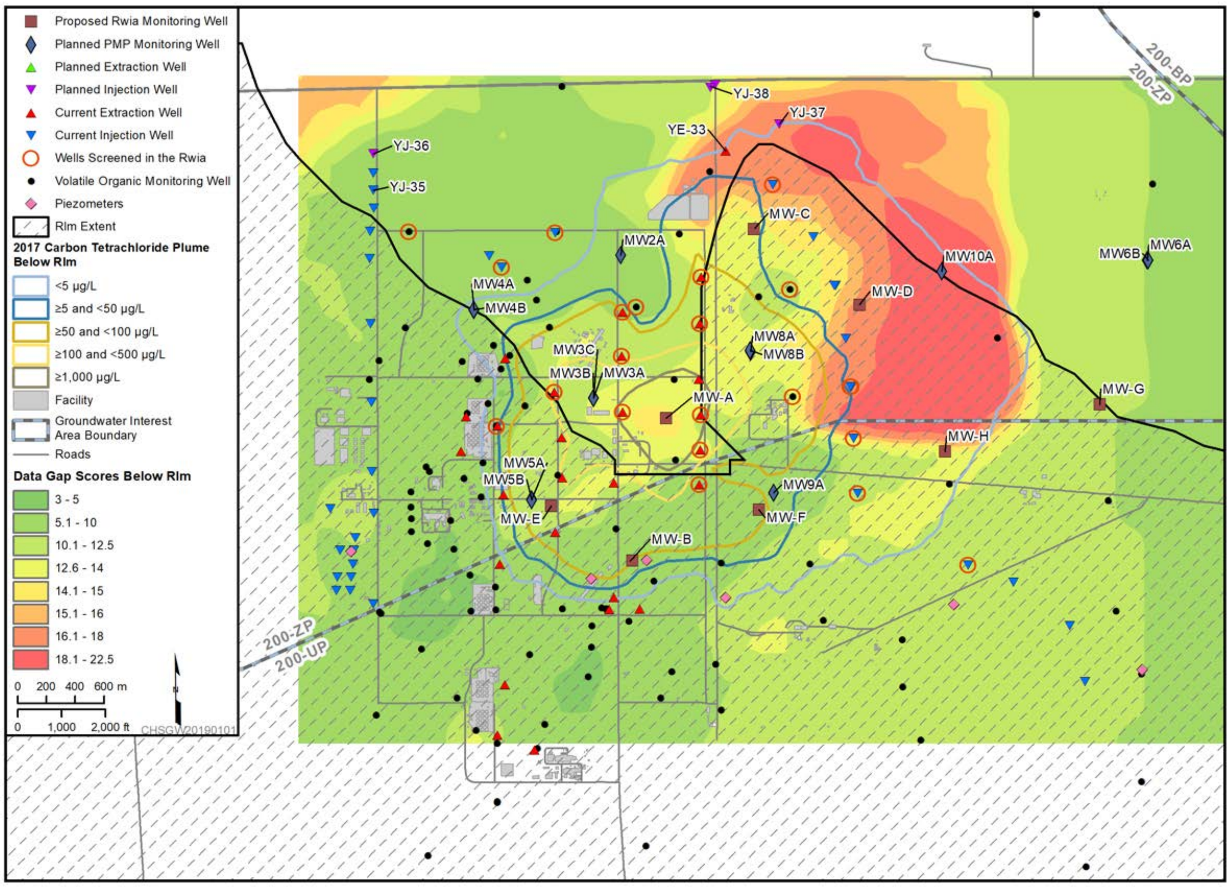

Figure 1.1. Basemap of the 200-ZP-1 OU. Approximate locations of the first phase of proposed Rwia monitoring wells are symbolized with magenta boxes (DOE/RL-2019-23, Rev. 0).

1.2 Document Organization

The following sections discuss the objectives of the hydraulic testing and provide background information on site hydrogeology and the test setting. Subsequent sections in the document provide details about selected test methods, test areas, well locations, and the selected approach for conducting hydraulic testing activities to accomplish the objectives identified in the Ringold A SAP. Appendix A provides an overview of the selected hydraulic testing methods. Appendix B provides results from pre-test analyses of constant-rate and shutdown-recovery pumping tests and single-well tracer tests to inform the recommendations and design elements presented in this test plan. Appendix C provides results from pre-test analyses of single-well tracer tests to support the planned use of these tests in this test plan. Appendix D summarizes the sequence and operational requirements related to each of the phases of field investigations, which supports planning and coordination of necessary resources and provides additional detail needed to create field instruction documents.

1.3 Hydraulic Testing Objectives

The Ringold A SAP explicitly defines the Rwia hydraulic characterization objectives (Table 1.1). The primary purpose behind these objectives is to improve the knowledge of the aquifer geometry and the understanding of F&T properties at a variety of scales to inform and parameterize fate-and-transport modeling, which is the primary tool used in the design and optimization of various P&T and MNA remedies for the 200-ZP-1 OU.

The scope and intended outcome of the Rwia hydraulic characterization elements in this test plan are tied to these purposes and designed to accomplish these objectives.

Table 1.1. Hydraulic Testing Objectives (from Ringold A SAP Table 4)

Objective Number	Objective Description
1	Hydraulic testing to better define large-scale transmissivity and storage properties to support F&T modeling
2	Hydraulic testing to better define the vertical profile of hydraulic conductivity for the Rwia associated with major zones of different transmissivity to support F&T modeling
3	Hydraulic testing to better define the vertical hydraulic conductivity (leakage factor) to support F&T modeling
4	Hydraulic testing to better define the effective porosity of the Rwia within the observed/interpreted plume migration pathways to support F&T modeling

1.4 Test Area Setting

This section reviews background information relevant to the 200-ZP-1 test area, including the hydrogeology and groundwater contamination. Note that the ZP-1 test area (as used in this document), includes wells located outside of the 200-ZP-1 OU. More information on the ZP-1 test area can also be found in DOE/RL-2008-78, Rev. 1.

1.4.1 Hydrogeology

The following summary is based on discussions presented in Last et al. (2009), CP-60925 (2018), and ECF-HANFORD-18-0035 (2019).

The subsurface hydrogeologic units within the 200-ZP-1 OU are, from top to bottom, the unconsolidated and relatively high-permeability Hanford formation, the semi-consolidated and lower permeability Cold Creek unit and Ringold Formation, and the Columbia River Basalt. Within the 200-ZP-1 study area, the units of the Ringold Formation present are, from top to bottom, the member of the Taylor Flat (Rtf), member of Wooded Island – unit E (Rwie), member of Wooded Island – lower mud unit (Rlm), and member of Wooded Island – unit A (Rwia). The Cold Creek unit and some of the Ringold Formation units may be absent locally due to the erosion and scouring that occurred during the cataclysmic flooding that deposited the Hanford formation sediments. The unconfined aquifer in most of the 200 West Area is within the Rwie. Where the underlying Rlm is present, it forms an aquitard of varying confinement and separates the Rwie unconfined aquifer from the confined to semi-confined Rwia aquifer below. The amount and location of confinement or leakage between the Rwia and Rwie is not fully understood and is a subject of this investigation.

The hydraulic properties for the Rwie, Rlm, and Rwia units are discussed in the pre-test analysis contained in Appendix B, Section B.1.

1.4.2 Groundwater Flow and Contamination

Groundwater flow in the Central Plateau is predominantly from west to east from the 200 West Area to the 200 East Area. Velocities typically range from 0.0001 to 0.5 m/d (0.00033 to 1.64 ft/d) (DOE/RL-2008-78, Rev. 1). The flow field has been altered historically due to large discharges of effluent in the 200 West Area. However, the water table has been declining and eastward groundwater flow now predominates.

The groundwater COCs identified in the 200-ZP-1 OU ROD (EPA et al. 2008) include carbon tetrachloride, total chromium, hexavalent chromium, iodine-129, nitrate, technetium-99, trichloroethene (TCE), and tritium. As discussed in more detail in the Ringold A SAP, carbon tetrachloride is the predominant COC and the primary risk driver in the 200-ZP-1 OU with a plume area of about 20 km^2 (7.9 mi^2). The carbon tetrachloride plume extends towards the north, south, and east from the source areas, primarily the 216-Z-1A, 216-Z-9, and 216-Z-18 Cribs and Trenches. The carbon tetrachloride source areas have been mitigated and there is no longer a continuing carbon tetrachloride source that would contribute to the groundwater plumes (DOE/RL-2014-48, Rev. 0).

Sources of other contaminants, such as chromium, iodine-129, nitrate, TCE, technetium-99, and tritium, in the 200-ZP-1 include releases from past leaks in single-shell tanks and pipelines in Waste Management Areas T and TX/TY, and liquid waste disposal from plutonium processing operations to cribs and trenches adjacent to the waste management areas. Except for nitrate, the remaining contaminant plumes in the 200-ZP-1 OU are considered to be predominantly located within the boundaries of the carbon tetrachloride plume. As part of the 200-ZP-1 OSP, biological treatment of nitrate as part of the P&T remedy has been suspended and nitrate is being reinjected into the aquifer at concentrations higher than the effluent criteria.

Groundwater data obtained following completion of the 200-ZP-1 OU feasibility study (DOE/RL-2007-28) and issuance of the 200-ZP-1 ROD indicate that carbon tetrachloride is present over a wider area and at concentrations more than two orders of magnitude greater than the cleanup level (compared to the available data at the time of the feasibility study). In particular, data obtained from the installation of new wells on the east side of the 200-ZP-1 OU indicated that higher concentrations of carbon tetrachloride were present below the Rlm and within Rwia (DOE/RL-2008-78, Rev. 1). The additional characterization data that result from drilling of the new Rwia monitoring wells under the Ringold A SAP and hydraulic characterization activities conducted under this test plan will help to better define contaminant characteristics and the physical, geochemical, and hydraulic properties of Rwia sediments to support groundwater F&T modeling and remedy implementation.

2.0 Field Testing and Characterization Plan

This section describes the overall approach and individual elements associated with the hydraulic testing and characterization activities designed to accomplish the objectives of the Ringold A SAP. The selected aquifer hydraulic test methods are reviewed and summarized. The challenges and opportunities associated with testing in the context of an active groundwater P&T remedy are then discussed, with an emphasis on minimizing impact to the P&T system. This section also summarizes the pre-test analyses that were conducted to inform and evaluate possible test designs and assess constraints, requirements, and feasibility.

The ZP-1 Rwia testing will be conducted in three phases of investigation focusing on accomplishing the objectives identified in the Ringold A SAP using multiple methods that investigate the Rwia and composite Rwie-Rwia aquifer at multiple scales. It is estimated that it will require 3 or more years to complete the hydraulic testing. The test methods, locations, and outcomes of each of the three testing phases are presented in this section. Lastly, the expectations for reporting the results are identified. Activities designed for each phase are described in this section.

2.1 Aquifer Hydraulic Testing Methods

Aquifer hydraulic testing will include multiple methods that interrogate the Rwia aquifer at varying scales of investigation, including sediment core sample testing, slug testing, shutdown-recovery testing, single-well tracer testing, electromagnetic borehole flowmeter (EBF) testing, groundwater flow characterization, and barometric response characterization, as summarized in Table 2.1 and Figure 2.1. Sediment core sample testing and initial depth-discrete slug testing are discussed in the Ringold A SAP because they are conducted/initiated with the drilling of the wells. Additional slug testing in completed wells is proposed in this test plan to supplement other testing activities. The remainder of the hydraulic testing activities are described in this document because they will be implemented after well completion. The selected methods were determined based on the previous work that demonstrated the applicability of these hydraulic testing methods for wells adjacent to the test locations identified in this document (Newcomer 2007; Spane et al. 2001; Spane 2008a,b, 2010; Spane and Newcomer 2004, 2008, 2009a,b, 2010; Spane and Thorne 2000). An in-depth technical discussion of these methods is presented in Appendix A.

The methods listed in Table 2.1 were evaluated to determine their applicability for meeting the objectives of the Ringold A SAP listed in Table 1.1. The test plan was developed from this evaluation, with consideration given to possible constraints associated with continuing operations of the 200 West Area P&T facility, and the availability of other existing wells for stressing the system and monitoring its response.

In addition to the aquifer hydraulic characterization activities described in this document, the Ringold A SAP directs geologic and borehole geophysical log data to be collected from the new Rwia wells to better define the hydrogeologic framework model of the 200-ZP-1 study. This related information collected during well installation will help to interpret results from the hydraulic testing.

As noted earlier, the hydraulic testing of the Rwia is being done to better understand aquifer hydraulic properties at multiple spatial scales. Figure 2.1 provides a visual comparison of the relative and approximate scales of investigation to consider when selecting, prioritizing, and investing in hydraulic testing activities. For example, local-scale hydrogeologic heterogeneities can impact remediation performance (e.g., remedy tailing caused by small-to-moderate-scale heterogeneities) and need to be characterized. Accordingly, the testing approach in this plan includes multiple methods to provide information across a broad and overlapping range of investigation scales.

Large-scale multi-well pumping tests (including the shutdown-recovery test) provide representative estimates of the bulk aquifer hydraulic properties. Other methods, such as slug testing, are needed to understand smaller-scale heterogeneities within that large-scale study area. EBF testing will provide information on the vertical distribution of permeability within the screened interval of a completed well to complement and compare with the depth-discrete slug tests performed (under the Ringold A SAP) during drilling of new Rwia wells. The characterization data obtained from these tests allows for identifying heterogeneities (e.g., high-permeability flow layers) at the local scale. The hydraulic information gained from these evaluations will be evaluated with the contaminant characterization data collected under the Ringold A SAP to support remedy decisions.

Table 2.1. Hydrologic Testing Methods

Testing Type		Approach	Resulting Information
Sediment core sample testing[(a)]		Laboratory analysis of physical and hydraulic properties	Core-scale measurements of particle-size distribution, moisture content, bulk density, particle density, n_t, and K_v
Slug testing[(b)]		Multi-stress level slug tests conducted at selected well locations Can be performed during drilling or after construction at discrete depths or within the entire screened interval following well construction	Localized K_h and T
Shutdown-recovery variant form of the constant-rate pumping test		Pumping and cessation of pumping of water and monitoring of resulting pressure responses in the pumping (stress) well(s) and adjacent monitoring wells	Intermediate to large-scale K_h, K_v/K_h, T, S, and S_y
Single-well tracer testing	Dilution testing	Monitoring of emplaced tracer concentration within the test well at multiple wellbore depths	V_w and vertical distribution of K_h
	Pump-back testing	Pumping and monitoring of recovered tracer within the test well	Local to intermediate scale V_a and n_e
EBF testing		Measurement of vertical flow at prescribed wells screen depths under ambient and pumped conditions	Localized vertical distribution of K_h and ambient vertical flow distribution of lateral flow conditions
Groundwater flow characterization		Analysis of monitoring well water-level data [i.e., automated water level network (AWLN) data]	Determination of large-scale groundwater flow direction and hydraulic gradient
Barometric response characterization		Monitoring well water-level response characteristics to barometric pressure changes	Aquifer type identification, correction of hydrologic testing responses for barometric fluctuations

K_h = horizontal hydraulic conductivity
K_v = vertical hydraulic conductivity
K_v/K_h = anisotropy
n_e = effective porosity
n_t = total porosity
T = transmissivity
S = storativity
S_y = specific yield
V_a = advective groundwater velocity within the aquifer (also known as the ambient linear or seepage velocity)
V_w = groundwater velocity through the wellbore
(a) Physical and hydraulic property analysis of borehole sediment samples is being performed under the Ringold A SAP (DOE/RL-2019-23, Rev. 0). It is included here for reference and will not be discussed in this test plan.
(b) Depth-discrete slug testing during drilling is being performed under the Ringold A SAP (DOE/RL-2019-23, Rev. 0). Additional slug testing on select new Rwia wells after they are constructed is proposed in this test plan.

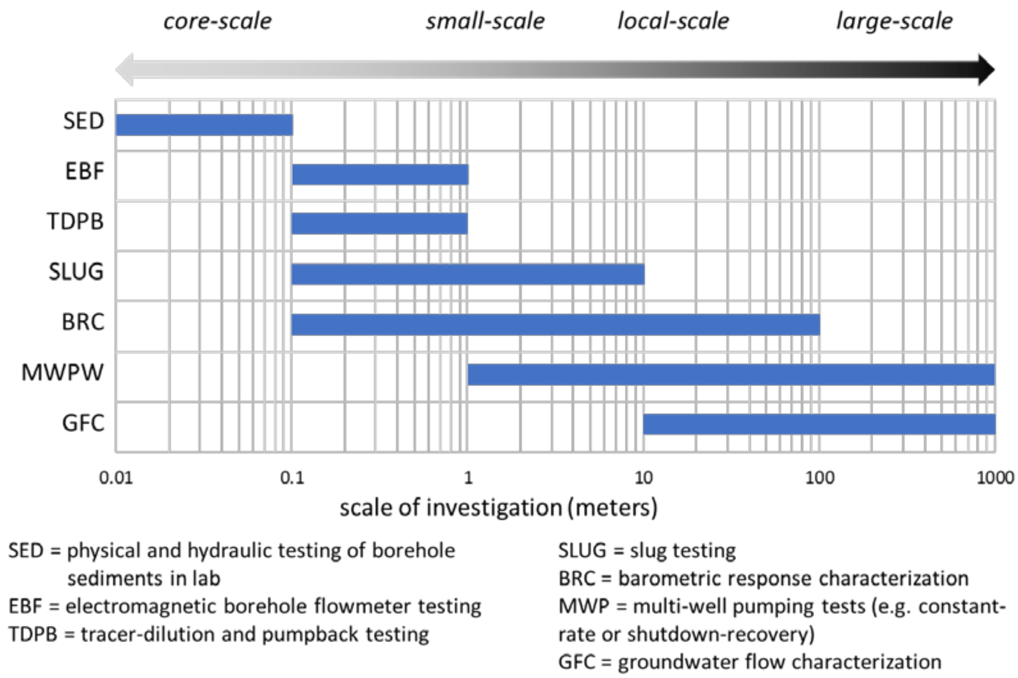

Figure 2.1. Illustration of the approximate scales of investigation related to the various aquifer hydraulic characterization methods described in Table 2.1.

2.2 Coordination with P&T Operations

Contaminated groundwater within the 200-ZP-1 OU is currently being remediated with a combination of P&T, flow-path control, and institutional controls, which will be followed by MNA. There are numerous active P&T extraction and injection wells connected to the 200 West P&T facility within the test area (Figure 1.1). This test setting presents a combination of challenges and opportunities for aquifer testing. Minimizing impact to P&T operations and continuing progress toward remedial action objectives was a major consideration in the development of the test plan.

Subsequent sections of the test plan detail specifics for the various hydraulic tests and identify the areas where coordination with the P&T operations is required. In general, the hydraulic testing approach using existing P&T extraction and injection wells as the "pumping" (into or out of the aquifer) wells for the shutdown-recovery pumping tests and is designed to minimize disruptions to P&T operations. This also reduces the need for temporary storage, handling, and disposal of purge water generated during testing, which would normally be a significant challenge and cost due to the relatively large pumping durations and volumes associated with the pumping tests proposed in this test plan.

The test plan activities will require close coordination with the P&T operations staff and require temporary changes to several established operational practices. For example, the shutdown-recovery tests require multiple months of constant injection and extraction flow rates before and during the testing. As currently configured, the injection wells receive P&T effluent from a common header and are not typically operated at a constant rate. This has been especially true when various treatment units have been taken offline to tie in new facilities. Activities related to cleaning and planned maintenance also impact well pumping rates. The facility is currently operating under an optimization test plan (DOE/RL-2019-38) that suspends biological treatment. The layup of these facilities is in process and once complete will make constant rate operation of extraction and injection wells more feasible.

Coordination with P&T operations has been initiated through the development of this test plan and will continue as test activities are implemented. It is expected that ZP-1 project staff will meet with the operations team to further evaluate the potential impacts to the P&T facility and operations and discuss the impacts and develop solutions together. Possible coordination actions include the following:

- Coordinate the timing of each test with planned operational activities to avoid conflicts and outages caused by tie-ins of new facilities (such as the air stripper or new wells).
- Consider operational goals consistent with the test objectives in place of traditional goals associated with treatment volume or contaminant mass removal.
- Hold multiple kick-off meetings to discuss test objectives and explain team roles and responsibilities of the integrated project and operations team members.
- Include flexibility in the testing to respond to unexpected outages.
- Collaborate with operations staff to identify specific actions and communications needed when an outage is to occur, or an unplanned outage does occur.
- Provide updates to operations staff on milestone progress and changes to the test plan.
- Integrate specific pump rates for extraction wells with the existing operational procedures for specifying extraction rates to avoid conflicting input from different sources.

Additional information on potential impacts and coordination with P&T operations is presented in Appendix D.

2.3 Testing Design

The field hydraulic testing activities and accompanying analyses are designed to accomplish the Rwia aquifer testing objectives identified in the Ringold A SAP (Table 1.1). Successful completion of these objectives requires careful consideration of the field setting and operational conditions, which are discussed in the following sections.

2.3.1 Well Completions and Target Hydrogeologic Units

Figure 2.2 shows the hydraulic testing study area, including the locations of existing and new wells screened in the target hydrogeologic units. Rwia monitoring wells planned for drilling and construction are listed in Table 2.2 and symbolized with magenta-colored boxes in Figure 2.2. Table 2.3 lists the existing wells with screened intervals constructed in only the Rwia unit (well locations circled in green in Figure 2.2). Composite aquifer wells with screened intervals constructed in both the Rwie and Rwia units are listed in Table 2.4 (well locations circled in red in Figure 2.2). Future monitoring wells drilled and installed under the PMP (DOE/RL-2009-115, Rev. 3) are shown as blue diamonds in Figure 1.1. The screened intervals of the PMP monitoring wells will be placed where the highest levels of groundwater contamination are found during drilling (DOE/RL-2009-115, Rev. 3). Future PMP wells completed in the Rwia unit within the hydraulic test areas described below will be incorporated as appropriate.

As shown in Figure 2.2, there are many existing wells in the 200-ZP OU screened in both the Rwia and Rwie units. These composite Rwie-Rwia aquifer wells are typically completed with blank casing between the screened intervals and with bentonite in the annulus in between the screened intervals. Injection/ extraction into/from a well screened in both the Rwia and Rwie units will preferentially displace water in the most permeable unit, which is typically Rwie. Therefore, for the purposes of this test plan, it is important to distinguish between wells that are screened in different parts of the aquifer.

Using wells that are screened across both the Rwie and Rwia units for characterization or monitoring may be more complicated because well response will be due to changes occurring in both units. New wells that are planned for Rwia characterization and aquifer testing will be screened only within the Rwia unit.

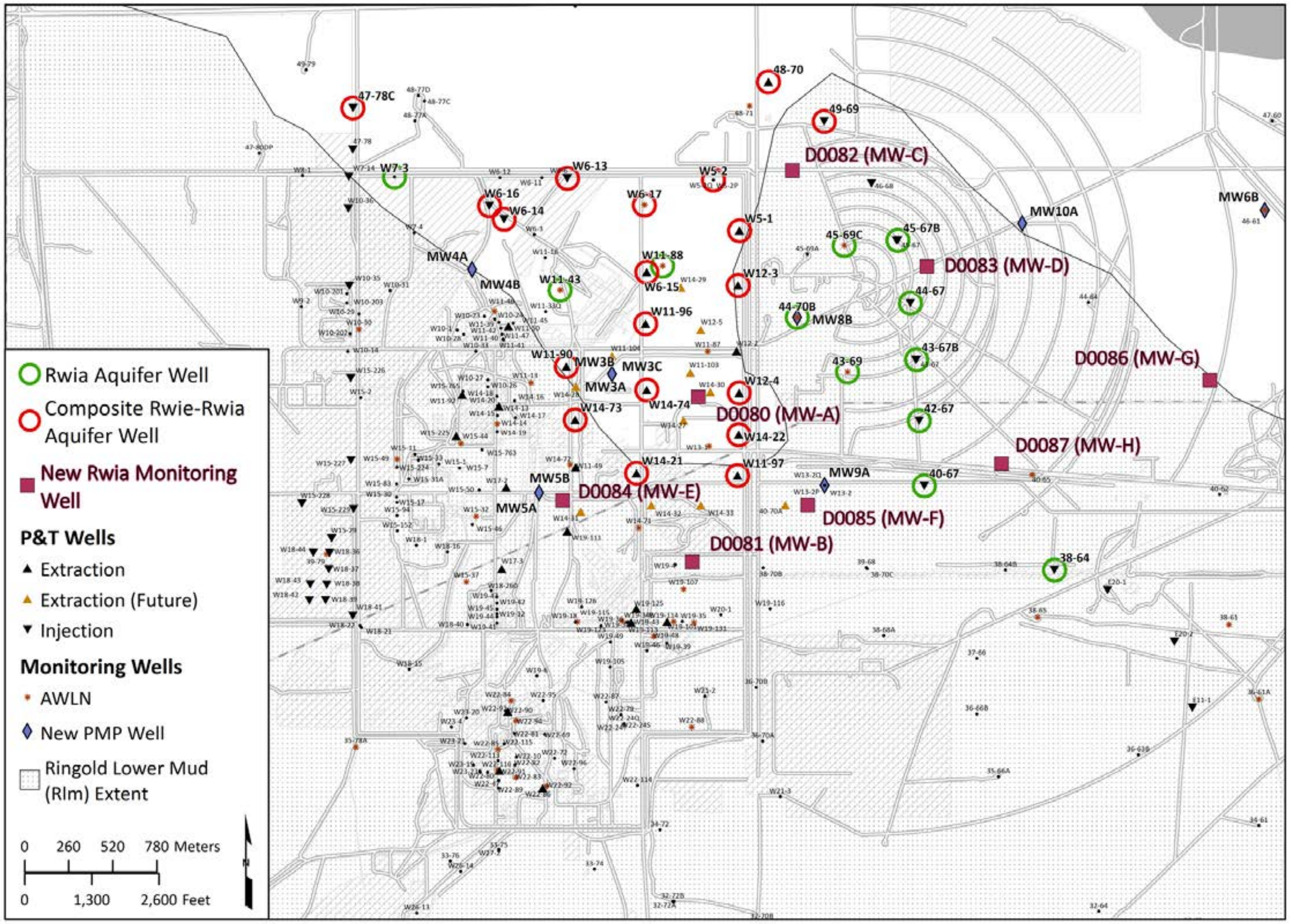

Figure 2.2. Locations of existing and planned wells available for hydraulic testing activities. Wells screened solely within the Rwia unit are circled in green and those screened across both the Rwie and Rwia units (composite aquifer wells) are circled in red. Rwia monitoring wells planned for drilling and construction under the Ringold A SAP are shown with magenta-colored boxes.

Table 2.2. Information for New ZP-1 Rwia Aquifer Monitoring Wells

Planned Installation Year[(a)]	Ringold A SAP Drilling Phase	Ringold A SAP MW ID	Well Name	Hanford Well ID	Top of Rwie (elev m)[(b)]	Top of Rlm (elev m)	Top of Rwia (elev m)	Top of Basalt (elev m)
FY22	1	MW-A	299-W13-4	D0080	168.0	NP	87.8	65.3
FY22	1	MW-B	299-W19-133	D0081	146.3	83.9	77.5	50.6
FY21[(c)]	1	MW-C	699-46-70	D0082	160.6	113.4	107.0	88.7
FY21[(c)]	1	MW-D	699-45-67C	D0083	156.4	123.5	110.0	83.2
FY22	1	MW-E	299-W14-26	D0084	167.6	85.9	73.8	51.5
FY22	1	MW-F	699-40-70	D0085	145.3	97.2	93.8	57.6
FY22	1	MW-G	699-42-62	D0086	127.1	NP	114.3	86.5
FY22	1	MW-H	699-42-65	D0087	144.1	117.9	103.6	75.6
TBD	2	MW-I	TBD	TBD	TBD	TBD	TBD	TBD
TBD	2	MW-J	TBD	TBD	TBD	TBD	TBD	TBD
TBD	2	MW-K	TBD	TBD	TBD	TBD	TBD	TBD
TBD	2	MW-L	TBD	TBD	TBD	TBD	TBD	TBD

NP = unit is not present

TBD = to be decided

(a) Planned FY dates for drilling and construction of new Rwia wells listed here may change based on available funding, Hanford Site priorities, delays in schedule, or other reasons. They are included here for planning purposes.

(b) Elevations for the top of stratigraphic units for the new Rwia wells are based on current geologic framework model [Hanford South Geologic Framework Model (HSGFM); ECF-HANFORD-13-0029, Rev. 5] as communicated in email correspondences from Sarah Springer (CHPRC) to Rob Mackley (PNNL) on 3/26/2020 and 4/13/2020.

(c) Drilling is planned to begin in late FY20 and continue into FY21.

Table 2.3. Information for Existing Wells Effectively Screened Only in the Rwia Unit within the ZP-1 Test Area

Well Name	Hanford Well ID	Well Type (P&T ID)[(a)]	Top of Rwie (elev m)[(b)]	Top of the Rlm (elev m)	Top of Rwia (elev m)	Top of Basalt (elev m)	Top of Screen (elev m)[(c)]	Bottom of Screen (elev m)
299-W11-43	C4694	MW	168.8	NP	88.3	NDE	87.3	82.7
299-W11-88	C5572	MW	171.5	NP	88.0	72.7	85.5	73.3
299-W7-3[(d)]	A5009	MW	177.5	NP	93.0	62.2	69.6	61.1
699-38-64	C8921	IW (YJ-16)	144.8	112.2	100.6	66.1	90.9	66.5
699-40-67	C8070	IW (YJ-15)	148.3	113.2	104.7	68.7	99.2	68.9
699-42-67[(e)]	C8069	IW (YJ-14)	145.8	113.0	101.7	72.1	103.4	72.9
699-43-67B	C8386	IW (YJ-17)	149.4	116.1	107.1	76.3	104.5	76.9
699-43-69	C5573	MW	153.4	115.5	104.5	74.1	104.5	93.9
699-44-67	C8068	IW (YJ-12)	155.8	120.5	112.3	80.7	111.5	81.1
699-44-70B	C9740	MW	152.3	117.4	105.8	73.9	102.4	96.3
699-45-67B	C8717	IW (YJ-10)	160.4	123.7	107.0	84.1	104.0	85.7
699-45-69C	C5574	MW	156.3	119.4	110.4	83.3	109.8	105.2

NP = unit is not present
NDE = well not drilled deep enough to encounter unit
MW = monitoring well
IW = injection well

(a) Plant ID used in the 200 West P&T system for extraction (EW) and injection wells (IW).
(b) Elevations for the top of stratigraphic units are based on current HSGFM (ECF-HANFORD-13-0029, Rev. 5) as communicated in email correspondences from Sarah Springer (CHPRC) to Rob Mackley (PNNL) on 6/17/2020 and 6/18/2020.
(c) The top and bottom elevations of screened intervals were calculated from well elevation and screen depth information obtained from well completion summary reports downloaded from the Environmental Dashboard Application (EDA; https://ehs.chprc.rl.gov/eda/) on 4/10/2020.
(d) The bottom of the screen in well 699-W7-3 extends 1.1 m into the basalt; however, it is assumed to function effectively as a Rwia-only well.
(e) The top of the screen in well 699-42-67 extends 1.7 m into the Rlm unit; however, it is assumed to function effectively as a Rwia-only well.

Table 2.4. Information for Existing Wells Screened in Both the Rwie and Rwia Units (composite aquifer wells) within the ZP-1 Test Area

Well Name	Hanford Well ID	Well Type (P&T ID)[(a)]	Top of Rwie (elev m)[(b)]	Top of the Rlm (elev m)	Top of Rwia (elev m)	Top of Basalt (elev m)	Top of Screen (elev m)[(c)]	Bottom of Screen (elev m)
299-W11-90	C7022	EW (YE-07)	167.2	NP	67.8	58.8	136.0	64.4
299-W11-96	C7754	EW (YE-08)	173.2	NP	87.4	NDE	130.9	79.1
299-W11-97	C8719	EW (YE-13)	139.9	90.7	87.6	61.5	121.3	67.9
299-W12-3	C7028	EW (YE-18)	183.6	NP	96.0	72.4	128.7	75.4
299-W12-4	C7029	EW (YE-19)	162.6	NP	91.8	65.9	113.0	70.4
299-W14-21	C7494	EW (YE-15)	168.8	88.6	84.9	59.4	124.8	62.3
299-W14-22	C7030	EW (YE-20)	165.6	NP	89.3	62.9	126.5	68.5
299-W14-73	C7021	EW (YE-03)	164.1	NP	71.9	NDE	128.1	67.1
299-W14-74	C7024	EW (YE-04)	164.0	NP	85.6	NDE	127.0	70.6
299-W5-1	C8721	EW (YE-17)	180.9	NP	119.8	80.2	128.8	83.0
299-W5-2	C9439	MW	175.9	NP	110.5	81.5	112.0	87.6
299-W6-13	C8064	IW (YJ-01)	184.2	NP	92.3	79.7	113.1	82.7
299-W6-14	C8065	IW (YJ-02)	183.1	NP	96.7	67.5	114.5	70.4
299-W6-15	C8720	EW (YE-14)	173.9	NP	116.1	74.6	126.5	77.7
299-W6-16	C9561	IW (YJ-29)	173.4	NP	86.9	67.7	134.8	69.3
299-W6-17	C9738	MW	174.2	NP	87.6	75.2	92.2	86.1
699-47-78C	C9880	IW (YJ-34)	169.7	NP	91.2	67.2	135.5	68.4
699-48-70	C9988	EW (YE-33)	157.2	NP	113.2	87.3	128.4	97.9
699-49-69	C8786	IW (YJ-09)	166.4	105.5	103.2	86.2	124.1	87.6

NP = unit is not present
NDE = well not drilled deep enough to encounter unit
MW = monitoring well
EW = extraction well
IW = injection well
(a) Plant ID used in the 200 West P&T system for extraction (EW) and injection wells (IW).
(b) Elevations for the top of stratigraphic units are based on current (HSGFM ECF-HANFORD-13-0029, Rev. 5) as communicated in email correspondences from Sarah Springer (CHPRC) to Rob Mackley (PNNL) on 6/17/2020 and 6/18/2020.
(c) The top and bottom elevations of screened intervals were calculated from well elevation and screen depth information obtained well completion summary reports downloaded from the Environmental Dashboard Application (EDA; https://ehs.chprc.rl.gov/eda/) on 4/10/2020.

2.3.2 Pre-Testing Analyses

A series of pre-test analyses were performed to evaluate key aspects related to the test design, feasibility for field implementation, potential for achieving Rwia hydraulic characterization objectives, and scale of investigation. Appendix B contains the analyses for constant-rate and shutdown-recovery pumping tests and Appendix C contains an analysis of the single-well tracer testing method.

Note the pre-test analyses are based on generalized representative test conditions for hydraulic testing of the Rwia unit in the ZP-1 OU. The pre-test analyses could be refined for each of the identified test locations as additional information becomes available from drilling of new Rwia wells or as results from hydraulic more locations become available. The refined pre-test analyses could be included in the associated field or work instruction document(s).

A brief summary of the pre-test analysis objectives and results is provided below.

2.3.2.1 Pumping Tests

The pre-test analysis first evaluated the predicted test response characteristics for constant-rate pumping tests for three operative aquifer models (unconfined, confined, and leaky-confined). In its more traditional or idealistic form, constant-rate pumping tests initiate from a static pre-test condition and pumping occurs only in the stress well(s). Pumping can involve injection or extraction. Given the numerous P&T wells operating in the ZP-1 test area, this type of approach would require a significant disruption in operations and negatively impact progress toward remedial performance. Accordingly, the shutdown-recovery testing approach, a variant form of the constant-rate pumping test that minimizes P&T operations impact by allowing most of the P&T wells in a test area to remain running (Appendix B, Section B.3), was also evaluated for application and suitability to the ZP-1 test area. The objectives of the analysis were as follows:

1. Assess the duration of pumping time required to meet analytical constraints (e.g., infinite-acting radial flow conditions) and achieve test objectives (e.g., identify confined vs. leaky-confined aquifer model).
2. Determine the radius of influence (ROI) for a pumping well based on predicted pressure response.
3. Evaluate the application of constant-rate pumping test analysis methods for analyzing the responses from shutdown-recovery tests.

This information can be used diagnostically to guide and select test areas and combinations of wells to be used in testing, and to indicate other possible design constraints and operational considerations. For pumping tests, the timing and magnitude of aquifer pressure response varies as a function of the test configuration (flow rate and duration), operative aquifer model exhibited (unconfined, confined, and leaky-confined aquifer), aquifer hydraulic properties (thickness, transmissivity, and storage values), and radial distance from the pumping well.

It is important to distinguish between "radius of influence" and "radius of investigation." The radius of influence is defined here as the distance from the test well in which the hydraulic response is still observable. The radius or scale of investigation refers to the distance from the test well over which the derived hydraulic property determined from hydrologic testing is relevant. The radius of investigation is generally smaller than the radius of influence, but both can potentially be estimated from observed pressure responses.

Pumping Duration Requirements

The pre-test analysis results indicate the following main points:

- Constant-rate pumping testing of the Rwia unit in the ZP-1 test area will require significant pumping time durations.
- For the fully-confined and unconfined aquifer model scenarios, pumping would need to continue for 2 to 6 months for infinite radial flow conditions to become established.
- Pumping durations of a year or more may be required to distinguish between fully-confined and leaky-confined conditions if vertical leakage through the Rlm is relatively small, and therefore quantification of the Rlm leakage factor is less likely to be successful.
- If vertical leakage through the Rlm is more pronounced, the leakage factor and K_v for the Rlm could be quantified after several months of pumping.

- Longer pumping durations are needed to observe test responses at larger radial distances, so tests should be designed to use the closest observation wells.

Radius of Influence (ROI)

The pre-test analysis results indicate the following main points:

- Although Rwia wells are spaced hundreds of meters apart in the ZP-1 test area, there are sufficient wells to observe the proposed pumping tests.
- The predicted ROI for Rwia pumping wells in the ZP-1 test area extends large radial distances (several hundreds of meters or more).
- Observation wells located 400 m or more from pumping (stress) well are likely to have an observable and analyzable response.
- P&T wells located within several hundreds of meters of the Rwia test and observation wells are likely to influence or interfere with test responses, and this needs to be considered in the test design and incorporated into the field test instructions.

Shutdown-Recovery Tests

The pre-test analysis results indicate the following main points:

- Shutdown-recovery tests involve stopping flow to one or more P&T wells (referred to as stress wells), while maintaining flow to the other P&T wells in the test area, and this results in less impact to the P&T system.
- The total composite aquifer response is a superposition of the impact from surrounding P&T wells (prior to and during the shutdown-recovery test) and the initiation of the shutdown of the stress well(s) (Todd 1980; Spane 2010).
- The shutdown-recovery component of the response can be isolated or de-superposed (Spane 2010) from the total composite response and analyzed as an equivalent constant-rate pumping test response.
- The shutdown-recovery response was simulated for a leaky-confined aquifer scenario, and results indicate this is a suitable approach for obtaining test objectives within the complex operational framework of the ZP-1 P&T system.
- Using more than one P&T stress well could amplify the shutdown-response signal in the relatively higher-transmissive composite Rwie-Rwia unconfined aquifer, where responses are relatively lower.
- Required durations for shutdown-recovery testing are consistent with those indicated above for constant-rate pumping tests.
- Additionally, the shutdown-recovery testing approach requires a pre-test period up to 3 months where flows are kept steady in all P&T wells within the test area to allow water levels in the test area to stabilize to a linear background trend (Spane 2010).

2.3.2.2 Single-Well Tracer Tests

The pre-test analysis evaluated several aspects associated with tracer-dilution and tracer pumpback tests. The tracer test pre-test analysis assessment components include the following:

1. Evaluate the relative amount or scale of aquifer investigated with single-well tracer tests.
2. Identify important operational and test parameter considerations for planning and design of single-well tracer test (e.g., tracer volume, drift duration, pumpback duration, purge-water volume).

These assessment components were evaluated for a Rwia aquifer well scenarios with varying duration and hydraulic conditions. The pre-test analysis results for the Rwia tracer-dilution and pumpback testing provide a perspective on the scale of representativeness for derived estimates of groundwater flow (V_a) and effective porosity (n_e) and an indication on the range of associated operational requirements.

Relative Aquifer Distance and Volume Investigated

The pre-test analysis results indicate the following main points:

- Single-well tracer tests investigate a relatively small aquifer volume compared to other aquifer hydraulic test methods such as pumping tests.
- For the ZP-1 Rwia aquifer scenarios considered here, typical tracer drift distances range from 0.25 to 0.63 m when the time for tracer drift is limited to less than 10 days.
- Tracer drift distances of a meter or more can be achieved when the tracer is allowed to drift under ambient groundwater flow conditions for extended periods of time (10 days or more).
- Despite the smaller scale of investigation, single-well tracer tests are worthwhile since they provide field-scale estimates of V_a and n_e not obtainable with other hydraulic testing methods.

Operational Requirements and Considerations

The pre-test analysis results indicate the following main points:

- There are minimal requirements from an operational and logistical perspective for single-well tracer tests.
- For tracer-dilution and pumpback tests, tracer volumes are relatively small (<10 L) and the times required to emplace and pump the tracer back are relatively minimal (<1 day).
- Purge water volumes will be <15,000 gallons per test and pumping rates can be adjusted to accommodate the capacities of the test well, downhole pump, and purge water storage tank or disposal truck
- Implementing the “push-pull” tracer test variation would involve emplacement of a larger tracer volume (hundreds to thousands of liters), but may help provide larger-scale and more representative estimates of V_a and n_e.

2.3.3 Phased and Prioritized Testing Approach

Hydraulic testing activities will proceed in a phased and prioritized approach. The results from the pre-test analyses were used to guide the testing approach and design. The test methods and locations for each phase were selected and prioritized based on the following considerations:

- Potential to directly achieve one or more of the test objectives identified in Table 1.1
- Well locations screened in the target hydrogeologic units (with Rwia-only wells having higher priority over composite Rwie-Rwia aquifer wells)
- Ability to minimize impact to P&T operations and use existing well resources
- Schedule and timing for drilling of new Rwia monitoring wells

Further evaluation of any changes in the operational conditions due to the Rwie optimization study and their potential impacts will have to be evaluated at the time of developing field-testing instructions. Information from each phase of testing will help inform and refine the testing design details for subsequent test phases. For example, information from drilling of the new monitoring wells and the physical and hydraulic property data obtained in Phase 1 can be used to update the hydrogeologic conceptual model. Data obtained in Phase 2 can be used to further refine the hydrogeologic conceptual model and determine how to best perform tracer tests for Phase 3.

2.3.4 Phase 1: Rwia Aquifer Testing

This phase will focus on providing aquifer hydraulic properties of the Rwia unit based on tests in new and existing wells screened only within the Rwia unit. This activity has the potential to accomplish multiple objectives identified in the Ringold A SAP for the Rwia unit. Table 2.5 contains a summary list of the Phase 1 hydraulic testing. A discussion of the Phase 1 testing is provided below. Additional details on the operational sequence and related support requirements (e.g., duration, impact to P&T operations, necessary equipment) for Phase 1 test activities are provided in Appendix D.

Table 2.5. Phase 1 Hydraulic Testing Summary

Testing Description and Locations	Obj 1 (large-scale T and S of Rwia)	Obj 2 (vertical distribution of K_h in Rwia)	Obj 3 (K_v and r/B of Rlm)	Obj 4 (n_e of Rwia)
Post-completion slug testing in all new Rwia monitoring well locations (Figure 2.3)	Yes[(A)]	No	No	No
EBF tests in all new Rwia monitoring wells and stress wells used in Phase 1 shutdown-recovery tests (Figure 2.4)	No	Yes	No	No
Install AWLN stations in each of the new Rwia monitoring well locations (Figure 2.3)		Prerequisite[(B)]		
Evaluate AWLN water-level data for responses to P&T and barometric effects. Diagnose and correct for barometric effects and identify operative aquifer model based on barometric response.	Prerequisite[(B)]	No	Yes[(C)]	Prerequisite[(B)]
Shutdown-recovery tests to determine large-scale aquifer properties in Rwia well locations within test areas 1a and 1b (Figure 2.5)	Yes	No	Yes	No

K_h = horizontal hydraulic conductivity
K_v = vertical hydraulic conductivity
n_e = effective porosity
T = transmissivity = K_h*b
b = aquifer thickness
S = storativity
S_y = specific yield
r/B = vertical leakage factor
(a) Slug tests provide a local-scale K_h estimate but when performed in multiple wells locations throughout the test area, they can provide an indication of the range in K_h values at a larger scale.
(b) Water-level information is fundamental to subsequent testing and analyses.
(c) Barometric response functions may help identify and quantify leakage through the Rlm aquitard.

2.3.4.1 Post-completion Slug Tests in Phase 1

Slug tests in new Rwia wells following construction and completion will provide local-scale estimates of horizontal hydraulic conductivity (K_h) for the Rwia unit throughout the ZP-1 test area (Figure 2.3). Collectively, this effort will provide an indication of the range in K_h values within the entire ZP-1 test area, which is directly related to test objective 2 of the Ringold A SAP.

Note that the post-completion tests proposed in this plan are in addition to the depth-discrete slug testing of new Rwia wells performed during drilling. The depth-discrete slug testing is being performed under the direction of the Ringold A SAP to provide the vertical distribution of K_h in the Rwia unit, whereas the post-completion slug tests in this test plan are designed to provide a single K_h estimate for the screened interval of the constructed well. This is needed for analysis of the follow-on Phase 3 tracer-dilution and pumpback tests (which may or may not be in the same intervals used for slug testing during drilling).

2.3.4.2 EBF Testing in Phase 1

EBF tests in each of the new Rwia monitoring wells and the two P&T stress wells locations (Figure 2.4) will provide estimates on the relative vertical distribution of K_h within the Rwia unit (test objective 2). This will help identify preferential high- and low-flow zones within the screened interval of the completed well. This information will be integrated with the slug test results to better understand the vertical range of K_h and heterogeneities within the Rwia unit across the entire ZP-1 test area.

EBF testing in the two P&T injection wells planned as stress wells for Phase 1 shutdown-recovery tests will provide the relative distribution of K_h within the test interval and the effective aquifer thickness, and will help to better interpret the results from the recovery tests. The EBF tests will also help identify ambient vertical in-well flow (e.g., strong up or downward flow in the wellbore even in the absence of pumping), which is needed to interpret single-well tracer testing planned in Phase 3.

2.3.4.3 New AWLN Stations in Phase 1

Installing AWLN stations in each of the new Rwia monitoring wells is considered a mandatory prerequisite activity since this provides the fundamentally important water-level information at these key locations. Well water-level data are needed to identify the hydraulic response of nearby P&T wells, diagnose and correct for barometric pressure effects, and help identify the operative aquifer model present. AWLN stations should be installed as soon as the wells are completed to allow data collection and evaluation (see below) to be initiated.

The pressure sensors in these AWLN stations need to be maintained and kept within calibration, and manual depth-to-water measurements need to be taken frequently (every 2 months at a minimum) to ensure data quality.

2.3.4.4 Characterize P&T and Barometric Responses

Water-level data collected in existing and new AWLN stations in the 200-ZP-1 test area should be evaluated to characterize the responses to changes in P&T operations and barometric pressure fluctuations. A minimum monitoring period of 2 months is required, but a period of > 6 months is preferred.

This activity should also be considered a mandatory prerequisite since it provides site-specific information needed for the final design and analysis of subsequent shutdown-recovery tests (in Phases 1 and 2). Additionally, pressure responses in Rwia wells to changes in P&T wells could help to identify the lateral hydraulic communication within the Rwia and between the Rwia and the Rwie.

The barometric response functions observed in a well can be used to identify the operative aquifer model (e.g., differentiate confined, unconfined, and leaky-confined aquifer conditions) and potentially estimate the hydraulic properties of the Rlm aquitard (Spane 2002; Butler et al. 2011). The importance of installing new AWLN stations and characterizing barometric responses needs to be further emphasized because barometric pressure fluctuations could potentially mask the test responses in observation wells where test response might be less (e.g., < 0.1 m) during the shutdown-recovery pumping tests. As noted by Spane (2010), water levels in the 200 West Area wells can respond to barometric fluctuations by as much as +/- 0.3 m. These barometric effects will need to be characterized and removed to properly analyze the shutdown-recovery test responses.

2.3.4.5 Shutdown-Recovery Tests in Phase 1

Shutdown-recovery tests will be conducted within two test areas located in the eastern portion of the ZP-1 test area, where there are abundant wells screened in the target test Rwia unit (Figure 2.5). The majority of these wells are P&T injection wells, so coordination and scheduling with the P&T operations will be needed to accomplish these tests. Appendix D contains additional information on associated P&T impacts and operational support requirements.

The wells involved in the two test areas (1a and 1b) are listed in (Table 2.6) and shown in Figure 2.5. The outcome of these shutdown-recovery tests will be large-scale estimates of T and S for the Rwia (test objective 1). The test responses can be analyzed to identify and quantify leakage through the Rlm aquitard, the vertical conductivity (K_v) and leakage factor (r/B) for the Rlm aquitard (test objective 3). The Rlm unit appears to be present within this test area, but the degree of hydraulic confinement remains uncertain.

The 1a and 1b designation for the Phase 1 test areas does not indicate a difference in testing priority, just a difference in test location. Both test areas use new Rwia monitoring wells to observe the test response, which are currently planned for completion in FY22 (Table 2.2). Appendix D contains additional information on the timing and sequence of Phase 1 shutdown-recovery testing.

Table 2.6. Wells Used in Phase 1 Shutdown-Recovery Test Areas 1a and 1b

Test Area	Well Name	Test Well Role	Screened Unit[(a)]	Hanford Well ID	Well Type (P&T ID)[(b)]	AWLN Station	Radial Distance[(c)] (m)	Critical Test Well[(d)]
1a	699-45-67B	SW	Rwia	C8717	IW (YJ-10)		0	Yes
	699-45-67	OW	Rwie[(e)]	C7578	IW (YJ-11)		8	Yes
	MW-D	OW	Rwia	D0083	MW	New	231	Yes
	699-45-69C	OW	Rwia	C5574	MW	Existing	319	Yes
	699-46-68	OW	Rwie[(e)]	C8067	IW (YJ-23)		370	Yes
	699-44-67	OW	Rwia	C8068	IW (YJ-12)		378	Yes
	699-45-69A	OW	Rwie[(e)]	A5196	MW		541	No
	MW-C	OW	Rwia	D0082	MW	New	746	No
	699-44-70B	OW	Rwia	C9740	MW	Existing	748	No
1b	699-43-67B	SW	Rwia	C8386	IW (YJ-17)		0	Yes
	699-43-67	OW	Rwie[(e)]	C7579	IW (YJ-13)		5	Yes
	699-44-67	OW	Rwia	C8068	IW (YJ-12)		336	Yes
	699-42-67	OW	Rwia	C8069	IW (YJ-14)		361	Yes
	MW-D	OW	Rwia	D0083	MW	New	552	No
	699-43-69	OW	Rwia	C7578	MW	Existing	713	No
	699-44-70B	OW	Rwia	C9740	MW	Existing	748	No
	699-45-69C	OW	Rwia	C5574	MW	Existing	798	No

IW = P&T injection well
SW = stress well
OW = observation well
(a) Hydrogeologic unit in which the screened interval is located.
(b) Plant ID used in the 200 West P&T system for extraction (EW) and injection wells (IW).
(c) Radial distance from stress well. Only those wells within 800 m were included.
(d) Wells within 500 m of the stress well are considered likely to exhibit an analyzable test response, but it is highly uncertain if a response will be identified beyond that radial distance.
(e) Wells screened solely within the Rwie are included to identify any possible inter-aquifer hydraulic communication.

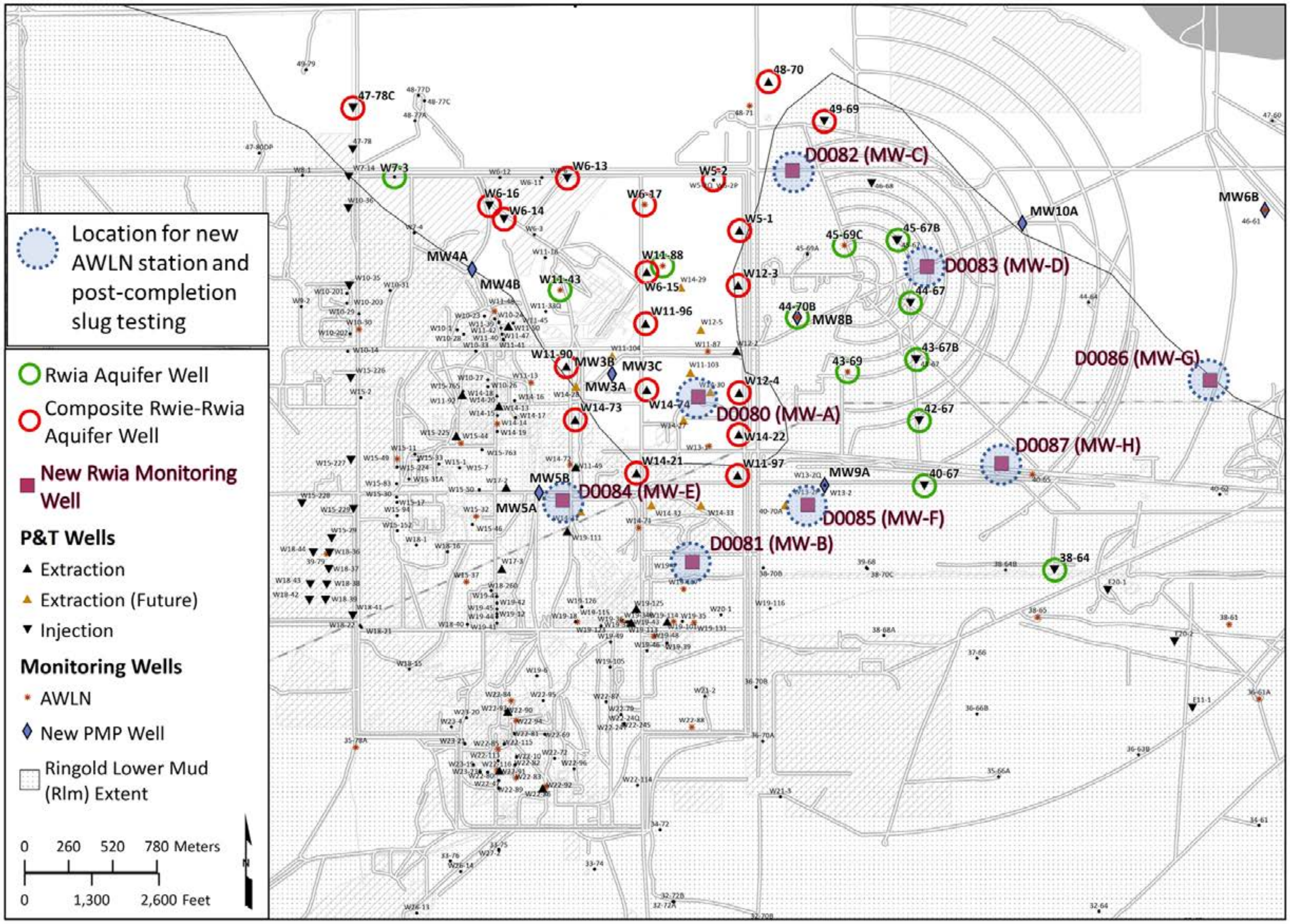

Figure 2.3. Locations for post-completion slug testing and installation of AWLN stations in new Rwia wells.

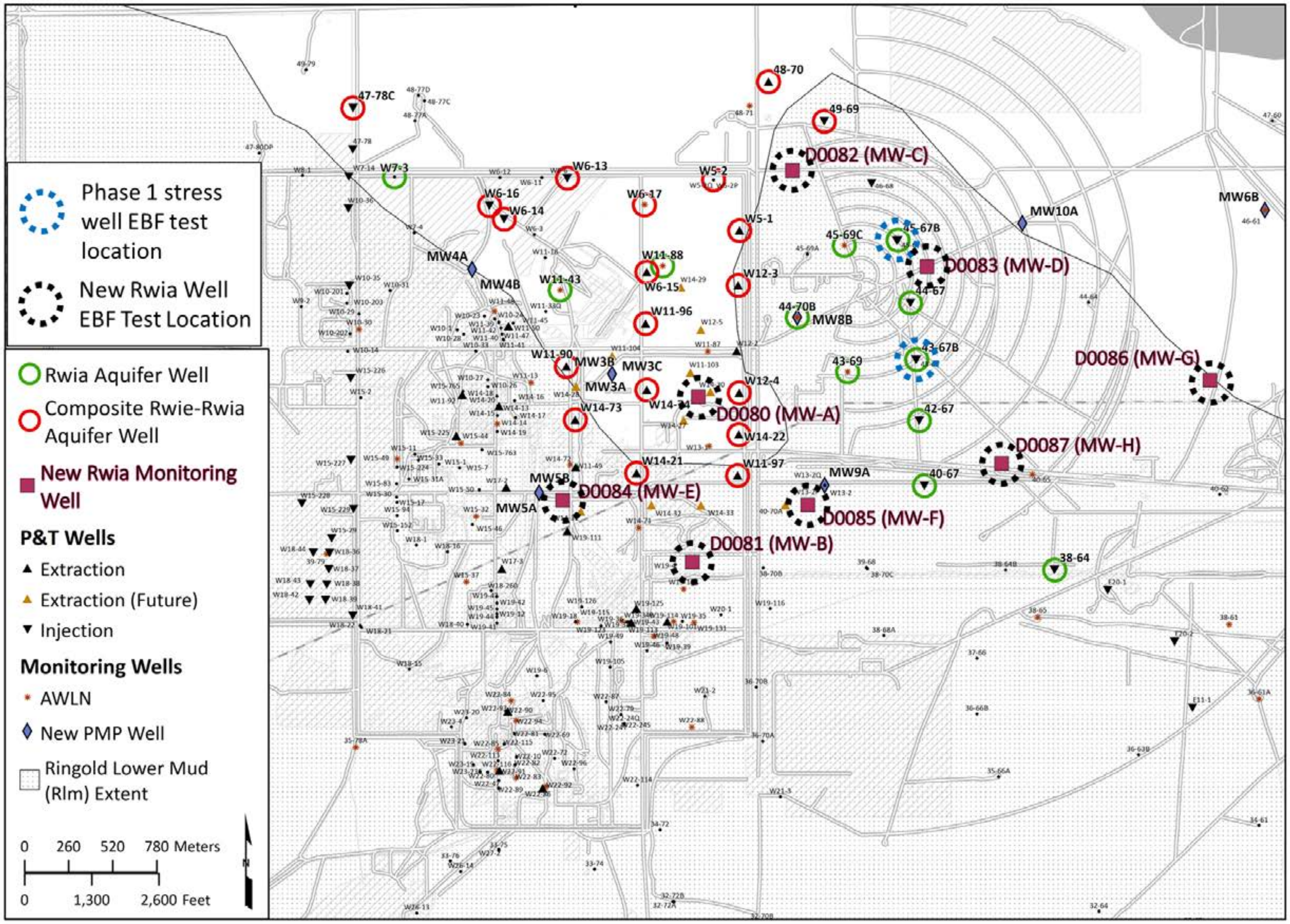

Figure 2.4. Locations of Phase 1 EBF testing of new Rwia wells (black dashed circles) and Rwia stress wells used in Phase 1 shutdown-recovery tests (blue dashed circles).

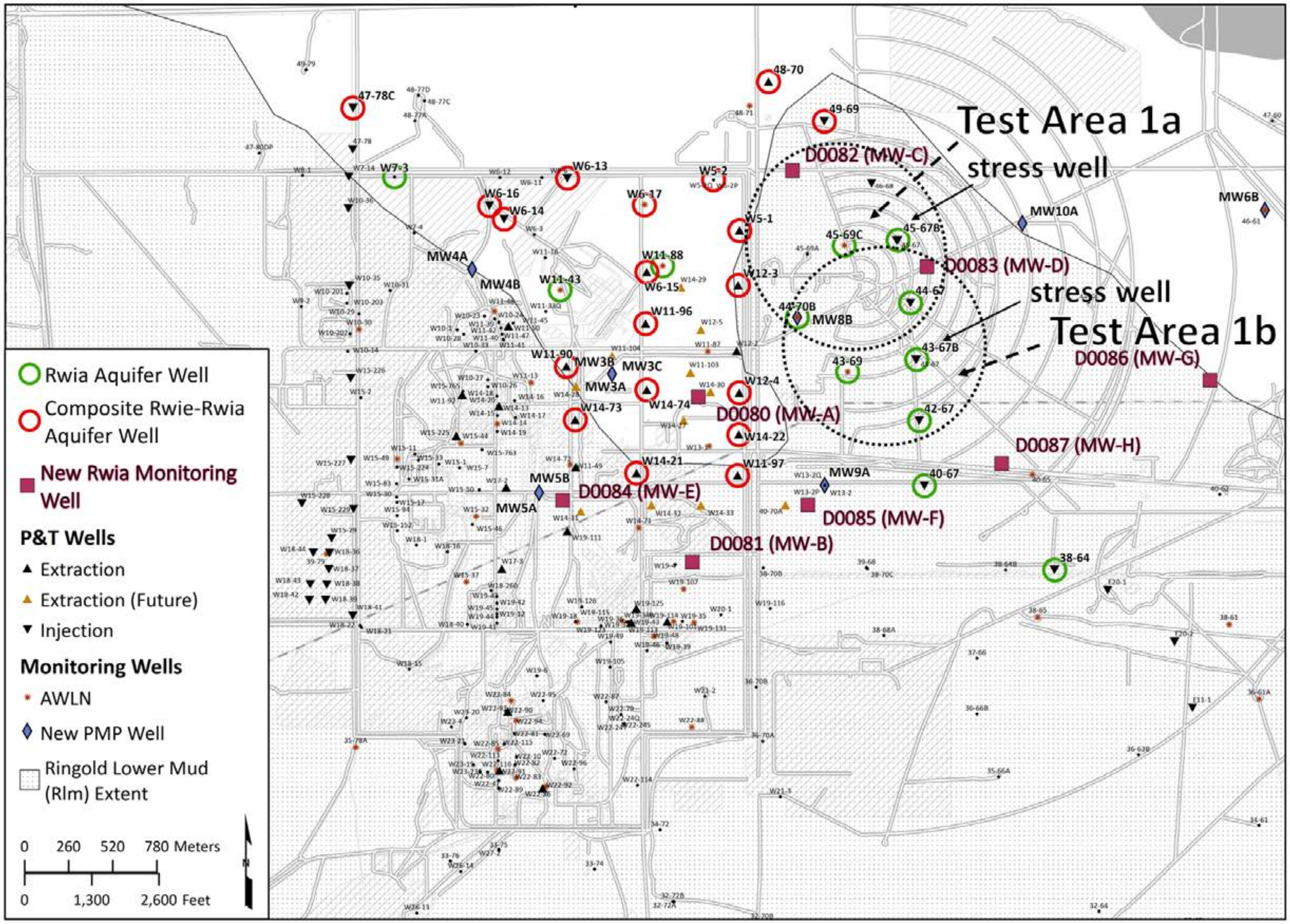

Figure 2.5. Test areas and stress well locations for Phase 1 shutdown-recovery testing of Rwia aquifer wells.

2.3.5 Phase 2: Composite Rwie-Rwia Aquifer Testing

This phase will focus on providing aquifer hydraulic properties for the composite Rwie-Rwia unconfined aquifer. Although the Ringold A SAP does not explicitly identify the Rwie as a target for hydraulic testing, a large portion of the groundwater flow and contaminant transport in the ZP-1 OU is within the composite Rwie-Rwia unconfined aquifer, where the Rlm is absent. Numerous P&T extraction wells are screened within this composite Rwie-Rwia aquifer, particularly in the northcentral portion of the OU where the Rlm is absent. Phase 2 testing will use existing P&T extraction and injection wells as stress wells to induce shutdown-recovery responses in nearby wells.

Table 2.7 contains a summary list of the Phase 2 hydraulic testing. A discussion of the Phase 2 testing is provided below. Additional details on the operational sequence and related support requirements (e.g., duration, impact to P&T operations, necessary equipment) for Phase 2 test activities are provided in Appendix D.

Table 2.7. Phase 2 Hydraulic Testing Summary

Testing Description and Locations	Obj 1 (large-scale T and S[(a)] of Rwia)	Obj 2 (vertical distribution of K_h in Rwia)	Obj 3 (K_v, and r/B of Rlm)	Obj 4 (n_e of Rwia)
Shutdown-recovery tests to determine large-scale aquifer properties in the composite Rwie-Rwia aquifer in well locations within test areas 2a-d (Figure 2.6)	YES[(a)]	NO	YES[(b)]	YES[(c)]
EBF tests in the four stress wells used in Phase 2 shutdown-recovery tests (Figure 2.7)	NO	YES[(a)]	NO	NO

K_h = horizontal hydraulic conductivity
K_v = vertical hydraulic conductivity
n_e = effective porosity
T = transmissivity = K_h*b
b = aquifer thickness
S = storativity
S_y = specific yield
r/B = vertical leakage factor
(a) The results from the shutdown-recovery testing provides a representative T estimate for the composite Rwie-Rwia aquifer at the test location. When combined with the results from the EBF tests, the K_h or T for just the Rwie or Rwia portion of the aquifer can be interpreted.
(b) If the Rlm is present.
(c) S_y, often used as an approximation for n_e, could be estimated from the shutdown-recovery tests for the upper portion of the unconfined aquifer where delayed yield occurs (likely in the Rwie portion of the aquifer above the Rwia).

2.3.5.1 Shutdown-Recovery Tests in Phase 2

Shutdown-recovery tests will be conducted within four test areas, where the majority of the P&T wells are screened in the composite Rwie-Rwia unconfined aquifer (Figure 2.6), for the purpose of determining the large-scale aquifer properties within the composite Rwie-Rwia aquifer (test objectives 1 and 4). Coordination and scheduling with the P&T operations will be needed to accomplish these tests, similar to Phase 1 testing. Appendix D contains additional information on associated P&T impacts and operational support requirements.

These tests will provide a representative T estimate for the composite Rwie-Rwia aquifer (where the Rlm is absent and the unconfined aquifer is within both units) within each test area. But when combined with the results from the Phase 2 EBF tests, the K_h or T for within the Rwie or Rwia portions of the aquifer can be delineated. Understanding the relative permeability between the Rwie and Rwia units will greatly help to interpret results generated in this test plan. It will also help inform, plan, and interpret future remediation activities (e.g., well screen placement and rebound studies).

Although not explicitly identified in the Ringold A SAP test objectives, the specific yield, S_y, is an important aquifer hydraulic property. It is often used to approximate the effective porosity, n_e, which is a key input parameter for groundwater fate and transport models. S_y could potentially be estimated from the shutdown-recovery tests, but it would be representative of the upper portion of the unconfined aquifer where delayed yield occurs (likely in the Rwie portion of the aquifer above the Rwia).

Tests in multiple locations within the expansive composite Rwie-Rwia aquifer system are needed. Borehole geologic information indicates that the lithologic character and thickness of the Ringold Formation sediments varies enough spatially throughout the test area that aquifer hydraulic properties are expected to vary between test areas. Table 2.8 lists the wells used in each of the four Phase 2 test areas (2a-d), in order from highest to lowest priority (but not necessarily in order of implementation). Figure 2.6 shows the locations of the Phase 2 test areas and wells. Higher priority was given to locations where carbon tetrachloride concentrations are higher and P&T extraction is expected to continue for a longer duration combined with the presence of new Rwia monitoring wells nearby. One exception is test area 2c. Although test area 2c is not located in the highest concentration portion of the carbon tetrachloride plume and there are no new Rwia wells planned nearby, it was prioritized above test area 2d given the proximity of the two wells involved and because testing can be performed before the new Rwia wells are constructed.

The large number of Phase 2 test areas may require the testing to be spread out over time to help minimize disruptions to the P&T operations.

2.3.5.2 EBF Testing in Phase 2

EBF tests will be run at each of four Phase 2 stress well locations shown in Figure 2.7 to provide the vertical distribution of relative K_h within the composite Rwie-Rwia aquifer test interval (related to test objective 2). As noted above, the EBF and shutdown-recovery test results can be combined to delineate the K_h or T within the Rwie or Rwia portions of the aquifer.

The results from EBF testing take on an increased importance for the composite Rwie-Rwia aquifer in the ZP-1 OU, where screened intervals are often longer than 50 m (Table 2.4), and the aquifer is vertically-heterogenous with many order-of-magnitude vertical contrasts in K_h. Without this information, it is not possible to correctly identify the depth(s) from which groundwater comes into the well when pumped or sampled. Future remediation activities such as optimizing screen placement for extraction wells and rebound studies will greatly benefit from a better understanding of how the vertical distribution of permeability and contaminant concentrations relate in the collection of a permeability-weighted samples.

Table 2.8. Wells Used in Phase 2 Shutdown-Recovery Test Areas 2a-d

Test Area	Well Name	Test Well Role	Screened Unit[a]	Hanford Well ID	Well Type (P&T ID)[b]	AWLN Station	Radial Distance[c] (m)	Critical Test Well[d]
2a	299-W12-4	SW	Rwie-Rwia	C7029	EW (YE-19)		0	Yes
	MW-A	OW	Rwia[e]	D0080	MW	New	243	Yes
	299-W14-22	OW	Rwie-Rwia	C7030	EW (YE-20)		246	Yes
	299-W12-2	OW	Rwie[e]	C7027	EW (YE-05)		247	Yes
2b	299-W14-21	SW	Rwie-Rwia	C7494	EW (YE-15)		0	Yes
	299-W14-71	OW	Rwie[e]	C5102	MW	Existing	322	Yes
	299-W14-72	OW	Rwie[e]	C5103	MW	Existing	396	Yes
	MW-E	OW	Rwia[e]	D0084	MW	New	465	Yes
	299-W14-73	OW	Rwie-Rwia	C7021	EW (YE-03)		480	Yes
2c	299-W6-16	SW	Rwie-Rwia	C9561	IW (YJ-29)		0	Yes
	299-W6-14	OW	Rwie-Rwia	C8065	IW (YJ-02)		118	Yes
2d	699-48-70	SW	Rwie-Rwia	C9988	EW (YE-33)		0	Yes
	699-48-71	OW	Rwie[e]	A5214	MW	Existing	182	Yes
	699-49-69	OW	Rwie-Rwia	C8786	IW (YJ-09)		404	Yes
	MW-C	OW	Rwia[e]	D0082	MW	New	543	No

IW = P&T injection well
SW = stress well
OW = observation well

(a) Hydrogeologic unit in which the screened interval is located.
(b) Plant ID used in the 200 West P&T system for extraction (EW) and injection wells (IW).
(c) Radial distance from stress well. Only those wells within 800 m were included.
(d) Wells within 500 m of the stress well are considered likely to exhibit an analyzable test response, but it is highly uncertain if a response will be identified beyond that radial distance.
(e) Wells screened solely within the Rwie or solely within the Rwia units will help better estimate how K_h varies with depth in the composite Rwie-Rwia aquifer and K_h/K_z.

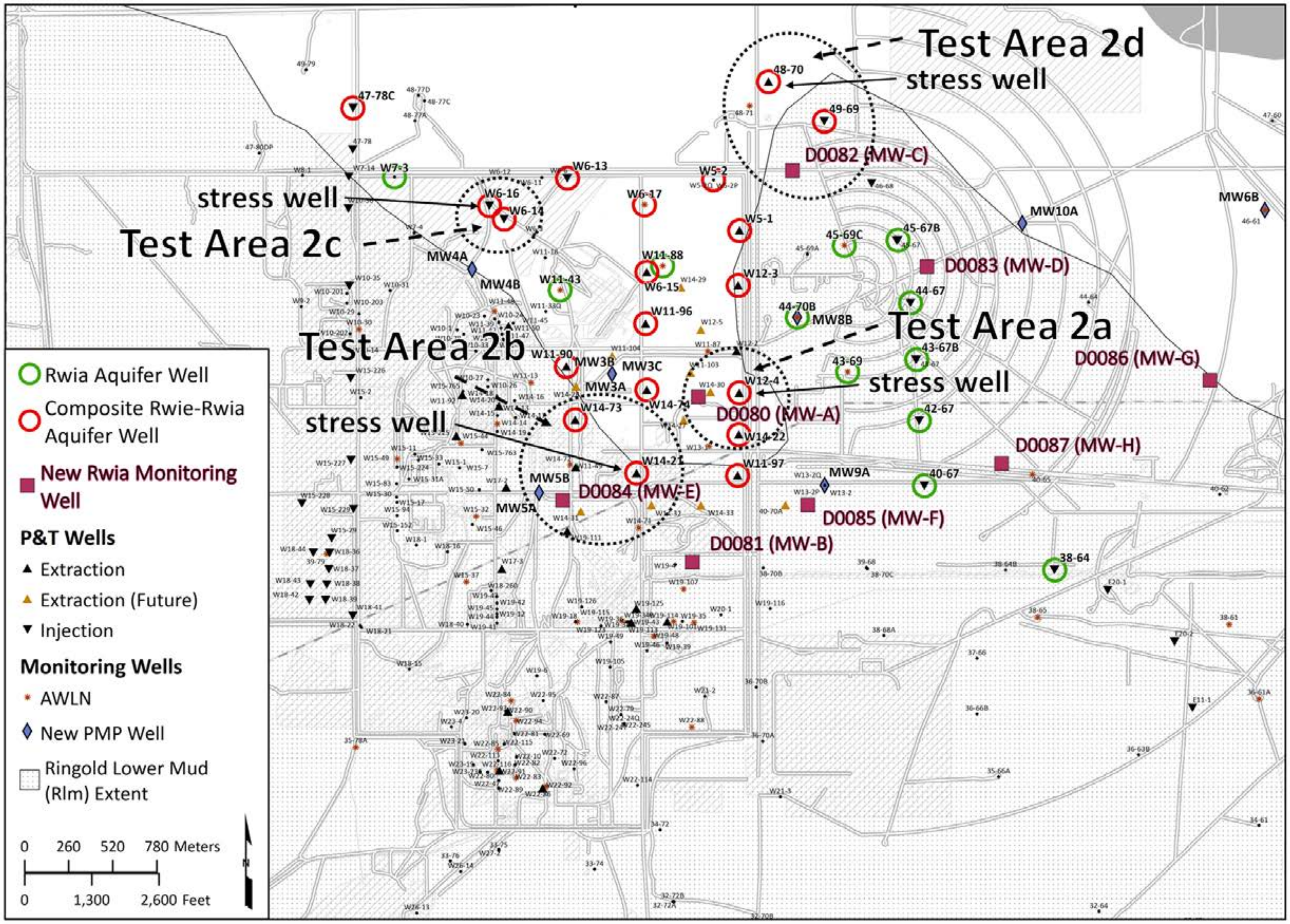

Figure 2.6. Test areas and stress-well locations for Phase 2 shutdown-recovery testing of composite Rwie-Rwia aquifer wells.

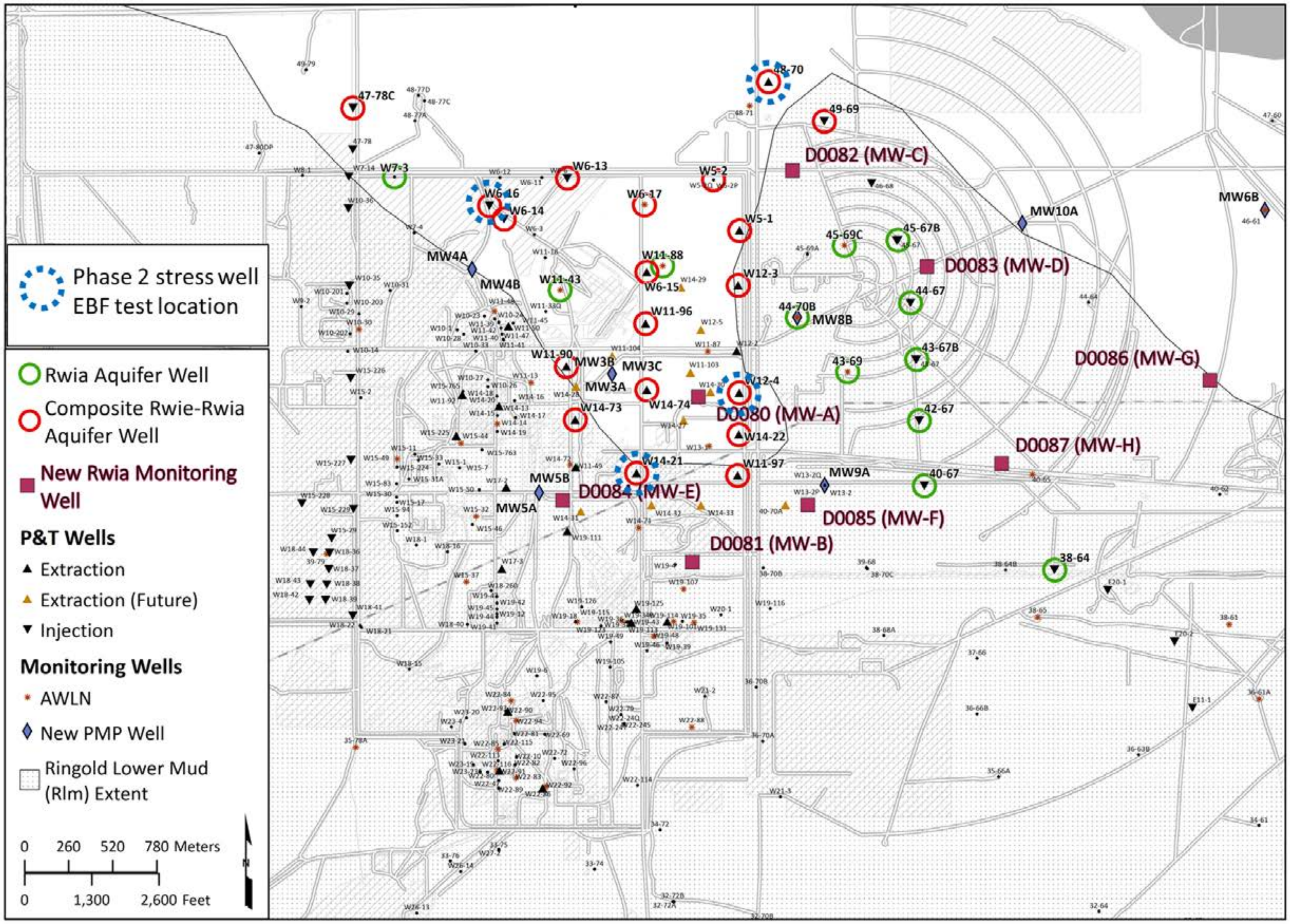

Figure 2.7. Locations of Phase 2 EBF testing of composite Rwie-Rwia aquifer stress wells used in Phase 2 shutdown-recovery tests (blue dashed circles).

2.3.6 Phase 3: Single-Well Tracer Testing

This phase involves single-well tracer tests to estimate n_e for the Rwia aquifer at the field scale (test objective 4). Table 2.9 contains a summary list of the Phase 3 hydraulic testing. A discussion of the Phase 3 testing is provided below. Additional details on the operational sequence and related support requirements (e.g., duration, impact to P&T operations, necessary equipment) for Phase 3 test activities are provided in Appendix D.

Table 2.9. Phase 3 Hydraulic Testing Summary

Testing Description and Locations	Obj 1 (large-scale T and S of Rwia)	Obj 2 (vertical distribution of K_h in Rwia)	Obj 3 (K_v and r/B of Rlm)	Obj 4 (n_e of Rwia)
Single-well tracer testing to determine n_e and V_a within test areas 3a-e (Figure 2.8)	No	No	No	Yes[(a)]

K_h = horizontal hydraulic conductivity
K_v = vertical hydraulic conductivity
n_e = effective porosity
r/B = vertical leakage factor
T = transmissivity = K_h*b
b = aquifer thickness
S = storativity
V_a = groundwater velocity in the aquifer
(a) Tracer-dilution-pumpback tests will provide a local-scale estimate of n_e.

2.3.6.1 Tracer Dilution and Pumpback Testing in Phase 3

Tracer dilution and pumpback tests in select new Rwia wells located along the southern perimeter of the ZP-1 test area (Figure 2.8) would provide a local-scale estimate of n_e (test objective 4) as well as a field estimate for groundwater velocity (V_a) under ambient hydraulic gradient imposed by the P&T system. As noted in Section 2.3.2.2, single-well tracer studies investigate a smaller radial distance and aquifer volume compared to multi-well tracer or pumping test tests. However, they are logistically easier and less costly to implement (e.g., low durations and purge water volumes) and do not impact P&T operations.

Five tests locations were selected from among the new Rwia wells for Phase 3 tracer testing (Figure 2.8). With some exceptions, these locations are generally relatively farther from P&T wells, which could negatively influence the test results. Currently, there is no priority assigned to the Phase 3 tracer testing locations. However, as the characterization activities described in the Ringold A SAP are implemented, resulting information on the contaminant and/or hydraulic characterization may be used to prioritize these locations.

The horizontal hydraulic gradient (I) during the tracer testing period is needed in the analysis to estimate n_e and V_a. The sparseness of Rwia aquifer wells and the potential interference from the P&T system pose a risk factor for the success of the tracer tests. There may be a need for estimates from other portions of the test area where there are more Rwia aquifer wells with AWLN stations and/or better geometry for calculating I. This will introduce uncertainty in the n_e and V_a estimates. Despite these limitations and uncertainties, the single-well tracer testing is still recommended since this is one of the only methods to obtain field-scale estimates of n_e, which is a key input parameter for groundwater fate and transport models.

Normally, the pressure drawdown response observed in the test well during the tracer pumpback would be analyzed to estimate T. However, the duration of the tracer pumpback would likely need to be extended by 2 to 6 months to reach infinite radial flow conditions necessary for single-well pumping test analysis (e.g., Cooper-Jacob straight line method). The large volume of associate purge water and the long duration make this impractical for combination with the tracer testing.

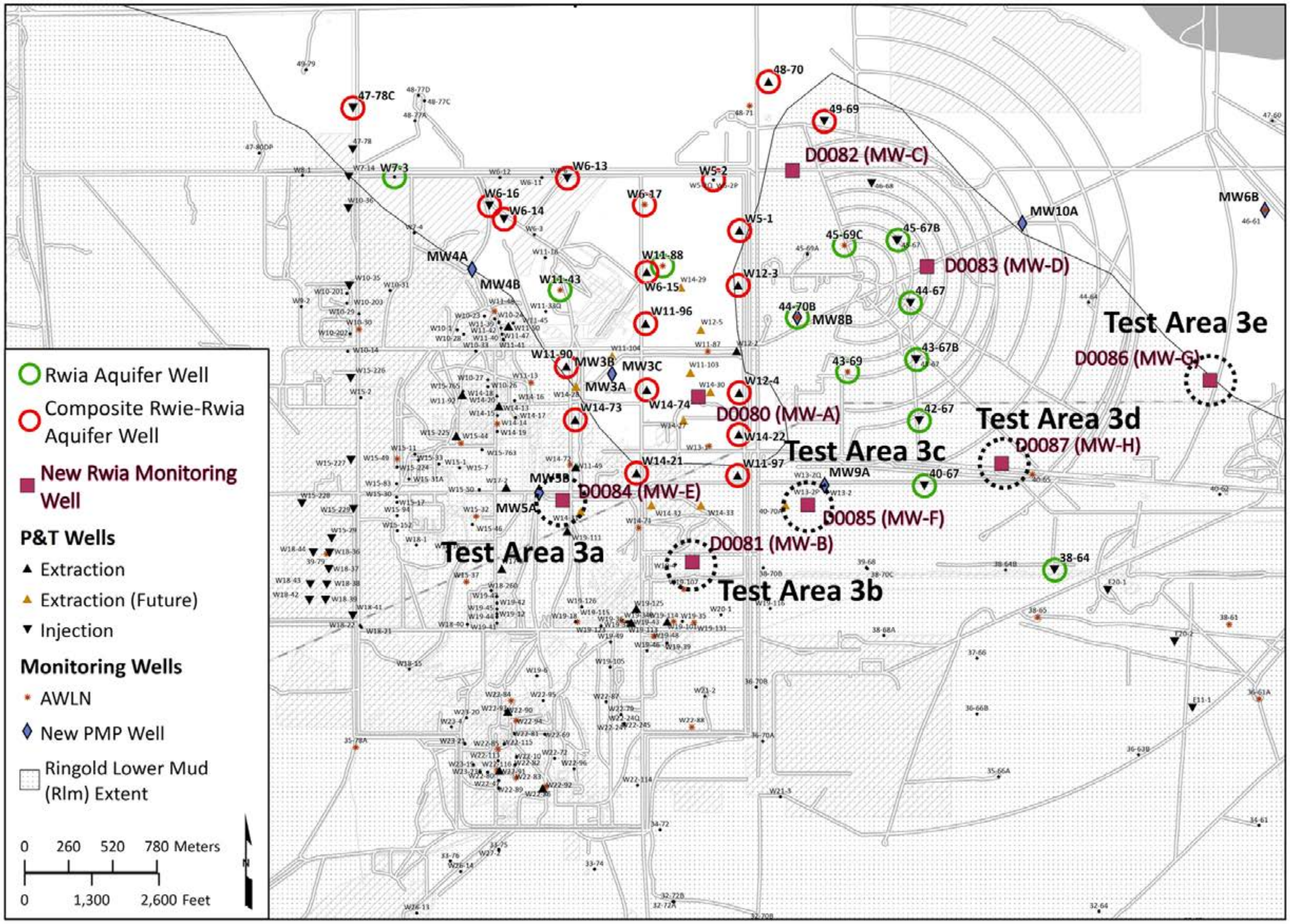

Figure 2.8. Locations of Phase 3 single-well tracer tests in new Rwia monitoring wells (dashed circles).

Information from each phase, as well as other relevant characterization data collected from the implementation of the Ringold A SAP, will inform and help refine the testing design for subsequent test phases. For example, information from drilling of the new monitoring wells and the physical and hydraulic property data obtained in Phase 1 can be used to update the hydrogeologic conceptual model. Data obtained in Phase 2 can be used to further refine the hydrogeologic conceptual model and determine how to best perform tracer tests for Phase 3. It is also recommended that pre-test numerical modeling be performed for any planned tracer tests.

2.4 Opportunistic Analyses

The three phases of aquifer testing involve field-based activities designed to provide specific results tied to the objectives of the Ringold A SAP. In addition to the controlled test activities within the scope of this, there are “opportunistic” events (historical and future) that have the potential to also provide information on aquifer hydraulic properties. Planned and unplanned P&T shutdown-restart events may impart an observable and analyzable pressure response in nearby wells where water-level data are available. These can and should also be analyzed to estimate aquifer properties.

For example, sulfate was added to groundwater during an ion exchange treatment process (pH adjustment by addition of sulfuric acid) and the treated groundwater was discharged in 100 Area P&T effluent. The data were opportunistically analyzed to estimate a revised mobile porosity to be used in the groundwater flow model for the 100 Areas (SGW-60606, Rev. 0). Similarly, recent changes to the treatment process in the 200 West P&T facility have resulted in discharge of nitrate concentrations above background levels. The nitrate in P&T effluent is being discharged in injection wells and has the potential to be analyzed as an opportunistic groundwater tracer, requiring no additional field operations or impact to the P&T system. These data are being analyzed currently for the 200-ZP-1 P&T optimization study

Analyses of data resulting from opportunistic events will typically require the use of numerical F&T models, or possibly the analytical element method, rather than simple analytical solutions. Analyses performed using the numerical F&T models, or more sophisticated analytical methods, of well water-level responses to variations in P&T well flow rates have the potential to provide estimates of the aquifer hydraulic properties at the scales that are most relevant to remediation.

2.5 Reporting of Results

Depending on testing schedules determined based on well drilling and construction activities, one or more technical reports will be prepared to document the methods and results following the completion of the hydraulic tests. In addition, hydraulic properties, injection and extraction flow rates, the timing of tests, pressures measurements, tracer concentrations, and other related tabular and metadata will be made available in electronic form, such as an Environmental Modeling Data Transmittal (EMDT), for potential use with numerical F&T models and inverse parameter estimation methods. As the Rwia hydraulic characterization information becomes available it will be incorporated into the overall ZP-1 remedy performance assessment and optimization efforts.

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Appendix A – Summary of Aquifer Testing and Analysis Methods

The following discussion is based on discussions presented in Spane and Newcomer (2010), Spane (2010), and Spane et al. (2001).

A.1 Slug Testing

Because of their ease of implementation and relatively short duration, slug tests are commonly used to provide initial estimates of hydraulic properties (e.g., range and spatial/vertical distribution of hydraulic conductivity, K). Because of the small displacement volumes employed during slug tests, hydraulic properties determined using this characterization method are representative of conditions relatively close to the well. For this reason, slug-test results are commonly used in the design of subsequent hydrologic tests having greater areas of investigation [e.g., slug interference (Novakowski 1989; Spane 1996; Spane et al. 1996), constant-rate pumping tests (Butler 1990; Spane 1993)].

Slug-withdrawal tests should be used rather than slug-injection tests (i.e., by rapidly immersing the slugging rod) because of their reported superior results for unconfined aquifer tests where the water table occurs within the well-screen section (e.g., Bouwer 1989). At all test sites, two different size slugging rods should be used to impart varying stress levels for individual slug tests. The slug tests should be repeated at each stress level to assess reproducibility of the test results. Comparison of the normalized slug-test responses is useful for assessing the effectiveness of well development and the presence of near-well heterogeneities and dynamic skin effects, as noted in Butler et al. (1996).

Two different methods, described in the following sections, can be used for slug-test analysis: (1) the semiempirical, straight-line analysis method described in Bouwer and Rice (1976) and Bouwer (1989) and (2) the type-curve-matching method for unconfined aquifers presented in Hyder et al. (1994), commonly known as the KGS (Kansas Geological Survey) model.

A.1.1 Bouwer and Rice

The Bouwer and Rice (1976) method is a well-known technique and is widely applied in the analysis of slug tests. A number of analytical weaknesses, however, limit the successful application of the Bouwer and Rice method for analyzing slug-test response. These weaknesses constrain its application to slug-test responses that exhibit steady-state flow, isotropic conditions, no well-skin effects, and no elastic (storage) formation response. Unfortunately, these limitations are commonly ignored, and the Bouwer and Rice method is applied to slug-test responses that do not meet the test analysis criteria. A more detailed discussion on the analytical limitations of the Bouwer and Rice method is provided in Hyder and Butler (1995), Brown et al. (1995), and Bouwer (1996).

For slug tests exhibiting elastic storage response, it should be noted that improved estimates can be obtained if analysis criteria specified in Butler (1996, 1998) are observed. The presence of elastic aquifer storage (i.e., specific storage, Ss) and effects of a high-permeability sand pack cause curvilinear test responses (concave upward) that deviate from the predicted linear, nonelastic formation response. When this diagnostic curvilinear response is exhibited in the slug-test response, Butler (1996, 1998) recommends that the late-time test analysis be employed (i.e., the normalized head segment between 0.3 and 0.2) when using the Bouwer and Rice (1976) method. Quantitative estimates for K can be obtained using the Bouwer and Rice method over a wide range of test-response conditions (nonelastic or elastic formation, high-K sandpack effects) if the proper analysis criteria are applied.

Because of its semiempirical nature, analytical results obtained using the Bouwer and Rice method (i.e., in contrast to results obtained using the type-curve-matching method) may be subject to error.

Bouwer and Rice (1976) indicated that the K estimate, using their analysis method, should be accurate to within 10% to 25%. Hyder and Butler (1995) state an accuracy level for the Bouwer and Rice method within 30% of actual for homogeneous, isotropic formations, with decreasing levels of accuracy for more complex well/aquifer conditions (e.g., well-skin effects). For these reasons, greater credence is generally afforded to the analytical results obtained using the type-curve-matching approach, which has a more rigorous analytical basis.

A.1.2 KGS Type-Curve Model

Because the type-curve fitting using the KGS model of Hyder et al. (1994) can use all or any part of the slug-test response in the analysis procedure, it is particularly useful for the analysis of unconfined aquifer tests. In addition, this method has none of the aforementioned analytical weaknesses of the Bouwer and Rice (1976) method. To facilitate the standardization of the slug-test type-curve analyses, a set of initial analysis parameters should be assumed:

- A vertical anisotropy, K_D, value of 1.0
- A specific storage, Ss, value of 0.00001 m^{-1}
- The well-screen interval below the water table can be assumed to be equivalent to the test-interval section.

To standardize the slug-test type-curve-matching analysis for all slug-test responses, a 1.0 K_D can be assumed. As noted in Butler (1998), this is the recommended value for slug-test analysis when setting the aquifer thickness to the well-screen length. Previous investigations have indicated that single-well slug-test responses are relatively insensitive to K_D; therefore, the use of an assumed (constant) value of 1.0 over a small well-screen section (i.e., <10 m long) is not expected to have a significant impact on the determination of hydraulic conductivity, Kh, from the type-curve-matching analysis.

To facilitate the unconfined aquifer slug-test type-curve analysis, an Ss value of 0.00001 m^{-1} can be used as a starting point. After initial matches are made through adjustments of transmissivity, T, additional adjustments of Ss can then be attempted to improve the overall match of the test-response pattern. In most test cases, slight modifications (i.e., increasing Ss) can be made to the input Ss values to improve the final analysis type-curve matches. It should be noted, however, that other factors influence the shape of the slug-test curve (e.g., skin effects, K_D). For this reason, the Ss estimate obtained from final slug-test analyses should be considered a qualitative value only and should not be used for quantitative applications.

For slug-test analysis, the well-screen interval below the water table (rather than the sandpack interval) can be used to represent the test interval. This may be used when the formation materials within the screened interval are expected to have a higher permeability than the sandpack; therefore, test-response transmission is expected to propagate faster laterally from the well screen to the surrounding test formation than vertically within the sandpack zone. In reality, only small differences exist between individual well-screen and sandpack-interval lengths (i.e., compared to the aquifer-thickness relationship), so no significant differences in analysis results would be expected. This assumption is consistent with recommendations listed in Butler (1996).

A.2 Pumping Tests

A.2.1 Constant-Rate Pumping Test

For simplicity, constant-rate pumping tests are discussed here in the context of the pumping withdrawal form of the test; however, the principles apply similarly to the pumping injection alternative. For the constant-rate withdrawal test, a submersible pump is used to remove water during each pumping test, while flow rates are monitored with a surface-mounted flowmeter. Flow is adjusted manually using a valve to maintain constant-rate conditions. During the initial minutes of pumping (e.g., first 5 minutes), “instantaneous” flow rates are determined by measuring the time required for a small volume of water to register on the flowmeter dials (e.g., 5 to 10 gallons). Flowmeter totalizer readings should be recorded, at a minimum every 5 to 20 minutes during pumping. Differential pressure transducers are used to monitor water levels in the pumping well and the nearby monitor wells during the testing. Pressure transducer measurements should be recorded continuously using a data logger.

Although not described here within the discussion of conventional pumping test analyses, it is noted that analytic element and numerical modeling can also be used to analyze constant-rate pumping tests. These may provide additional analysis capabilities, particularly when multiple pumping and observation wells are involved.

A.2.2 Shutdown-Recovery Test

In complex test settings, such as the ZP-1 OU where numerous P&T wells are continuously operating to meet remedial action objectives, it may not be feasible to perform a traditional constant-rate pumping test where the test initiates from a static pre-test condition. The shutdown-recovery test is an alternative approach that can still be performed within the operational framework of an active P&T remedy and have relatively less impact to normal P&T operations. Spane (2010) describes the feasibility of analyzing the total or composite pressure response imposed on the unconfined aquifer by turning on a single new ZP-1 extraction well, while other nearby P&T extraction wells continue to run. The recovery response observed in the unconfined aquifer during the shutdown of the interim ZP-1 P&T system in 2012 was evaluated using a transient analytic element model to verify aquifer hydraulic properties (ECF-200ZP-1-12-0074, Rev. 0). The shutdown-recovery test described here is similar in concept and analysis approach. One or more P&T stress wells are shut down, and the total composite response is analyzed for aquifer hydraulic and storage properties. The shutdown-recovery test involves the following steps and requirements:

1. All the P&T wells within the test area or radius of influence are held at a stable and constant flow rate for a sufficient period of time to result in a near-linear background water-level trend. Spane (2010) noted up to 3 months of uniform flow to surrounding ZP-1 P&T wells is necessary.
2. Barometric effects will need to be removed for wells in the test area in order to effectively identify the pre-test water-level trends and the shutdown-recovery response.
3. The P&T injection or extraction stress well is abruptly turned to an off condition (shutdown). The recovery response is a superposition of the impact from surrounding P&T wells (prior to and following the shutdown) and the initiation of the shutdown of the stress well(s). This will be a relative decrease or increase in pressure for the shutdown of an injection or extraction well, respectively.
4. The shutdown-recovery response is de-superposed from the total composite response and analyzed similar to constant-rate pumping tests using analytical type-curve or analytic element analysis methods.

A.2.3 Barometric Pressure Effects Removal

The analysis of well water-level responses during hydrologic tests provides the basis to estimate hydraulic properties that are important to evaluating groundwater-flow velocity and transport characteristics. Barometric pressure fluctuations, however, can have a discernible impact on well water-level measurements. This response effect is commonly ascribed to confined aquifers; however, wells completed within unconfined aquifers may also exhibit associated responses to barometric changes (Weeks 1979; Rasmussen and Crawford 1997). Water levels in unconfined aquifers typically exhibit variable time-lagged responses to barometric fluctuations. This time-lag response is caused by the time required for the barometric pressure change to be transmitted to the water table through the vadose zone compared to the instantaneous transmission of barometric pressure through the open well.

To determine the significance of barometric effects, water-level changes should be monitored during a baseline period before or after each pumping test and compared to the corresponding barometric pressure changes. Barometric pressures can be obtained from the Hanford Meteorology Station (located immediately east of the 200 West Area), where they are recorded hourly. The barometric responses are then analyzed and removed from the recorded water levels using the multiple-regression deconvolution techniques described in Rasmussen and Crawford (1997) and Spane (1999). This technique relies on a least-squares fit of the water-level change to the corresponding barometric pressure change and time-lagged earlier barometric pressure changes. As noted in Spane (1999), under prevalent conditions in the 200 West and East Areas, no significant difference in removal efficiency was derived in using data collected at higher recording frequencies (e.g., 10 minutes). Therefore, data can be collected at a 1-hour frequency.

Because barometric changes are recorded at a constant 1-hour frequency, the relationship between water-level and barometric change can be represented as follows:

$$h_w = X_0\Delta h_{ai} + X_1\Delta h_{ai-1} + X_2\Delta h_{ai-2} + \ldots + X_n\Delta h_{ai-n} \tag{A.1}$$

where:

Δh_w = water level change over the last hour

Δh_{ai} = barometric pressure change over the last hour

Δh_{ai-1} = barometric pressure change from 2 hours to 1 hour ago

Δh_{ai-2} = barometric pressure change from n hours to n-1 hours ago

n = number of hours that lagged barometric effects are apparent

After calculating $X_0 \ldots X_n$, simulated well water levels associated with the hourly barometric responses can be calculated from the above equation for the baseline period. The results are then compared to the actual observed well water-level response for a “goodness of fit” evaluation. To remove barometric effects from water levels recorded during the pumping test, a simulated well water-level response is calculated based on the hourly barometric changes that were observed over the test period. The predicted barometric induced response is then subtracted from the recorded pumping test water-level measurements. Analysis techniques described in the following section are then applied to the data after removal of barometric effects.

A.2.4 Diagnostic Analysis and Derivative Plots

Log-log plots of water level vs. time have traditionally been used for diagnostic purposes to examine pumping test drawdown data. More recently, the derivative of the water level or pressure has also been used (Bourdet et al. 1989; Spane 1993) as a diagnostic tool. Use of derivatives has been shown to significantly improve the diagnostic and quantitative analysis of various hydrologic test methods (Bourdet et al. 1989; Spane 1993). The improvement in test analysis is attributed to the sensitivity of pressure derivatives to various test/formation conditions. Specific applications for which derivatives are particularly useful include the following:

- Determining formation-response characteristics (confined or unconfined aquifer) and boundary conditions (impermeable or constant head) that are evident within the test data
- Assisting in the selection of the appropriate type-curve solution through combined type-curve/ derivative plot matching
- Determining when infinite-acting, radial flow conditions are established and, therefore, when straight-line analysis methods are applicable

The early data, occurring before the straight-line approximation is valid or where wellbore storage is dominant, produce a steep, upward-trending derivative. The derivative normally decreases during transition from wellbore storage to radial flow and stabilizes at a constant value when infinite-acting, radial flow conditions are established. The stable derivative reflects the straight line on the semi-log plot for infinite-acting radial flow. Unconfined aquifers and formations exhibiting double-porosity characteristics (e.g., fractured media) may show two stable derivative sections at the same vertical position separated by a “valley” that represents the transition from one storage value to the other. Diagnostic derivative plots are also useful to identify boundary effects.

A linear, no-flow boundary will result in a doubling of the magnitude of the derivative. If radial flow is established before the influence of the boundary is seen, a stable derivative will occur for a time followed by an upward shift to twice the original value. Constant-head boundaries display a downward trend in the derivative, which may be preceded by a stable derivative if radial flow conditions occur before the boundary effect becomes dominant.

A.2.5 Type-Curve Matching Analysis Methods

Type-curve-matching methods (Theis 1935; Hantush 1964; Neuman 1972, 1974, 1975) are commonly used in the analysis of pumping test responses. In the type-curve-matching procedure, the log-log drawdown or recovery data and its associated derivative response for an individual well are matched simultaneously with dimensionless type-curve responses. The dimensionless responses depend on the assumed values of sigma, $\sigma = S/S_y$, and vertical anisotropy, $K_D = K_v/K_h$. For initial type-curve-matching runs, the values for σ and K_D can be set at 0.001 and 0.10, respectively. The predicted response also is influenced by the assumed storativity, S, value because of its effect on wellbore storage. After an appropriate match to the dimensionless observed test data is obtained, dimensional curves are generated by using the given well/test conditions (e.g., well radius, radial distance to observation well, average pumping rate) and adjusting aquifer properties (T, S_y) until the best match with the observed data is obtained. (Note that adjusting S_y also changes the value of S because σ is held constant.)

A.2.6 Straight-Line Analysis Methods

For straight-line analysis methods, the rate of change of water levels within the well during drawdown and/or recovery is analyzed to estimate hydraulic properties. Because well effects are constant with time during constant-rate tests, straight-line methods can be used to analyze quantitatively the water-level response at both pumping and observation wells. The semi-log, straight-line analysis techniques commonly used are based on either the Cooper and Jacob (1946) method (for drawdown analysis) or the Theis (1935) recovery method (for recovery analysis). These methods are theoretically restricted to the analysis of test responses from wells that fully penetrate nonleaky, homogeneous, isotropic, confined aquifers.

Straight-line methods, however, may be applied under nonideal well and aquifer conditions if infinite-acting, radial flow conditions exist. Infinite-acting, radial flow conditions are indicated during testing when the change in pressure, at the point of observation, increases in proportion to the logarithm of time. As discussed above, the use of diagnostic derivative methods (Bourdet et al. 1989) makes it easier to identify the portions within the test data where straight-line analysis is appropriate.

A.3 Electromagnetic Borehole Flowmeter Testing

Electromagnetic borehole flowmeter (EBF) surveys are effective for accurately measuring the vertical groundwater-flow distribution in wells under ambient (static) and dynamic (e.g., pumping-induced) test conditions. They provide direct measurements of groundwater in-flow along the saturated well screen during a constant-rate of pumping. The various measured inflow rates vs. depth are directly related to the vertical profile of hydraulic conductivity outside the well screen within the surrounding aquifer formation.

To correct the dynamic flowmeter survey results for natural, in-well vertical flow conditions, an ambient (i.e., non-pumping) EBF survey is normally conducted before the dynamic flowmeter test. A detailed description of EBF instrumentation and application of surveys for site characterization is presented in Spane and Newcomer (2008).

The theory that governs the operation of the EBF is Faraday’s law of induction, which states that the voltage induced by a conductor moving orthogonally through a magnetic field is directly proportional to the velocity of the conductor moving through the field. For EBF surveys, flowing water is the conductor, an electromagnet generates a magnetic field, and the electrodes within the flowmeter are used to measure the induced voltage. For sign convention, upward flow represents a positive voltage signal, and downward flow represents a negative voltage signal. More detailed descriptions of the EBF instrument system and field test applications are provided in Molz et al. (1994) and Young et al. (1998).

A schematic depiction of the field setup and configuration for an EBF well test is shown in Figure A.1. The EBF probe consisted of an electromagnet and two electrodes 180 degrees apart inside a hollow cylinder. The inside diameter of the hollow cylinder is 2.5 cm (1 in.), and the outside diameter of the probe cylinder is just under 5.1 cm (2.0 inches). The probe is typically connected to an electronics box at the surface with a jacketed cable. The electronics attached to the electrodes transmit a voltage signal directly proportional to the velocity of water acting as the conductor. Computer software is used to record the voltage signal and convert the signal to a flow-rate measurement.

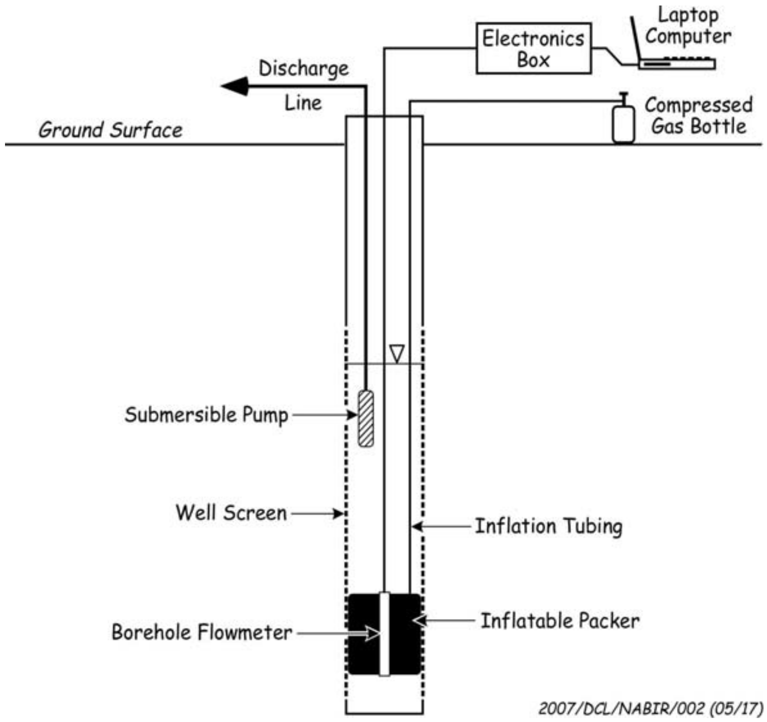

Figure A.1. General field setup and configuration for EBF surveying (from Spane and Newcomer 2009a)

The inflatable packer consists of a rubber sleeve attached to a stainless steel assembly and is sealed with hose clamps. The EBF probe cylinder is mounted inside the stainless steel assembly. At each prescribed depth, the packer is inflated and controlled with either compressed nitrogen gas or an air compressor with an attached regulator. Flow conditions in the well are allowed to re-establish for several minutes because of disturbances caused by movement of the packer/probe assembly. After recording the flow measurement, the packer is deflated using a vented valve and raised very slowly to the next depth, and the measurement procedure is repeated.

Both ambient (i.e., static) and dynamic (i.e., pump-induced) flowmeter tests were performed. During the dynamic flowmeter tests, groundwater pumped from the well is typically discharged to a portable tank. The discharge rate is held constant during the dynamic test. The well is pumped for a minimum period of time until flow conditions reach near-equilibrium before recording the EBF measurements. The discharge rate is measured and recorded periodically with an in-line flowmeter. After near-equilibrium conditions are established, EBF measurements are made in succession from bottom to top of the saturated well-screen section. Zero flow point measurements are taken with the EBF probe in a container of water at the surface and within the saturated blank casing above the top of the well screen to provide a reference for the survey measurements.

For EBF survey test analysis, it is assumed that the aquifer within the well-screen section is composed of a series of horizontal layers, possessing layer-specific hydraulic properties. Under ambient-flow conditions (i.e., non-pumping), the difference between two successive well-screen depth measurements is the portion of ambient flow entering the well screen between depths where the flow measurements were taken. The portion of flow entering the well screen between these successive depths under pump-induced conditions is calculated in the same manner. Ambient-flow survey-profile information is used to correct dynamic flowmeter survey results for background natural vertical-gradient conditions.

The analytical method used for calculating the vertical distribution of relative hydraulic conductivity from dynamic EBF surveys is summarized in Molz et al. (1989) and Boman et al. (1997) and presented in detail in Spane and Newcomer (2009b). The normalized relative hydraulic-conductivity value can be determined directly from measuring specific depth inflow rates as they relate to total flow pumped from the entire test interval. An absolute or actual hydraulic-conductivity-value depth profile, however, can be developed if an estimate of the average hydraulic conductivity has been determined from a standard hydrologic test method (e.g., pumping or slug test).

As noted by Spane and Newcomer (2009b), the analysis method is strictly valid for EBF surveys conducted within fully penetrating confined aquifer wells. For EBF surveys conducted within partially penetrating unconfined aquifer wells, adverse boundary effects associated with flow convergence (i.e., non-horizontal flow) at the water table and at the base of the well screen are possible. If the well is completed at a considerable depth (e.g., 5 to 10 m) below the water table, no significant water-table boundary effects are expected for flowmeter measurements obtained at the top of the well screen. Any apparent flow convergence effects that occur at the base (or top) of the well screen can be accounted for by taking into account the well/aquifer penetration relationship. Additionally, if significant groundwater-flow bypass occurs within the sandpack outside the well screen, the EBF results may not be valid. Non-uniform sandpack flow during testing is difficult to quantify and remains an unknown. However, since the head loss for groundwater flow through the well screen is significantly lower than through the outside annular sandpack, this factor may be relatively unimportant except where unknown heterogeneities may occur within the sandpack.

A.4 Tracer Testing

Two types of single-well groundwater tracer methods, tracer-dilution and tracer pumpback, are described here.

A.4.1 Tracer-Dilution Testing

During a tracer-dilution test, a tracer solution (i.e., bromide) of known concentration is mixed within the well-screen section. The decline of tracer concentration (i.e., “dilution”) with time within the well screen is monitored directly using an array of ion-electrode sensors located at known depth intervals. The sensors should be laboratory calibrated with standards of known bromide concentration prior to and following performance of the tracer-dilution test. Based on the dilution characteristics observed, the vertical distribution (i.e., heterogeneity) of hydraulic properties and/or in-well flow velocity can be estimated for the formation section penetrated by the well screen. The presence of vertical flow within the well screen can also be identified from the sensor/depth-dilution-response pattern. Descriptions of the performance and analysis of tracer-dilution test characterization investigations are provided in Halevy et al. (1966), Hall et al. (1991), and Hall (1993).

Essential design elements of a tracer-dilution test include establishing a known, constant tracer concentration within the test section by mixing or circulating the tracer solution in the wellbore/test interval and monitoring the decline of tracer concentration with time within the test interval. The decline in tracer concentration within the wellbore can be analyzed to ascertain the hydraulic gradient, I (if the formation’s K is known), the test-interval K (if the hydraulic gradient is known), and the groundwater-flow velocity within the well, V_w.

Various aspects of conducting tracer-dilution tests (i.e., test design, influencing factors) have been previously discussed by a number of investigators (e.g., Halevy et al. 1966; Freeze and Cherry 1979). Following completion of the tracer-dilution test, the tracer can be recovered from the formation by pumping, and the results analyzed to assess the effective porosity within the test interval. Some investigators have noted differences in hydraulic property estimates obtained with tracer-dilution techniques and other test methods (e.g., Drost et al. 1968; Kearl et al. 1988). These differences have been attributed, in some cases, to distortions in the flow field caused by increased (or decreased) permeability near the well.

A.4.2 Tracer Pumpback Tests

Detailed procedures for conducting standard, single-well, conservative tracer tests are provided in Pickens and Grisak (1981) and Molz et al. (1985). A tracer pumpback test includes the following basic test procedure:

1. Inject a conservative tracer (i.e., bromide) within the well/aquifer system.
2. Define a prescribed residence (drift) time for the tracer to be dispersed within the aquifer.
3. Withdraw the tracer from the well/aquifer system by pumping at a constant rate.
4. Monitor tracer concentrations at the test well (i.e., bromide sensor/flow cell) and collect discrete groundwater samples for quantitative laboratory analysis.

Typically, the tracer is emplaced in the wellbore (without injection) and allowed to migrate into surrounding aquifer under natural groundwater flow (tracer-dilution described above). Because of the relatively small area represented by the well (i.e., in comparison to the aquifer) and volumes of tracer involved, the results obtained from these tracer tests may be more susceptible to wellbore effects (e.g., groundwater flow distortion and possible downgradient dead zone). The variant “push-pull” tracer test (Istok 2013) involves injecting a larger tracer volume to interrogate a relatively larger aquifer volume to overcome this issue. Whether the tracer is emplaced and allowed to leave the wellbore under ambient groundwater flow conditions (tracer-dilution) or injected radially into the aquifer (“push-pull”) prior to pumping the tracer back, the analysis of pumpback phase of the test remains the same.

For the tracer-pumpback tests, a constant-rate pumping test is initiated after the average tracer concentration has decreased (i.e., diluted) to a sufficient level within the well screen (usually a one-to-two-order of magnitude reduction from the original tracer concentration). The objective of the pumpback test is to “capture” the tracer that has moved from the well into the surrounding aquifer. Tracer recovery is monitored qualitatively by measuring the tracer concentration at the surface using a sensor or flow cell installed in the discharge line. Discrete samples are collected at the surface at preselected times for quantitative laboratory tracer analysis. The time required to recover the center of tracer mass from the aquifer provides information concerning the effective porosity (n_e) and the advective groundwater velocity (V_a).

Analytical methods available for the analysis of single-well, tracer injection/withdrawal tests include (in addition to the previously cited references) Leap and Kaplan (1988), and Hall et al. (1991). The hydraulic conductivity of the test interval is required in the analysis to determine V_a and n_e. and can be determined either from an analysis of the constant-rate pumping tests for the test well (i.e., during the tracer pumpback) or a hydraulic test (e.g. slug test). The horizontal hydraulic gradient is also required in the analysis.

A.5 Groundwater Flow Characterization

To support the detailed hydrologic characterization program, groundwater-flow direction and hydraulic gradient conditions are calculated at the various test sites. In addition to traditional methods such as trend surface analysis, the groundwater-flow direction and hydraulic gradient should be determined using methods that have been developed specifically for mapping groundwater flow directions and gradients in complex pump-and-treat settings (Karanovic et al. 2009; Tonkin et al. 2015).

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Appendix B – Pre-test Analysis of Pumping Tests

This appendix contains results from a series of pre-test analyses that evaluate three key aspects related to test design and efficacy in achieving hydraulic characterization objectives for the Ringold Formation member of Wooded Island – unit A (Rwia). The analyses follow the approach of Spane (2010) but extend the assessment to consider how results vary for three possible aquifer model scenarios that may be present for the Rwia unit: unconfined, confined, and leaky-confined aquifer conditions. The two pre-test analysis assessment components are as follows:

1. Assess the duration of pumping time required to meet analytical constraints [e.g., infinite-acting radial flow (IRF) conditions] and achieve test objectives (e.g., identify confined vs. leaky-confined aquifer model).
2. Determine the radius of influence for a pumping well based on predicted pressure response.
3. Evaluate the application of shutdown-recovery tests for the ZP-1 test area as an approach for estimating aquifer hydraulic and storage property estimates with less disruptions in flow to the ZP-1 P&T wells than traditional constant-rate pumping tests.

This information was used diagnostically to guide and select test areas and combinations of wells to be used in testing, and to indicate other possible design constraints and operational considerations. For hydraulic tests such as constant-rate pumping and shutdown-recovery tests, the timing and magnitude of aquifer pressure response varies as a function of the test configuration (flow rate and duration), operative aquifer model exhibited (confined, unconfined, or leaky confined), aquifer hydraulic properties (aquifer thickness, hydraulic conductivity, and storage values), and radial distance from the pumping well.

B.1 Input Parameters for Pre-testing Analyses

Table B.1 lists the parameters that were used in these analyses. Type-curve analytical solutions as implemented in the AQTESOLV software Version 4.5 (Duffield 2007, 2009) were used in the pre-test analyses. It was assumed that wells were fully penetrating, and the early-time effects of wellbore storage were ignored. The leaky-confined solutions assume flow though the Ringold Formation member of Wooded Island – lower mud unit (Rlm) aquitard is vertical and allow for varying aquitard storage. A similar leaky-confined solution was used to match pumping responses from pumping tests performed in the Ringold Formation member of Wooded Island – upper mud unit (RUM) in the 100-H Area of the Hanford Site (SGW-60571).

Time-drawdown and distance-drawdown curves were generated using analytical solutions for confined (Theis 1935; Hantush 1961a,b), leaky-confined with and without aquitard storage (Hantush and Jacob 1955; Hantush 1960; Hantush 1964), and unconfined (Neuman 1972, 1974) aquifer model scenarios for a range of pumping flow rates and radial distances. The degree of confinement for the Rwia aquifer is not fully understood within portions of the ZP-1 test area. The Rlm unit, where present as a fine-grained aquitard unit, locally forms a confining layer between the Ringold Formation member of Wooded Island – unit E (Rwie) and Rwia units. In locations where the Rlm is absent (e.g., within the central and eastern portions of the ZP-1 test area), the Rwie and Rwia units together comprise an unconfined operative model (referred here as the composite Rwie-Rwia aquifer). In areas where the Rlm is locally or regionally present as a fine-grained layer, it creates vertical confinement between the Rwie and Rwia units, and the Rwia aquifer would exhibit a confined or leaky-confined aquifer. The amount of leakage between the Rwia and the Rwie is unknown, and quantification of leakage is one of the objectives of the proposed field hydraulic testing activities. Previous work has indicated that analysis of barometric pressure response may be used to support leakage assessment (Spane and Newcomer 2009a,b, 2010a,b). For the pre-test design analysis, leakage through the Rlm layer was varied to determine its potential effects on constant-rate pumping tests.

Table B.1. Pumping Test Pre-test Design Analyses Parameters

Hydrologic Scenario	Parameter	Value(s)	Comments and Basis
Composite Rwie-Rwia unconfined aquifer model	Pumping rate (Q)	100 gpm	On the lower end of the typical obtainable flow rates for pump and treat (P&T) wells in the test areas
	Saturated aquifer thickness (b)	57.0 m	Average saturated thickness of the composite Rwie-Rwia aquifer at the eight new Rwia well locations based on a combination of the Hanford South Geologic Framework Model (HSGFM; ECF-HANFORD-13-0029) and the 2018 water table elevation map from DOE/RL-2018-68, Rev. 0.
	Horizontal hydraulic conductivity (Kh)	20 m/day	Average for Ringold Unit E (Rwie) unit from the Central Plateau Groundwater Model (CPGM).[a] This is an upper estimate for the Rwie-Ringold Unit E (Rwia) composite aquifer since the model has a K value of 1 m/day for the Rwia unit.
	Transmissivity (T=Kh*b)	1,133 m^2/day	
	Specific yield (S_y)	0.08	Value for Rwie and Rwia from CPGM.
	Specific Storage (Ss)	2.9x10-5 m^{-1}	Value from CPGM.
	Storativity (S=Ss*b)	1.6x10-3	
	Vertical anisotropy (Kz/Kh)	0.1	Typical value used for Ringold Formation layered sediments and value used in CPGM.
Rwia confined and leaky-confined aquifer models	Pumping rate (Q)	20 gpm	Conservative estimate for a sustainable flow rate for the lower-permeability Rwia formation. ZP-1 injection wells screened in the Rwia ranged from about 20 to 100 gpm during 2019.
	Aquifer thickness (b)	26.1 m	Average thickness of the Rwia aquifer at the eight new Rwia well locations based on a combination of the HSGFM (ECF-HANFORD-13-0029) and the 2018 water table elevation map from DOE/RL-2018-68, Rev. 0.
	Horizontal hydraulic conductivity (Kh)	1 m/d	Value from CPGM for the Rwia.
	Transmissivity (T=Kh*b)	26.1 m^2/day	
	Specific yield (Sy)	0.08	Value from CPGM.
	Specific Storage (Ss)	2.9x10-5 m^{-1}	Value from CPGM.
	Storativity (S=Ss*b)	7.6x10-4	
	Vertical anisotropy (Kz/Kh)	0.1	Typical value used for Ringold Formation layered sediments and value used in CPGM.
	Rlm confining layer thickness (b’)	7 m	Average from eight wells where Rlm unit is present in the ZP-1 OU in the HSGFM (ECF-HANFORD-13-0029).
	Rlm confining layer vertical hydraulic conductivity (Kv’)	8.e-4 m/d	Value from CPGM.
	Rlm confining layer leakage curve relationships (r/B)	0, 0.05, 0.1, and 0.5	Leakage curve relationship values ranging from fully confined (r/B = 0) to significantly leaky (r/B = 0.5) consistent with previous leaky-confined aquifer investigations (Spane 1993 and SGW-60571, Rev. 0). The leakage factor, B (Kruseman and de Ridder 2000), is a measure of the leakage through an aquitard into a leaky-confined aquifer. $B = (T b'/Kv')^{1/2}$. Higher B values indicate lower leakage, so 1/B is also used to represent the leakage factor.

(a) Values from the CPGM (Table 4-4 in CP-47631, Rev. 4).

B.2 Pre-testing Analysis Results

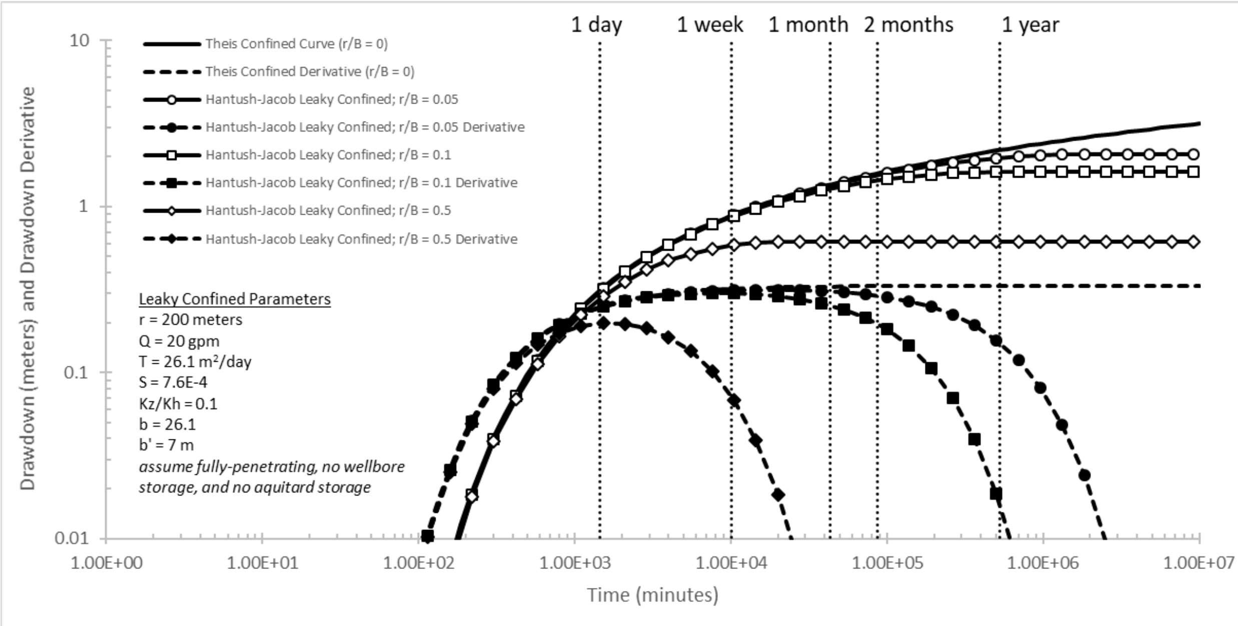
Results from the pre-testing analysis indicate several important aspects to consider for planning and designing pumping tests for the Rwia unit in the ZP-1 study area. Figure B.1 through Figure B.5 present the results for the temporally and radially variant pressure responses for the three aquifer model scenarios. The general test response characteristics, pumping duration requirements, and radius of influence assessment components are summarized below.

B.2.1 Operative Aquifer Model Type-Curve Characteristics

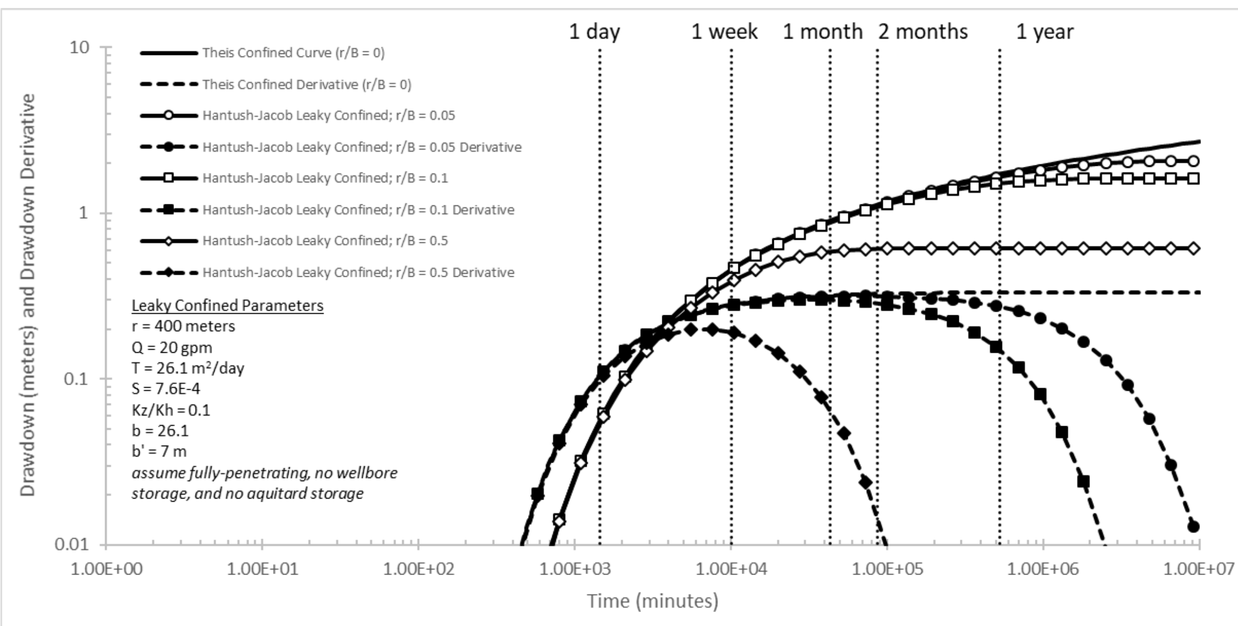
As expected, the results of the pre-test analysis demonstrate the aquifer model exhibited in the Rwia unit is the dominant factor determining the magnitude, timing, and type-curve pattern characteristics for a constant-rate pumping test. However, distinguishing the aquifer model can require extended pumping durations (>1 week).

Figure B.1 shows the drawdown and drawdown derivative response with time for a pumping test at 200 m and 400 m radial for confined aquifer conditions with varying amounts of leakage through the Rlm unit, assuming no aquitard storage (Hantush and Jacob 1955; Hantush 1964). The additional effects of aquitard storage are evaluated in the next subsection. Leaky-confined aquifer conditions are distinguished from fully-confined conditions by (1) the drawdown stabilizes to a constant value that is lower than the Theis-like response and (2) the resulting concave-down decreasing pattern in the drawdown derivative toward zero, unlike the non-leaky confined aquifer response, which stabilizes to a constant drawdown value (Spane 1993; Spane and Wurstner 1993).

Increased leakage through the Rlm (as represented with the family of r/B leakage curves) shows earlier stabilization to a lower drawdown value and earlier decrease of the drawdown derivative toward zero. Stabilization in the derivative response means that the pressure response slope does not change with the log of time (horizontal derivative line). The leakage response is not stable and exhibits an increasing slope over time after departing the horizontal derivative response.



(a)

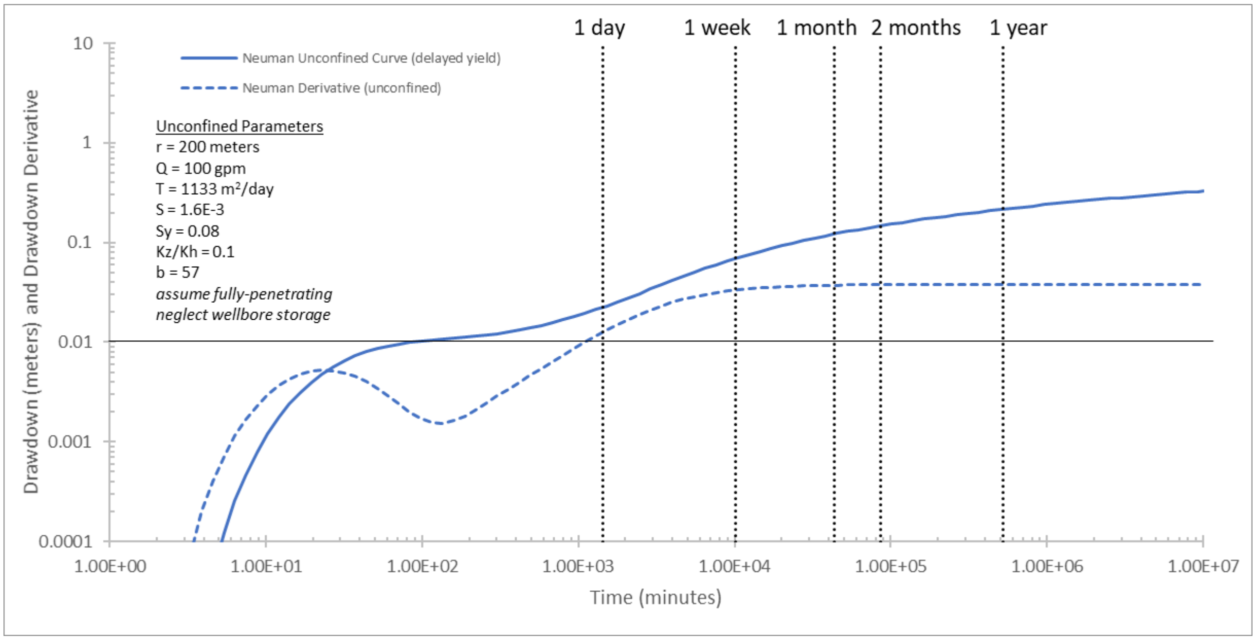


(b)

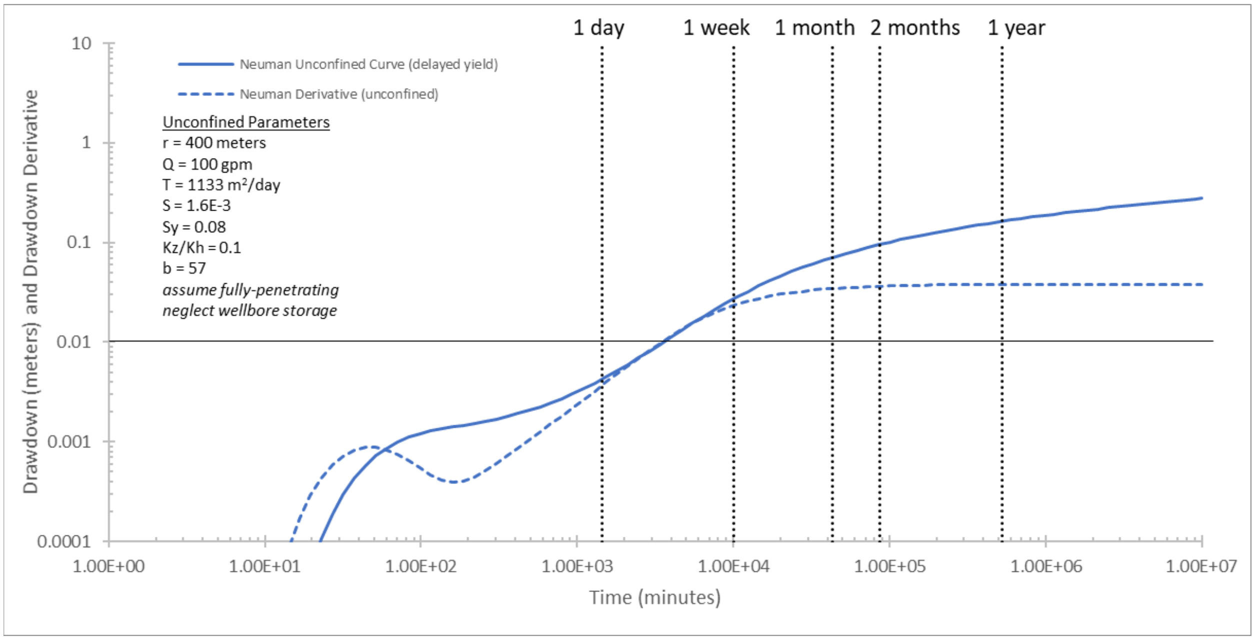
Figure B.1. Time-drawdown and derivative type curves for constant-rate pumping tests in the Rwia aquifer at radial distances of 200 m (a) and 400 m (b) for varying amounts of leakage through the Rlm confining layer.

Spane (1993) discusses characteristics of unconfined aquifer test responses in detail. For the Rwia-Rwie composite unconfined aquifer model scenario evaluated here (i.e., where the Rlm is either absent or does not act as a confining layer), the drawdown and derivative responses predicted at 200 m and 400 m radial distances are shown in Figure B.2. Constant-rate pumping tests in unconfined aquifers initially exhibit an elastic storage response (with aquifer storage represented by the storativity term, S, similar to a confined aquifer) and then as pumping continues the response becomes dominated by the delayed-yield or gravity drainage response (with aquifer storage represented primarily by the specific yield term S_y) as water is release from the aquifer with a lowering of the water table (Kruseman and de Ridder 2000).

Based on the composite Rwie-Rwia unconfined aquifer conditions represented here, only the delayed-yield portion of the drawdown response is observable at these radial distances. The early-time elastic response falls below the practical observation limit of 0.01 m of drawdown (solid black lines in Figure B.2). Typical water-level instrumentation used to monitor hydraulic testing such as these are capable of finer precision than 0.01 m, but this represents a practical limit in terms of resolution and accuracy. For this reason, the drawdown and drawdown derivative type-curve patterns for the composite Rwie-Rwia unconfined aquifer scenario would appear similar in general shape to the non-leaky confined aquifer scenario (r/B = 0), but with the aquifer storage equal to the combined elastic storativity (S) and specific yield (S_y) components (Spane and Wurstner 1993). Note this analysis assumes homogeneity; however, the S_y estimate in the composite Rwie-Rwia aquifer scenario would likely be most representative of the top portion of the aquifer, where delayed yield occurs (in the Rwie portion of the aquifer above the Rwia).



(a)



(b)

Figure B.2. Time-drawdown and derivative type curves for constant-rate pumping tests in the composite Rwie-Rwia unconfined aquifer at radial distances of 200 m (a) 400 m (b).

B.2.2 Leaky-Confined with Aquitard Storage

The leaky-confined responses shown in Figure B.1 assume there is no release of groundwater from storage in the Rlm aquitard when pumping in the Rwia. The analytical solution of Hantush (1960), which incorporates aquitard storage for the leaky-confined case, was used to evaluate the potential effect of aquitard storage on the type-curve characteristics, the required pumping duration, and the ability to distinguish leakage when there is aquitard storage. Specific storage (Ss) values of 1.0x10-5, 1.0x10-4, and 1.0x10-3 m^{-1} for the Rlm were prescribed for the moderate leakage scenario of r/B = 0.1. These Ss values provide a two-order magnitude range that brackets above and below the Ss value of 2.9x10-5 m^{-1} used in the CPGM (CP-47631, Rev. 4). It is likely the Ss value for the Rlm is less than 1.0x10-3 m^{-1}, but this was used as an upper bound for conservatism in evaluating the effect of aquitard storage. Since leakage becomes more difficult to identify with increasing radial distance (as shown in Figure B.1), only the 400-m observation well distance case was considered in order to better emphasize the possibility of aquitard storage affecting the test response and hampering the ability to distinguish leakage.

Figure B.3 shows the drawdown derivative response for the leaky-confined case of r/B = 0.1 for varying values of aquitard storage at a radial distance of 400 m. Although not shown, the time-drawdown values are nearly indistinguishable for these scenarios. The drawdown derivative response for the lowest Ss value of 1.0x10-5 m^{-1} for the Rlm (dashed line with black circles in Figure B.3) is nearly identical to the response for the same r/B = 0.1 and r = 400 m distance with no aquitard storage case (dashed line with black circles in Figure B.1b). Not surprisingly, there is no additional effect on the pumping-test response at this minimal value of aquitard storage.

However, when storage in the Rlm aquitard is increased (Ss = 1.0x10-4 m^{-1} and 1.0x10-3 m^{-1}), more groundwater is released from storage in the Rlm aquitard during pumping. There is increasing delay in the concave-down decrease pattern in the drawdown derivative (Figure B.3) for these two Ss cases compared to the no-storage or minimal-storage cases. The Ss =1.0x10-3 m^{-1} case is likely an overestimated aquitard storage scenario, but it emphasizes the additional pumping duration required to identify Rlm leakage from the fully-confined aquifer model when leakage factors are low to moderate (r/B < 0.1).

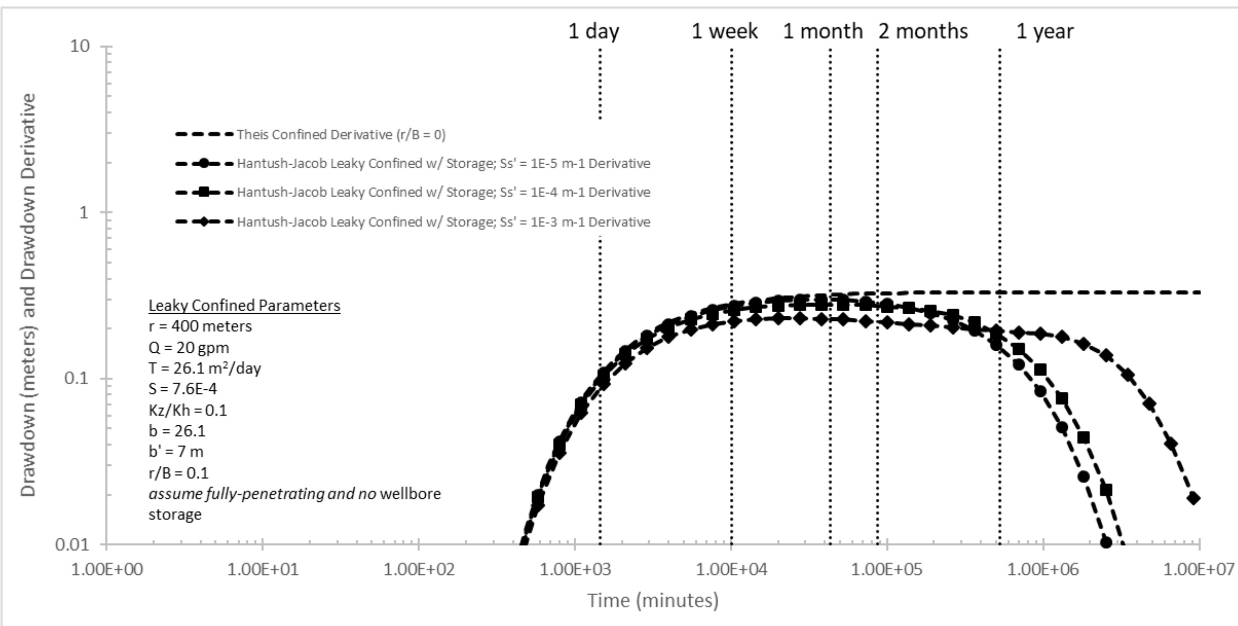


Figure B.3. Time-drawdown derivative type curves for constant-rate pumping tests in the Rwia aquifer at a radial distance of 400 m for a moderately leaky-confined aquifer model (r/B = 0.1) with varying amounts of aquitard storage.

B.2.3 Pumping Duration Requirements

Drawdown and drawdown derivative type-curves for all three operative aquifer model scenarios demonstrate several important aspects related to pumping duration when considering the Rwia hydraulic testing objectives. These include the following:

1. The time required to achieve an observable drawdown response ($\geq$ 0.01 m) varies with radial distance and the operative aquifer model exhibited (Figure B.1)
   a. Regardless of radial distance, the unconfined response requires a longer pumping duration for the response to be observed than the pumping durations for the confined or leaky-confined aquifer models.
   b. More than 3000 minutes are required to observe the initial drawdown for the composite Rwie-Rwia unconfined aquifer scenario at a radial distance of 400 m (Figure B.2b).
2. The time for IRF conditions to become established for non-leaky confined and unconfined aquifers helps to identify when steady-state or single-well analysis methods such as the Cooper and Jacob (1946) straight-line approximation can be applied. Since leakage through the confining layer to another overlying aquifer acts as a pressure source/sink, IRF conditions do not become established and these types of steady-state or single-well analyses cannot be used for the leaky-confined aquifer model scenario. IRF conditions can be identified in the log-log scale drawdown plots as the point in time when the drawdown-derivative reaches a constant value (Spane and Wurstner 1993).
   a. For the Rwia confined aquifer scenario and pumping rates considered, it could take 1 to 4 months for IRF conditions to become established at radial distances of 200 to 400 m (Figure B.1).
   b. For the composite Rwie-Rwia aquifer scenario and pumping rates considered, IRF becomes established after about 2 to 6 months (Figure B.2).
   c. As noted by Spane (2010), the arrival of IRF conditions for unconfined aquifers for a given radial distance is inversely proportional to the specific yield (S_y) term (assuming all other aquifer properties and test parameters are the same). This suggests the onset of IRF could take even longer than suggested here if the S_y is higher than the 0.08 value prescribed in this analysis.
   d. A very long pumping duration is needed to evaluate the Rlm.
3. The pumping duration required to differentiate non-leaky confined from leaky-confined aquifer conditions based on the drawdown derivatives increases when then leakage through the Rlm is less (Figure B.1), the observation well radial distance increases (Figure B.1), or the storage increases in the aquitard (Figure B.3).
   a. It may require 12 months (or more) of pumping to diagnose leakage through the Rlm for relatively low Rlm leakage conditions (r/B < 0.1).
   b. Leakage through the Rlm at the relatively higher leakage factor conditions (r/B > 0.1) is more easily identified, but may still require pumping durations beyond 1 to 2 months for diagnosing and quantifying the Rlm leakage factor.
   c. For typical values of Rlm aquitard storage (e.g. Ss = 2.9x10-5 m^{-1} used in the CPGM), the required pumping duration to identify leakage is similar to the no-storage leaky-confined scenarios. However, longer pumping durations may be required to identify leakage if the Rlm aquitard has a higher amount of storage than what is currently represented in the CPGM (e.g., Ss > 1.0x10-4 m^{-1}).

B.2.4 Radius of Influence

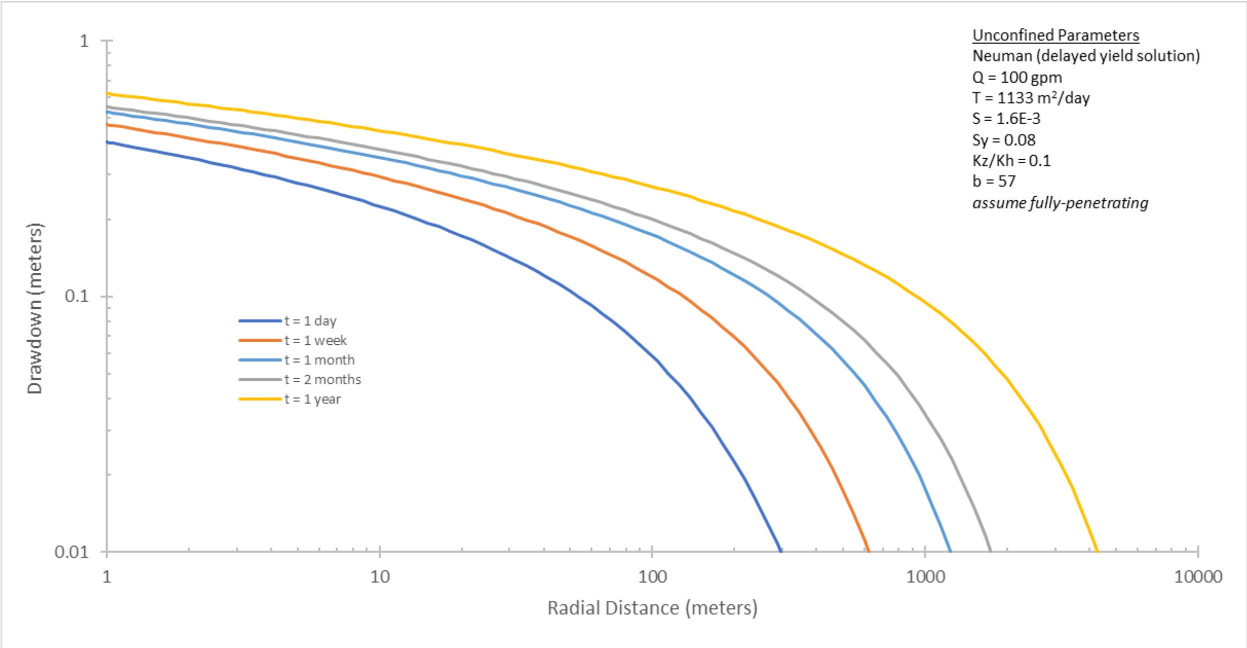
The results of the pre-test analysis demonstrate the radius of influence (defined here as the distance corresponding to the practical observational limit of 0.01 m) depends on the operative aquifer model exhibited. Figure B.4 shows the distance-drawdown relationships for increasingly longer pumping durations for the three aquifer models considered.

The results of the radius of influence analysis suggest the following:

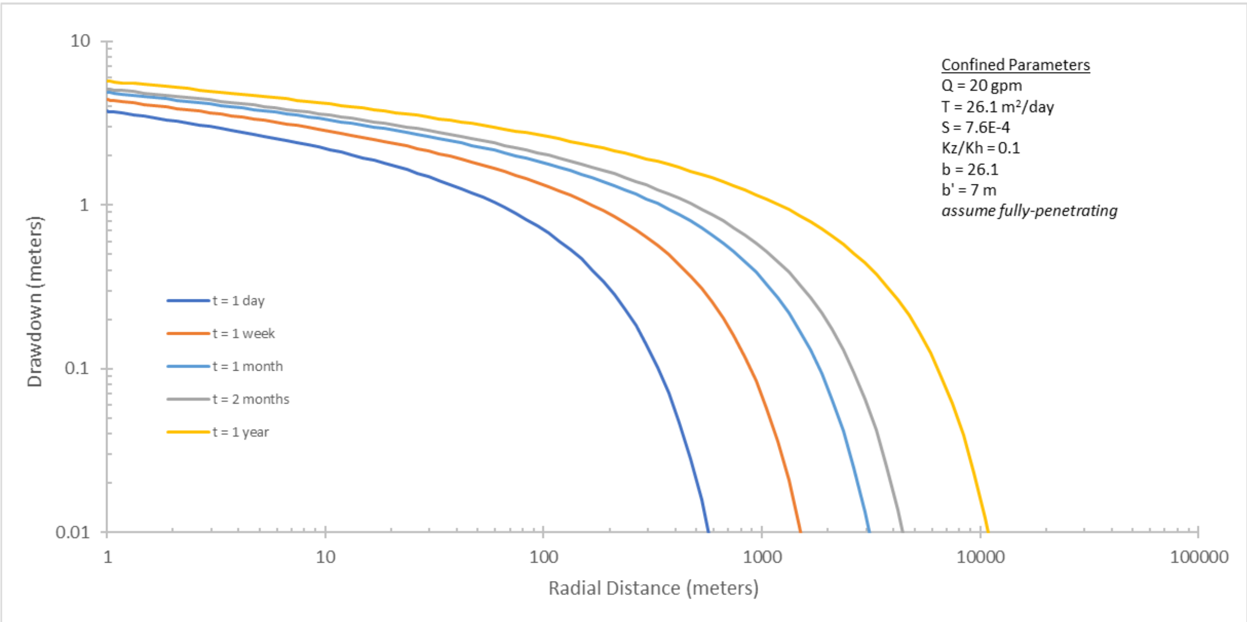
1. Leakage through the Rlm confining layer has the effect of decreasing the drawdown radially.
2. Regardless of the operative aquifer model exhibited, the predicted radius of influence for pumping wells extends to large radial distances.
    a. Neighboring P&T wells (i.e., located within several hundreds of meters) are very likely to impart a measurable pressure interference on any Rwia aquifer test.
    b. Observation wells located within about 400 m of the pumping (stress) well are also very likely to show observable response to pumping.
    c. Although Rwia wells are spaced hundreds of meters apart in the ZP-1 test area, there are sufficient wells to observe the proposed pumping tests.
3. The distance-drawdown predictions presented here are hypothetical and assume the aquifer is homogeneous and of infinite areal extent and likely overpredict pumping effects radially. They are intended to be used semi-quantitively to provide a general prediction of the range of expected radius of influence to pumping.

As noted previously, there is a difference between the hypothetical radius of influence (i.e. radial distance a response can be observed) and the representative radius of investigation. One approach for determining the radius of investigation is to analyze semi-log plots of the distance-drawdown curves. Figure B.5 contains a group of semi-log distance-drawdown plots showing the radial distances at which the drawdown is predicted to fall below early-time straight-line sections of the curves for each of the three aquifer models considered.

Radius of investigation estimates based on this approach range from 1100 m to 6000 m for the unconfined (Figure B.5a) and confined (Figure B.5b) aquifer models, respectively, following a year of pumping. The leaky-confined aquifer model ($r/B = 0.5$; Figure B.5c) after a year of pumping has a much lower estimated radius of investigation of 1050 m. The drawdown corresponding to the radius of investigation for all pumping duration and aquifer model scenario combinations falls into a relatively narrow range of about 0.09 to 0.17 m (Figure B.5), which is about an order of magnitude higher than the defined practical observational limit of 0.01 m used to determine the radius of influence.


Unconfined Parameters
Neuman (delayed yield solution)
Q = 100 gpm
T = 1133 m²/day
S = 1.6E-3
Sy = 0.08
Kz/Kh = 0.1
b = 57
assume fully-penetrating
t = 1 day
t = 1 week
t = 1 month
t = 2 months
t = 1 year
Drawdown (meters)
Radial Distance (meters)
1
0.1
0.01
1
10
100
1000
10000

(a)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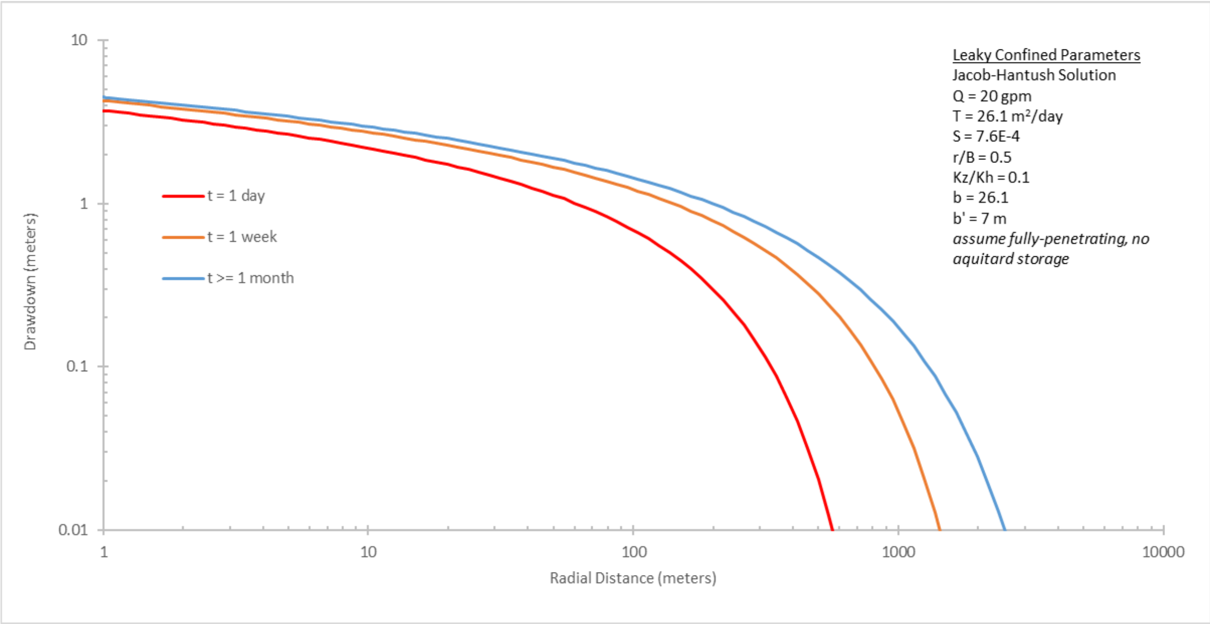
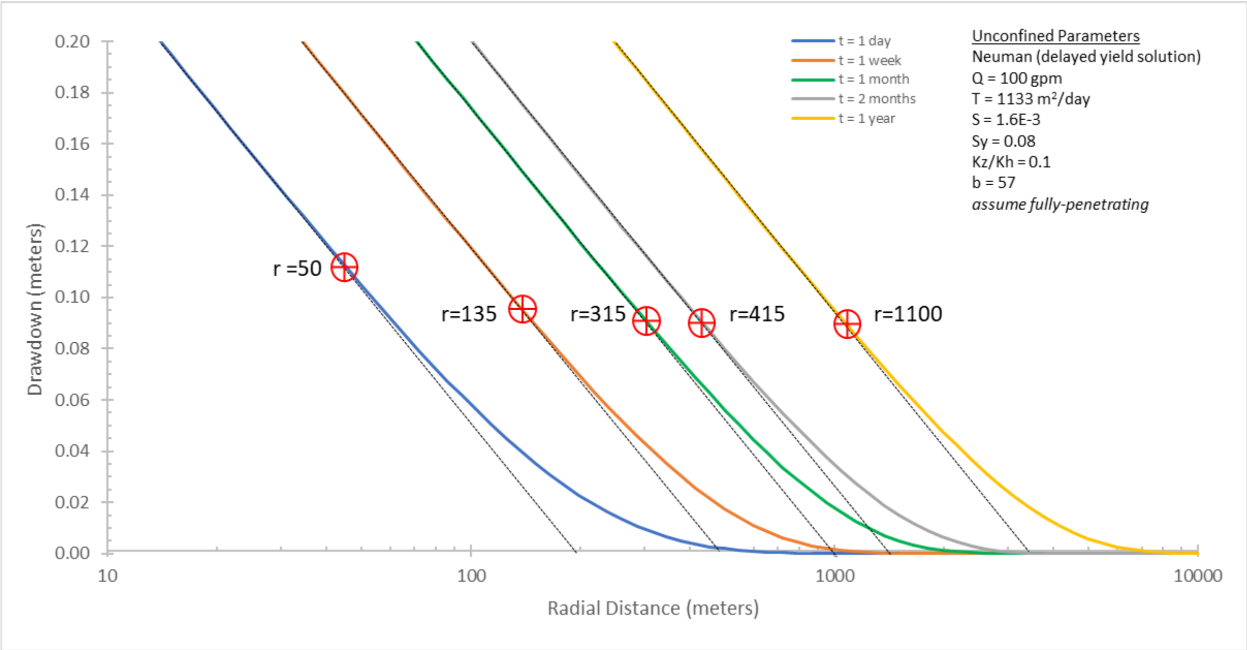
T = 26.1 m²/day
S = 7.6E-4
Kz/Kh = 0.1
b = 26.1
b' = 7 m
assume fully-penetrating
t = 1 day
t = 1 week
t = 1 month
t = 2 months
t = 1 year
Drawdown (meters)
Radial Distance (meters)
10
1
0.1
0.01
1
10
100
1000
10000
100000

(b)

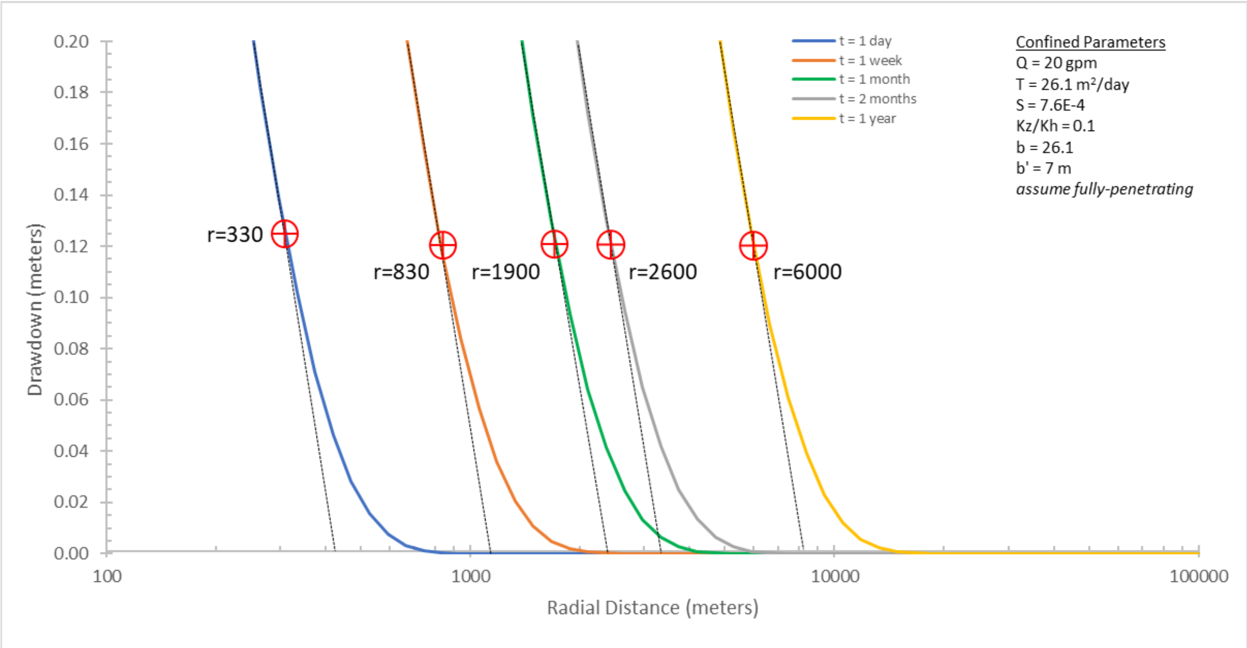


(c)

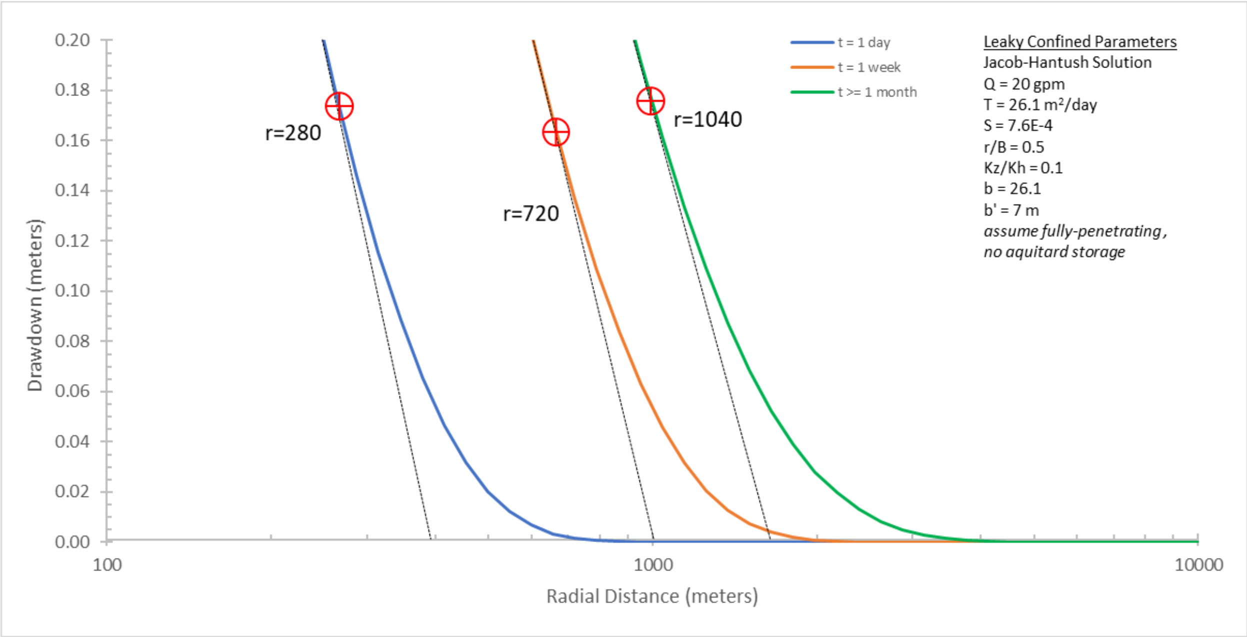
Figure B.4. Distance-drawdown curves for constant-rate pumping tests in the Rwia aquifer at increasingly longer pumping durations for unconfined (a), confined (b), and leaky-confined (c) aquifer models.


Unconfined Parameters
Neuman (delayed yield solution)
Q = 100 gpm
T = 1133 m²/day
S = 1.6E-3
Sy = 0.08
Kz/Kh = 0.1
b = 57
assume fully-penetrating
t = 1 day
t = 1 week
t = 1 month
t = 2 months
t = 1 year
r =50
r=135
r=315
r=415
r=1100
Drawdown (meters)
Radial Distance (meters)
0.20
0.18
0.16
0.14
0.12
0.10
0.08
0.06
0.04
0.02
0.00
10
100
1000
10000

(a)


Confined Parameters
Q = 20 gpm
T = 26.1 m²/day
S = 7.6E-4
Kz/Kh = 0.1
b = 26.1
b' = 7 m
assume fully-penetrating
t = 1 day
t = 1 week
t = 1 month
t = 2 months
t = 1 year
r=330
r=830
r=1900
r=2600
r=6000
Drawdown (meters)
Radial Distance (meters)
0.20
0.18
0.16
0.14
0.12
0.10
0.08
0.06
0.04
0.02
0.00
100
1000
10000
100000

(b)



(c)

Figure B.5. Semi-log distance-drawdown curves and straight-line fits (dashed lines) for constant-rate pumping tests in the Rwia aquifer at increasingly longer pumping durations for unconfined (a), confined (b), and leaky-confined (c) aquifer models. The y-axis has been enlarged to identify the radial distance at which the drawdown falls below an early-time straight-line fit to provide an estimate of the radius of investigation of the test.

B.3 Shutdown-Recovery Testing

In its simplest form, a constant-rate pumping test involves stressing the aquifer through extraction or injection in one or more stress wells, with pumping initiated from a static pre-test condition. Given the numerous P&T wells operating within the ZP-1 test area, this would require turning off P&T wells within the radius of influence of the test area for an impractical period of time. Disruptions in flow to the ZP-1 P&T wells would have an undesirable impact to the operation and remedial performance of the 200 West P&T facility.

The shutdown-recovery variant of the constant-rate pumping test involves shutting down flow to one or more P&T wells (referred to as stress wells), while maintaining flow to the other P&T wells in the test area (Appendix A). As noted by Spane (2010), the total composite response is a superposition of the impact from surrounding P&T wells (prior to and during the shutdown-recovery test) and the initiation of the shutdown of the stress well(s). As will be demonstrated in the example below, the shutdown-recovery component of the response can be de-superposed from the total composite response and analyzed as an equivalent constant-rate pumping test response.

B.3.1 Shutdown-Recovery Example in Test Area 1a

An example shutdown-recovery test was simulated for the ZP-1 test area 1a (Figure 2.5) to illustrate the application and analysis approach of this method.

B.3.1.1 Test Configuration and Parameters

Table B.2 contains the test parameters for the shutdown-recovery test example scenario. P&T injection well 699-45-67B, screened only in the Rwia aquifer (Table 2.3 and Table 2.6), was selected as the stress well. Flow rates from four Rwia-only aquifer P&T injection wells within or near the test area were included in the simulation (699-44-67, 699-43-67B, 699-42-67, and 699-40-67; see Table 2.6). P&T wells with screened intervals in the composite Rwie-Rwia aquifer to the west of the test area or P&T wells screened in the overlying Rwie unconfined aquifer within the test area were assumed to have no influence on the test response.

Flow rates for each of the five P&T injection wells were prescribed based on the 2019 average values reported for these wells (Table B.2). The AQTESOLV software Version 4.5 (Duffield 2007, 2009) was used to generate type curves for the leaky-confined aquifer model assuming no aquitard storage (Hantush and Jacob 1955; Hantush 1964). The multiple pumping wells were included using the principle of superposition, which holds that the combined response within the area of influence resulting from pumping of multiple wells is equal to the sum of the individual responses imparted by each pumping well (Todd 1980). The five P&T injection wells were set at their prescribed flow rates for a pre-test period of two years to allow the aquifer to reach a stable and linear background trend prior to the shutdown event. The shutdown-recovery test initiates by turning off injection to the stress well 699-45-67B, and injection continues in the other four P&T wells.

Table B.2. Shutdown-Recovery Test Parameters for ZP-1 Example

Parameter	Value(s)	Comments and Basis
P&T well flow rates (Q)	699 45-67B (stress well): 33 gpm until shutdown, then set to zero. 699-44-67: 37 gpm 699-43-67B: 20 gpm 699-42-67: 101 gpm 699-40-67: 78 gpm	Average flow rates during calendar year 2019 for Rwia aquifer P&T wells within or near the example test area. Values were calculated from the monthly P&T pumping rates[(a)].
Aquifer thickness (b)	26.1 m	Average thickness of the Rwia aquifer at the eight new Rwia well locations based on a combination of the HSGFM (ECF-HANFORD-13-0029) and the 2018 water table elevation map from DOE/RL-2018-68, Rev. 0.
Horizontal hydraulic conductivity (Kh)	1 m/d	Value from CPGM for the Rwia.
Transmissivity (T=Kh*b)	26.1 m^2/day	
Storativity (S=Ss*b)	7.6x10-4	
Vertical anisotropy (Kz/Kh)	0.1	Typical value used for Ringold Formation layered sediments and value used in CPGM.
Rlm confining layer thickness (b’)	7 m	Average from eight wells where Rlm unit is present in the ZP-1 OU in the HSGFM (ECF-HANFORD-13-0029).
Rlm confining layer leakage curve relationships (r/B)	0.1	Represents an intermediate leakage value. The leakage factor, B (Kruseman and de Ridder 2000), is a measure of the leakage through an aquitard into a leaky-confined aquifer. B = (T b’/Kv’)$^{1/2}$. Higher B values indicate lower leakage, so 1/B or r/B are typically used to represent the leakage factor.

(a) Monthly P&T flow rate summary spreadsheet file as communicated in email correspondences from Jason Hulstrom (CHPRC) to Rob Mackley (PNNL) on 4/7/2020.

B.3.1.2 Results

The simulated impacts of the surrounding P&T injection wells and the total composite response created by the stress-well shutdown are shown for monitoring well MW-D in Figure B.6, the closest monitoring well to the stress well (radial distance of 231 meters). Prior to the shutdown of the stress well, water level conditions are stable and changing very little with time, consistent with a leaky-confined aquifer model.

The shutdown-recovery response was de-superposed from the total composite response by subtracting the total composite response from the background response, and then plotted as an equivalent constant-rate pumping test and matched with type curves (Figure B.7). As expected, the simulated shutdown-recovery response is similar in characteristics to the leaky-confined scenarios presented in Section B.2 since the same aquifer properties were used (Figure B.1).

The simulated total composite and shutdown-recovery responses illustrate the applicability of the shutdown-recovery test. The leaky-confined Rwia aquifer scenario was considered in this evaluation. However, shutdown-recovery responses (following de-superposing) for the other two aquifer model scenarios are expected to be generally similar in characteristics to those presented in Section B.2 (Figure B.1 and Figure B.2). As shown in Figure B.2, a lower amount of displacement is expected for the composite Rwie-Rwia unconfined aquifer scenario given the relatively higher transmissivity. Rather than using a single P&T stress well, additional P&T wells could be shut down together to amplify the shutdown-response signal for testing in this operative aquifer model scenario.

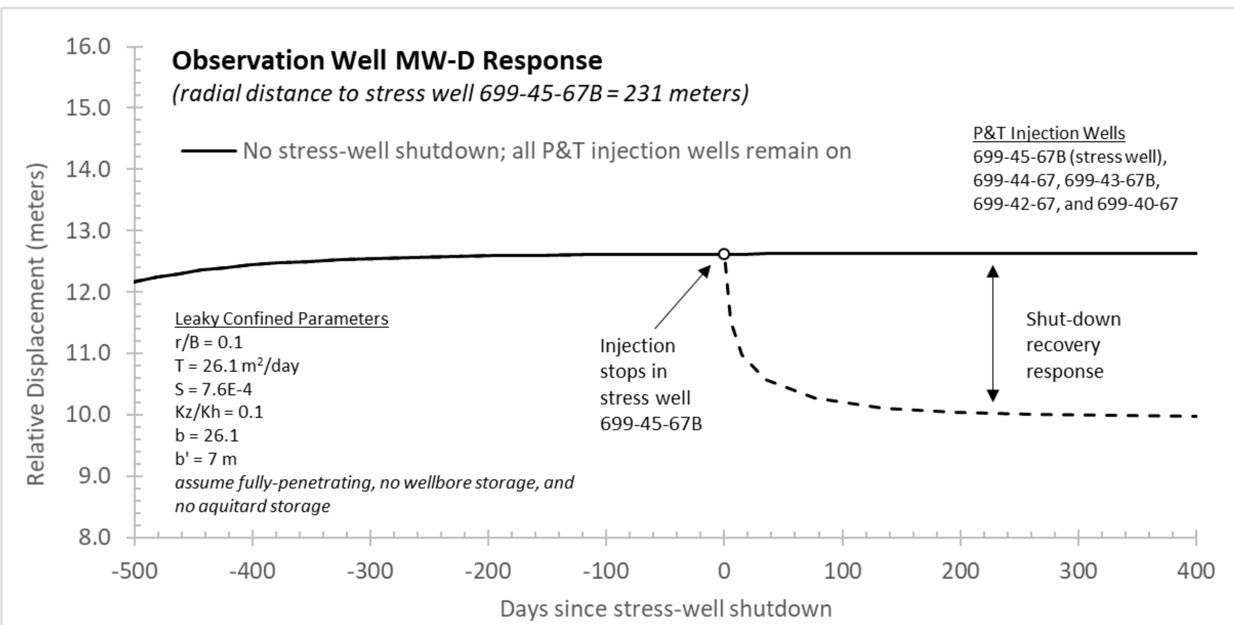


Figure B.6. Simulated leaky-confined aquifer response in MW-D to five P&T injection wells (solid line) combined with a stress-well shutdown event (dashed line).

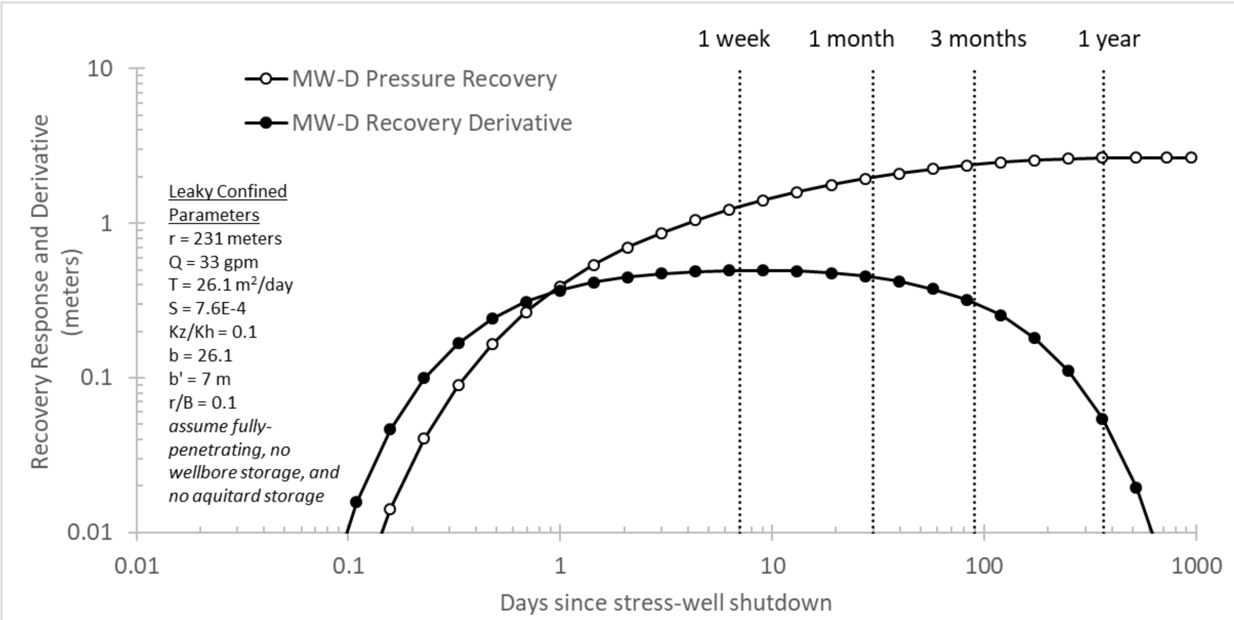


Figure B.7. Simulated shutdown-recovery response (white circles) and derivative (black circles) analyzed as an equivalent constant-rate pumping test with type-curve fits from a leaky-confined aquifer model.

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Appendix C – Pre-test Analysis of Single-Well Tracer Tests

This appendix contains results from pre-test analyses that evaluate several aspects related to test design and efficacy of single-well tracer tests for achieving specific hydraulic characterization objectives for the Ringold Formation member of Wooded Island – unit A (Rwia). This assessment evaluates the design elements and requirements for a hypothetical tracer-dilution and tracer pumpback in a fully-screen Rwia well. The tracer test pre-test analysis assessment components include the following:

1. Evaluate the relative amount or scale of aquifer investigated for single-well tracer tests (in terms of distance and volume).
2. Provide operational and test parameters important for planning and design (e.g. tracer volume, drift duration, pumpback duration, purge-water volume) of single-well tracer test.

These assessment components are evaluated for a Rwia aquifer well scenarios with varying duration and hydraulic conditions.

C.1 Tracer-Dilution Test

The analysis of a tracer-dilution test is based on the observed pattern of decrease or dilution of the emplaced tracer within the wellbore through time. The presence of ambient vertical flow within the well screen or distortions in the flow field caused by increased (or decreased) permeability near the well can complicate the analysis or invalidate the results of a tracer-dilution test. As noted in Appendix A, Section A.4.1, hydraulic property estimates obtained with tracer-dilution techniques do not consistently match estimates from other test methods. The results from tracer-dilution tests are heavily influenced by in-well and near-well influences and may not be robust and representative estimates for the aquifer.

Since these near-well influences vary by test location, are not known *a priori*, and dominate the tracer-dilution response, a hypothetical test scenario for a tracer-dilution test in a Rwia-aquifer well was not developed. Instead, the results from a previous test in another 200 West Area well (299-W22-47) reported by Spane and Newcomer (2008) are used to provide the general test conditions and durations that could be expected for a tracer-dilution test in a Rwia aquifer well. Table C.1 summarizes the operational parameters associated with this test as reported by Spane and Newcomer (2008).

The test in well 299-W22-47 is a representative example of the operational test parameters for a tracer dilution test that can be accomplished in 2 to 3 days. Tracer volumes are typically small (<10 L) and the time period for the tracer to be emplaced is brief (<1 hour). The bromide tracer declined from an initial concentration of about 80 mg/L to <2 mg/L after a period of 2854 minutes (2 days). As discussed in Appendix A, Section A.4.1, the rate of tracer dilution is used to estimate the groundwater-flow velocity within the well (V_w). It is important to note that V_w is not the same as the actual groundwater velocity in the aquifer (V_a). They are related by $V_w = V_a n_e \propto$, where n_e is the effective porosity and $\propto$ represents a dimensionless groundwater-flow-distortion factor ranging from 0.5 to 4 (Spane and Newcomer 2008).

For a given value of n_e and $\propto$, and all other test parameters being equal, the time required for a tracer-dilution test is inversely proportional to V_a (under ideal test conditions). For tracer-dilution tests in Rwia wells in 200-ZP-1, similar tracer volumes and emplacement times would be expected. The time required for the tracer to dilute one to two orders of magnitude from an initial concentration is estimated to be 2 to 10 days for Rwia well locations. Although the hydraulic conductivity is relatively lower in the Rwia aquifer compared to the Ringold Formation member of Wooded Island – unit E (Rwie) (Appendix B, Table B.1), if the horizontal hydraulic gradients are similar or comparatively higher in Rwia aquifer, the resulting groundwater velocity in the Rwia may be similar and require only slightly longer tracer-dilution test durations as required in the test in 299-W22-47.

If the tracer does not dilute within a practical and specified time period due to significantly low groundwater velocity in the Rwia aquifer and/or other non-ideal test conditions occur, the test could be terminated. The tracer could either be left to slowly migrate into the aquifer over time or pumped back.

Table C.1. Operational Test Parameters for the Tracer-Dilution Test in Well 299-W22-47 (from Spane and Newcomer 2008)

Parameter	Value(s)	Comments
Saturated screen length	10.45 m	Screened in the upper portion of the unconfined aquifer within the Rwie; total saturated thickness is 67.6 m
Screen and casing diameter	10.16 cm	
Horizontal hydraulic conductivity (K_h)	16.5 m/day	Calculated from constant-rate pumping analysis of subsequent tracer pumpback test
Hydraulic gradient (m/m)	1.65×10^{-3} m/m	Calculated from trend surfaced analysis
Groundwater velocity in the aquifer (V_a)	0.093 m/day	Calculated from subsequent tracer pumpback test
Effective porosity (n_e)	0.294	Calculated from tracer pumpback test
Tracer volume	5.3 L	
Initial bromide tracer concentration	80 mg/L	Varied initially from 70 to 100 mg/L depending upon wellbore depth
Time required for tracer emplacement and equilibration	<1 hour	
Duration of tracer-dilution test	2,854 minutes (2 days)	
Final bromide tracer concentration	<2 mg/L	
Estimated groundwater-flow velocity within the well	0.13 m/day	Ambient vertical flow in the wellbore was observed and the authors consider this estimate “questionable”

C.2 Tracer Pumpback Test

A pre-test design analysis for a tracer pumpback test in a Rwia well under varying hydraulic conditions was performed to (1) evaluate the relative aquifer distance or volume investigated (conceptually similar to the radius of investigation evaluation for pumping tests provided in Appendix B) and (2) to provide expected operational test parameters needed for planning and design of pumpback tests in the Rwia aquifer.

In all cases, it was assumed the Rlm is present and locally-confines the Rwia aquifer. It is also assumed that the groundwater tracer was previously emplaced into the aquifer using a tracer-dilution test (previous section) or injected during the first phase of a “push-pull” test (Istok 2013), and the tracer concentration in the test well has decreased one to two orders of magnitude below the initial concentration.

Table C.2 lists the pre-test tracer pumpback analysis parameters. Typically, tracer pumpback tests are used to estimate groundwater velocity in the aquifer (V_a) and effective porosity (n_e) based on the time required to recover the tracer’s center of mass (Istok 2013), the observed hydraulic gradient during the test for a given set of test conditions and aquifer properties. However, this analysis prescribed n_e to a value of 0.08 and a varied hydraulic gradient over a range of values ($I = 1.0 \times 10^{-3}$, 5×10^{-3}, and 1×10^{-2}) to evaluate test and operational parameters with the above-mentioned objectives in mind. Horizontal hydraulic conductivity (K_h) and aquifer thickness were set to 1 m/day and 26.1 m, respectively, for the Rwia aquifer (Table C.2).

Intuitively, the amount of the aquifer investigated by a tracer test is proportional to the time and distance the tracer is allowed to migrate downgradient under ambient groundwater flow conditions prior to pumpback (this is referred to as tracer *drift*). To better evaluate the relation between operational parameters and constraints (e.g. time required for the drift and pumpback phases of the test, pumping rate, and volume of purge water generated), three different tracer drift durations (t_d = 2, 5, and 10 days) were considered for each of the three hydraulic gradient cases. Table C.3 summarizes the results from the nine gradient-drift duration combinations considered in the pre-test analysis.

C.2.1 Tracer Drift Time and Distance

The pre-test analysis results (Table C.3) emphasize the need for larger drift durations (t_d), which generate tracer drift distances (D) large enough to provide meaningful and representative estimates of groundwater velocity (V_a) and effective porosity (n_e). All three of the 0.001 gradient scenarios (1a, 1b, and 1c) and the 2-day drift scenario with 0.005 gradient (2a) result in a D < 0.20 m (which might be considered the minimum D required to obtain meaningful results from single-well tracer tests). A $t_d \geq 5$ days is needed to achieve D > 0.20 m for the other two 0.005 gradient scenarios (2b and 2c). For the maximum gradient condition considered (I = 0.010), D ranges from 0.25 to 1.25 m for the three t_d scenarios (3a, 3b, and 3c).

C.2.2 Tracer Pumpback Times and Volumes

The time required to pump the tracer's center of mass (t_{50}) or to recover the entire tracer mass (t_e) is relatively small compared to the drift time (t_d). Both can be reduced (or expanded) by using a constant pumping rate (Q) that is relatively higher (or lower). The flow rates shown in Table C.3 were scaled proportionately to keep t_d < 10 hours in consideration of field-support staffing resources. The t_{50} and t_e values range from 0.7 to 1.7 hours and 3.5 to 8.7 hours, respectively, for the five test scenarios considered above as meaningful.

The volume of purge water (equal to vol_p) generated during tracer pumpback ranges from 558 to 3,446 gallons, except for scenario 3c, where there would be 13,734 gallons.

Table C.2. Input Parameters for Tracer Pumpback Pre-Test Analyses

Parameter	Value(s)	Comments and Basis
Aquifer thickness (b)	26.1 m	Average thickness of the Rwia aquifer at the eight new Rwia well locations based on a combination of the HSGFM[(a)] and the 2018 water table elevation map from DOE/RL-2018-68, Rev. 0.
Horizontal hydraulic conductivity (K_h)	1 m/day	Value from CPGM[(b)] for the Rwia.
Horizontal hydraulic gradient (I)	$1.0x10^{-3}$, $5x10^{-3}$, and $1x10^{-2}$	These values bracket the range of reported hydraulic gradients for seven RCRA[(c)] units within the 200 West Area (average = $5.6x10^{-3}$; ranges from $2.6x10^{-3}$ to $9.2x10^{-3}$) from DOE/RL-2019-65, Rev. 0.
Effective porosity (n_e)	0.08	Value from CPGM[(b)] for the Rwia
Groundwater velocity in the aquifer ($V_a = K_h*I*1/n_e$)	Calculated values of 0.013, 0.063, and 0.5 m/day	These are calculated based on the prescribed values for K_h, I, and n_e and provide values above and below the range of reported V_a values for seven RCRA[(c)] units within the 200 West Area during 2019 (0.09 to 0.31 m/day; average = 0.19 m/day) from Table 1-2 in DOE/RL-2019-65, Rev. 0.

(a) Hanford South Geologic Framework Model (HSGFM; ECF-HANFORD-13-0029)
(b) Values from the Central Plateau Groundwater Model (CPGM) (Table 4-4 in CP-47631 Rev 4)
(c) Resource Conservation and Recovery Act of 1976 (RCRA)

Table C.3. Operational Parameter Results for Rwia Tracer Pumpback Tests

V_a (m/day)	n_e	I (m/m)	Test Scenario	t_d (days)	D (m)	Q (gpm)	t_{50} (h)	t_e (h)	vol_p (gal)
0.013	0.08	0.001	1a[(a)]	2	0.03	0.5	0.1	0.7	5
			2b[(a)]	5	0.06	0.5	0.9	4.3	34
			3c[(a)]	10	0.13	2	0.9	4.3	137
0.063	0.08	0.005	2a[(a)]	2	0.13	5	0.3	1.7	138
			2b	5	0.31	10	1.1	5.4	862
			2c	10	0.63	40	1.1	5.4	3,415
0.125	0.08	0.010	3a	2	0.25	10	0.7	3.5	558
			3b	5	0.63	40	1.1	5.4	3,446
			3c	10	1.25	100	1.7	8.7	13,734

(a) Indicates results are not considered representative or meaningful for the aquifer due to the exceptionally low tracer drift distance predicted (D <0.2 m)
V_a = groundwater velocity in the aquifer
n_e = effective porosity
I = horizontal hydraulic gradient
t_d = elapsed time of tracer drift in the aquifer
D = lateral distance of tracer drift in the aquifer
Q = constant pumping rate during extraction
t_{50} = elapsed pumping time until the tracer center of mass is recovered
t_e = total elapsed pumping time while majority of remaining tracer mass is recovered; assumed to be five times longer than t_{50} based on a review of previous tests
vol_p = total volume extracted during pumpback test

C.3 Single-Well Tracer Testing Summary

The pre-test analysis results for the Rwia tracer-dilution and pumpback testing provide a perspective on the scale of representativeness for derived estimates of groundwater flow (V_a) and effective porosity (n_e) and an indication on the range of associated operational requirements.

C.3.1 Relative Aquifer Distance and Volume Investigated

Overall, the results indicate that single-well tracer pumpback tests investigate a relatively small radial distance or aquifer volume compared to other aquifer hydraulic tests such as pumping tests. For the Rwia aquifer scenarios considered here, tracer drift distances over a meter can be achieved when allowed to drift for a period of 10 days (Table C.3). However, the typical drift distances range from 0.25 to 0.63 m.

Spane and Newcomer (2008) note the small tracer volumes associated with tracer-dilution-pumpback tests, which result in minimal aquifer volume investigated. Additionally, results can be influenced by near-well effects such as well skin (decreased permeability near the well from incomplete well development). Implementing the “push-pull” approach, involving emplacement of hundreds to thousands of liters of tracer through injection, may help provide larger-scale and more representative estimates of V_a and n_e compared to tracer-dilution-pumpback tests, which involve only tens of liters of emplaced tracer solution.

C.3.2 Operational Requirements and Considerations

Single-well testing has relatively minimal requirements from an operational and logistical perspective. Tracer volumes are relatively small (<10 L) and the times required to emplace and pump the tracer back are within practical amounts (Table C.1 and Table C.3). Typically, purge water volumes are expected to be < 5000 gallons per test and pumping rates can be adjusted to accommodate the capacity of the test well, pump, and purge water tank.

C.4 References

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Appendix D – Field Testing Sequence and Requirements

This appendix contains additional information on the sequence of field activities and operational steps related to the Phases 1 through 3 of the Ringold Formation member of Wooded Island – unit A (Rwia) hydraulic testing. This information can be used for planning and coordination of necessary resources and provides additional detail needed to create field instruction documents. Section 2.3 in main body of this test plan contains details on the objective and outcomes from these testing activities, tables containing well information, and maps showing test areas and locations.

The following types of information are provided for each test type within a given test phase (where applicable):

- Number of tests or locations
- Sequence of activities for a given test or series of related tests
- Duration of activities which require field support (estimated)
- Notable impacts or disruptions to pump and treat (P&T) operations
- Purge water volumes

D.1 Miscellaneous support requirements General Impacts to Operations

In addition to the specific impacts related to each phase of testing listed below, there are general operational impacts and requirements. These should be considered and addressed in coordination with the operations and maintenance organizations prior to development of field instruction documents and implementation of the testing. Some examples of these general impacts and requirements include:

- Development of work packages
- Procurement of materials
- Environmental safety and health evaluation of tracer chemicals
- Industrial health (IH) evaluations
- Changes to the P&T facility control logic (e.g. ability to set constant flow rate to injection wells)
- Specify target flow rate ranges for injection and extraction wells for each test

D.2 Phase 1 Testing in Rwia Wells

This phase of testing includes slug testing, electromagnetic borehole flowmeter (EBF) testing, installation of automated water level network (AWLN) stations in new Rwia wells, and shutdown-recovery tests in wells with screened intervals completed solely in the Rwia unit.

D.2.1 Slug Testing in Rwia Wells

Only the post-completion slug tests are discussed here. Refer to the Ringold A SAP[1] for information on the depth-discrete slug testing performed during drilling.

Number of tests: Twelve (12)

Sequence: The wells should be slug-tested after they have completed and fully developed.

Duration: 1-2 days per slug test location

P&T Impacts: None

Purge water: None

Miscellaneous: None

D.2.2 EBF Testing in Phase 1 Stress Wells and New Rwia Wells

Number of tests: Twelve (12)

Sequence: EBF testing of the new Rwia wells should take place after the post-completion slug testing has been performed.

For EBF testing of the two P&T injection wells used as stress wells, the flows to the wells will need to be shut off, the well taken offline (virtually) from the 200 West P&T system, and the downhole injection piping and instruments will need to be removed from the wells during EBF testing. Reinstallation of the downhole injection piping, reconnection to the P&T facility, and resumption of injection in the well can take place immediately after EBF testing is complete.

Testing of the two P&T injection wells could be spread out in time to minimize the short-term impact to injection capacity or done back-to-back within the same time window to utilize mobilized resources.

Duration: 2-3 days for EBF survey at each test location, plus 1 day before/after for physical and electrical disconnection/reconnections. P&T injection will be disrupted for 4-5 days.

P&T Impacts: None for the new Rwia wells. See durations above for P&T wells being tested.

Purge water: < 2000 gallons per EBF test

Miscellaneous: A borehole camera survey should be performed at each EBF test location prior to EBF testing survey to identify visual signs of fouling, damage to the well casing or screen, and verification of the depth of joints and blank sections in the screened interval. If there is evidence of fouling, the well should be redeveloped, cleaned, or rehabilitated according to the contractor’s standard methods or procedures.

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[1] DOE/RL-2019-23. 2019. *200 ZP-1 Groundwater Operable Unit Ringold Formation Unit A Characterization Sampling and Analysis Plan (Ringold A SAP).* Rev. 0, U.S. Department of Energy, Richland Operations Office, Richland, Washington.

D.2.3 New AWLN Stations in Rwia Wells

Number of locations: Twelve (12)

Sequence: Installation of the AWLN stations should take place as soon as the wells are completed, either before or after the post-completion slug and EBF testing has been performed.

Duration: None (from a field-testing perspective)

P&T Impacts: None

Purge water: None

Miscellaneous: None

D.2.4 Shutdown-Recovery Tests in Rwia Wells

Number of tests: Two (2)

Sequence: Given the extended test durations and P&T impacts, the testing schedule could be spaced out in time between the two test areas.

The new Rwia wells within the test areas need to be completed and added to the AWLN station prior to testing. Also, baseline monitoring of the P&T and barometric fluctuations (from the Hanford Meteorological Station in 200 West Area) in the associated test area wells needs to take place for a minimum period of 2 months (but a period of >6 months is preferred) before the shutdown-recovery testing can begin.

For each test area, the P&T wells within test area will be held to a stable and constant rate (±10% of targeted set point) for a minimum period of 1 month (3 months is preferable) prior to initiation of the test. (This can overlap with the baseline P&T and barometric response monitoring.) Target flow rate set points for the stress well and P&T wells in the test area will be specified through test instruction documents. The test will be initiated by abruptly turning off injection to the stress well, which will result in a pressure recovery response in the stress and observation wells. The test is terminated by resuming flows into all the P&T wells and resuming normal P&T operations.

Duration: Flow to the stress well will need to remain off for an expected duration of 2 to 6 months per test, and potentially longer [e.g., if the response shows a small vertical leakage through the Ringold Formation member of Wooded Island – lower mud unit (Rlm) aquitard]. Other P&T wells in the test area need to remain at stable and constant flow rates (±10% of targeted set point). The recovery response will need to be evaluated periodically by the subject matter experts to inform a decision to terminate or continue the test. During the test, flows to the nearby P&T wells will need to remain stable to minimize pressure interferences. An unplanned outage of the P&T system involving the stress well or nearby P&T wells would likely have a negative impact on the test results. The impact would vary depending on the duration, number, and location of affected P&T well(s) within the test area. If the impact is significant, the test may need to be repeated.

P&T Impacts: Lower injection capacity and less flexibility for varying injection flow rates near the test areas

Purge water: None

Miscellaneous: None

D.3 Phase 2 Testing in Composite Rwie-Rwia Wells

This phase of testing includes shutdown-recovery tests in wells with screened in the composite Ringold Formation member of Wooded Island – unit E (Rwie)-Rwia aquifer and EBF testing in the related stress wells.

D.3.1 Shutdown-Recovery Tests in Composite Rwie-Rwia Wells

Number of tests: Four (4)

Sequence: Given the extended test durations, the associated P&T impacts, and the multiple test locations, the testing schedule could be spaced out in time between the two test areas.

Test areas using new Rwia wells as observation wells need to be completed and added to the AWLN station prior to testing. Also, baseline monitoring of the P&T and barometric fluctuations in the associated test area wells needs to take place for a minimum period of 2 months (but a period of >6 months is preferred) before the shutdown-recovery testing can begin.

The P&T wells within test area will be held to a stable and constant rate (±10% of targeted set point) for a minimum period of 1 month (3 months is preferable) prior to initiation of the test (this can overlap with the baseline P&T and barometric response monitoring). Target flow rate set points for the stress well and P&T wells in the test area will be specified through test instruction documents. The test will be initiated by abruptly turning off flow in the P&T well used as the stress well. Test areas 2a, 2b, and 3d use an extraction well as the stress well, and test area 2c uses an injection well. This will result in a pressure recovery response in the stress and observation wells. The test is terminated by resuming flows into all the P&T wells and resuming normal P&T operations.

Duration: Flow to the stress well will need to remain off for an expected duration of 2 to 6 months per test, and potentially longer. Other P&T wells in the test area need to remain at stable and constant flow rates (±10% of targeted set point). The recovery response will need to be evaluated periodically by the subject matter experts to inform a decision to terminate or continue the test. Flows to the nearby P&T wells will also need to remain stable to minimize pressure interferences. An unplanned outage of the P&T system involving the stress well or nearby P&T wells would likely have a negative impact on the test results. The impact would vary depending on the duration, number, and location of affected P&T well(s) within the test area. If the impact is significant, the test may need to be repeated.

P&T Impacts: Loss of injection or extraction capacity (see above) and less flexibility for varying flow rates near the test areas

Purge water: None

Miscellaneous: None

D.3.2 EBF Testing in Phase 2 Stress Wells

Number of tests: Four (4)

Sequence: EBF testing of the composite Rwie-Rwia wells can be completed before or after the shutdown-recovery test in each test area.

Flows will need to be turned off in the P&T well prior to the EBF testing. The well will be taken offline (virtually) from the 200 West P&T system, and the downhole injection piping, pump (if an extraction well), and instruments will need to be removed from the wells. Reinstallation of the downhole injection piping, reconnection to the P&T facility, and resumption of injection in the well can take place immediately after EBF testing is complete.

EBF testing of the four P&T wells could be spread out in time to minimize the short-term impact to injection or extraction capacity or done as a group within the same time window to use mobilized resources.

Duration: 2-3 days for EBF survey at each test location, plus 1 day before/after for physical and electrical disconnection/reconnections. P&T injection will be disrupted for 4-5 days.

P&T Impacts: See durations above.

Purge water: < 4,000 gallons per EBF test. Note: The longer screened intervals in the composite Rwie-Rwia wells will require more EBF measurements than the Rwia-only wells.

Miscellaneous: A borehole camera survey should be performed at each EBF test location prior to EBF testing survey to identify visual signs of fouling and damage to the well casing or screen, and to verify the depth of joints and blank sections in the screened interval. If there is evidence of fouling, the well should be redeveloped, cleaned, or rehabilitated according to the contractor’s standard methods or procedures.

D.4 Phase 3 Tracer Testing in New Rwia Wells

This phase of testing involves single-well tracer testing in five of the new Rwia wells located along the southern perimeter of the ZP-1 test area.

D.4.1 Tracer-Dilution and Pumpback Test

Number of tests:	Five (5)
Sequence:	The tracer-dilution and pumpback tests should be performed following completion of the EBF testing and baseline monitoring of the P&T and barometric fluctuations for each respective tracer test location. The tracer test in well MW-E (test area 3a) should take place prior to the shutdown-recovery test in test area 2b to provide additional hydraulic characterization information, which could help inform the design and interpretation of that test. The tracer will be emplaced into the test well using a tracer-dilution test, allowed to drift out of the well and into the aquifer, then recovered in the same well during a tracer pumpback test.
Duration:	5-20 days per test location
P&T Impacts:	None
Purge water:	< 15,000 gallons per test
Miscellaneous:	None

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