KONNOWAC PASS AQUIFER STORAGE AND RECOVERY FEASIBILITY STUDY

Prepared for

Yakima Basin Integrated Plan, Groundwater Storage Subcommittee

Prepared by

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Project PNG0983

May 3, 2024

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EXECUTIVE SUMMARY

The primary goals of this project were to evaluate the groundwater storage potential for artificial recharge to the Wanapum Aquifer in the Columbia River Basalts and to identify the feasibility of a large-scale ASR program that could stabilize groundwater levels while also providing access to underground storage that could improve water supply reliability. The Study Area referred to in this report is centered around the Roza Irrigation District, and generally includes the Moxee Valley and the Lower Yakima Valley from Yakima to near Benton City. The Study Area crosses Rattlesnake Hills at Konnowac Pass and is surrounded by other prominent geographic features including Yakima Ridge, and Horse Heaven Hills. The Wanapum Aquifer in this area is primarily used for irrigation. During state-declared droughts, Wanapum provides relief to agricultural irrigation when deliveries from surface water sources are limited. Groundwater levels in the Wanapum Aquifer have experienced long-term declines, with as much as 260 feet of decline in some wells over the past 30 years. While this water level decline indicates that groundwater storage has been mined because of historical pumping, it also indicates that groundwater storage capacity is available in some portions of the basalt aquifer system through managed aquifer recharge (MAR).

This report specifically evaluates MAR via Aquifer Storage and Recovery (ASR) by injecting surface water to the Wanapum Aquifer in the Roza Irrigation District. A separate report discussing the feasibility of infiltration to the basalt aquifer system is being prepared by Coho Water Resources and is not included in this report. As discussed later in this report, our hydraulic analyses and hypothetical operation scenarios of an ASR system are focused on the Roza Irrigation District main canal, from Konnowac Pass toward Benton City (i.e., the target area).

One of the original goals of this project was to conduct a pumping test in an existing well to estimate site-specific aquifer properties in the Wanapum Aquifer. However, due to several failed attempts to find a willing well owner to participate in the study, and other complications in collecting field data, we (Geosyntec and CWU) diverted the field effort component into assessing the storage capacity of the Wanapum Aquifer with an analytical model using published aquifer data.

Hydrogeologic Setting

The general Study Area is located in a structural region of the Columbia Plateau known as the Yakima Fold and Thrust Belt. This region is defined by generally east-west trending anticlines and synclines and associated thrust faults. Locally, the Study Area is bounded to the north and south by anticlinal ridges and thrust faults. These anticlinal ridges (Yakima Ridge to the north and Toppenish Ridge to the south) are asymmetrical with a steeply dipping north limb and a relatively shallow dipping south limb. The geologic structures create barriers to groundwater flow to the north and south, thus creating a confined and dipping structural "compartment" in the basalt aquifer system within the Study Area. Faults of varying extent and offset are also present both along the synclinal axis (east-west) and roughly perpendicular to it (north-south).

Groundwater flow directions within the basalt aquifers in the study area are generally north-south, toward the Yakima River with a component of eastward down-valley flow toward the Columbia River near Richland.

The Study Area is comprised of the following stratigraphy, from youngest to oldest (typically shallowest to deepest):

- **Overburden** is typically a few feet to tens of feet thick in the Study Area. Locally includes alluvium, mass wasting deposits (i.e., landslides), Touchet beds, Thorp gravels, loess, and Missoula flood deposits.
- **Ellensburg Formation** is an unconsolidated to consolidated sedimentary unit that overlies, intercalates, and underlies the Columba River basalts. In the western portion of the Study Area within the Yakima Valley, this unit is nearly 1,200 feet thick. To the eastern half of the Study Area, this unit is typically less than 800 feet thick.
- **Saddle Mountains Basalt** averages about 700 feet thick in the Study Area and locally contains individual flow members of Elephant Mountain, Pomona, and Umatilla, which are all separated from each other by the sedimentary Ellensburg Formation (Rattlesnake Ridge and Selah members).
- **Wanapum Basalt** averages about 900 feet thick in the Study Area and locally contains the Priest Rapids, Roza, and Frenchman Springs members, which are separated by the sedimentary Ellensburg Formation (i.e., Mabton and Squaw Creek members).
- **Grande Ronde Basalt** thickness is not well understood due to limited wells that have penetrated this formation in the Study Area, but thickness could be more than 15,000 feet. The Vantage member of the Ellensburg Formation separates the Grande Ronde from the upper Wanapum.

Groundwater typically occurs in the rubbly, brecciated, or fractured flow tops and bottoms of individual basalt flows, and in sedimentary interbeds. These water-bearing zones typically have much greater hydraulic conductivity and storativity compared to the dense flow interiors of individual basalt flows. The published average hydraulic conductivity of the flow tops in the Wanapum Basalt range from 4.3 to 130 feet per day with an estimated average storativity of 5×10^{-5}.

Water Quality

The native groundwater quality in the Wanapum Basalt Aquifer is generally defined as a calcium-magnesium-bicarbonate-type water ($Ca\text{-}Mg\text{-}HCO_3$-type water). Based on limited water quality sampling of wells in the Study Area and review of published reports, the overall water quality in the Wanapum is excellent, with the exception of a few potential constituents that may have elevated concentrations above the Department of Ecology’s Groundwater Criterion (Washington Administrative Code 173-200); these may include nitrate/nitrite as nitrogen (N), arsenic, and pH.

The source water for MAR in the study area would originate from the Roza Irrigation District (RID), which diverts water from the Yakima River. RID is supplied by surface water from the Cle Elum, Kachess, and Keechelus reservoirs via the Yakima River to the Roza Diversion Dam. Water quality in the RID canal system is essentially the same as the water quality of the Yakima River, which is defined as a $Ca\text{-}Mg\text{-}HCO_3$-type water. Water quality sampling of the RID canal and analysis of data collected by Rosa Sunnyside Joint Board of Control (RSJBOC) water quality program indicate that treatment will likely be necessary for the following constituents:

bacteriological agents, pH, and total suspended solids/turbidity. If chemical treatment is used, disinfection byproducts will also need to be monitored and managed. Timing of withdrawal of canal water will need to be coordinated with any herbicide application that is planned by RID near the withdrawal location to ensure herbicides are not injected into the aquifer.

Isotope analysis indicates that the Wanapum well that was sampled draws water from two isotopically distinct aquifers, likely the Wanapum and Saddle Mountain units, at different times of year. Care should be taken to avoid this configuration in future injection wells. The isotope results also verify that Roza Canal water is very different isotopically from Wanapum Aquifer groundwater. As a result, isotope ratios and mass balance considerations can be used to calculate proportions of these two end members in any mixture of the two (e.g., during a pilot test).

Modeling of ASR Injection

To evaluate the feasibility of an aquifer storage and recovery (ASR) system in the Study Area, an analytical model was developed to simulate the predicted build-up of head in the Wanapum Aquifer under selected injection rates. The model accommodated multiple injection wells at varying spacings using superposition of the predicted head build-up (injection phase) and drawdown (recovery phase) from individual wells using the Theis solution. The model assumed a 20-well ASR system with wells completed in the Wanapum Aquifer and spaced 10,000 feet apart along the RID main canal from Konnowac Pass to Benton City. The maximum head build-up capacity (i.e., the difference between static water level and the ground surface) was assumed to be approximately 400 feet. The model evaluated injection under a range of hydraulic parameters from the United States Geological Survey Yakima Groundwater Model. Each well was assumed to inject 1,900 gallons per minute over a 120-day period, which equates to approximately 20,000 acre-feet (AF).

Based on the results of the analytical model, a 20-well ASR system is predicted to be feasible for most scenarios of hydraulic parameters. Under the most conservative scenario (i.e., the lowest values of aquifer transmissivity), the system may need more than 20 wells to achieve a 20,000 AF injection volume target. The model indicated a peak build-up after a 120-day injection cycle of over 350 feet in the center of the wellfield using conservatively low aquifer properties and a low well efficiency. These “worst case” conditions could bring hydraulic heads near the ground surface, particularly after repeated injections, which would not be favorable. Higher well efficiencies result in lower peak build-up, indicating that careful well design and injection head control will be necessary for ASR wells at locations with lower bulk transmissivity. Using, “best case” hydraulic properties, peak build-up is significantly lower (less than 100 feet) and the feasibility of injection is quite favorable. However, a pilot test using a properly designed ASR well is needed to better determine the expected head build-up, maximum injection volumes, and design constraints for an ASR wellfield.

Water Quality Modeling

Source water quality was evaluated for compatibility with the native groundwater quality in the Wanapum Basalt Aquifer using a geochemical model. The modeling indicates that adding the more dilute Roza Canal water tends to reduce solubilities of saturated minerals such as smectite, talc, and dolomite. Overall, the source water quality appears to be compatible with native groundwater quality. No adverse impacts from the precipitation or dissolution of minerals are anticipated based on currently available data. However, because of the very low arsenic concentration threshold in the state groundwater quality criteria, arsenic should be monitored in pilot testing to determine if mixing gives rise to an increase in arsenic concentrations above the background levels.

Example Operations Analysis

An example operational analysis of surface water delivery, ASR injection, and ASR withdrawal system was prepared based on historical reservoir data from 1981 to 2023. The generalized approach to the exercise was to combine the injection and withdrawal capacity of a theoretical ASR wellfield with potential constraints on the availability of surface water for ASR injection and demand for ASR recovery during dry years. A hypothetical long-term (40+ years) water budget of ASR operations was prepared to illustrate how 20,000 AF per year of surface reservoir water, conveyed during the spring to an ASR wellfield, could be stored in, and selectively recovered from, the Wanapum Aquifer within the Study Area. The intent was to demonstrate that a regulated ASR program using a modest but consistent spring delivery of surface water from the Yakima River can restore storage volumes to the Wanapum Aquifer while also providing valuable beneficial use for agriculture during dry years and/or used for mitigation as emergency drought wells. There are numerous simplifying assumptions that are necessary to produce this analysis. The intent of the analysis is not to propose specific ASR operations scenarios, but to provide an example for demonstration and discussion with potential stakeholders or project sponsors for an ASR Pilot study.

Over the 42-year period, the total injection volume into the Wanapum Aquifer was about 790,000 AF, which represents approximately 95% of the cumulative estimated storage loss from the Wanapum over that same period. Recovery at the full 20,000 AF per year withdrawal capacity occurred on 11 occasions, and the total recovery volume was about 435,000 AF. The residual volume remaining in aquifer storage at the end of the simulation was about 355,000 AF. This volume represents potential storage that would “stay” in the aquifer to help restore or lessen the rate of water level decline in the Wanapum Aquifer.

Conclusions and Recommendations

To further evaluate the feasibility of ASR in the Study Area, we recommend conducting an injection and/or pumping test in a well completed in the Wanapum Aquifer. The goals of the test are as follows:

- Determine site-specific hydraulic parameters of the Wanapum Aquifer.
- Evaluate well performance, such as the specific capacity (pumping rate per drawdown or head-build up) and well/aquifer efficiency.
- Analyze groundwater quality data to further evaluate compatibility of native (ambient) groundwater with source water.

Given the reluctance of area well owners to agree to testing in their existing wells, we recommend constructing a new ASR test well. A well siting evaluation should be conducted to determine the suitability of a new well, taking into consideration distance to the RID main canal on the southside of Rattlesnake Hills, property ownership, and anticipated total drilling depth to complete the well within the Wanapum Aquifer.

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ACRONYMS AND ABBREVIATIONS

µg/L	microgram per liter
AF	acre-feet
Al	aluminum
asl	above sea level
ASR	aquifer storage and recovery
Ba	barium
bgs	below ground surface
Ca	calcium
cfs	cubic feet per second
Cl	chlorine
Coho	Coho Water Resources, LLC
CRBG	Columbia River Basalt Group
Cu	copper
CWU	Central Washington University
DMR	discharge monitoring report
DNR	Washington State Department of Natural Resources
DO	dissolved oxygen
Ecology	Washington State Department of Ecology
EIM	Environmental Information Management
Fe	iron
ft^2	feet-squared
Golder	Golder Associates, Inc.
gpm	gallons per minute
GQC	groundwater quality criteria
GWMA	Groundwater Management Area
HCO_3	bicarbonte
IC	ion chromatograph
in/yr	inch per year
K	hydraulic conductivity
kg	kilogram
KID	Kennewick Irrigation District

LHG	licensed hydrogeologist
Ma	million years ago
MAR	managed aquifer recharge
MCL	maximum contaminant level
Mg	magnesium
mg/L	milligram per liter
mL	milliliter
MP	mile post
MPN	most probable number
mV	millivolt
N	nitrogen
Na	sodium
NAQWA	National Water Quality Assessment
NO_3	nitrate
NTU	Nephelometric units
NWIS	National Water Information System
ORP	oxidation reduction potential
Pb	lead
PCB	polychlorinated biphenyl
ppb	parts per billion
ppm	parts per million
QAPP	quality assurance project plan
RC	Roza Canal
RID	Roza Irrigation District
RSBOJC	Roza Sunnyside Board of Joint Control
S	storativity
SMCL	secondary maximum contaminant level
SO_4	sulfate
T	transmissivity
TOC	total organic carbon
TSS	total suspended solids
USEPA	United States Environmental Protection Agency
USGS	United States Geological Survey

V	vanadium
WAC	Washington Administrative Code
YBIP	Yakima Basin Integrated Plan
YR	Yakima River
Zn	zinc

Geosyntec consultants

1. INTRODUCTION

1.1 Project Description

This project was funded by the Groundwater Subcommittee of the Yakima Basin Integration Plan (YBIP) to evaluate the groundwater storage potential and identify best methods of artificial aquifer recharge to the Columbia River Basalt formations east of the Yakima River and in the Konnowac Pass area. The overall project scope of work included three tasks:

Task 1 – Project Management

Task 2 – Data Compilation and Field Reconnaissance

Task 3 – Surface Infiltration and Injection Testing and Assessment

This report specifically addresses the feasibility of developing an aquifer storage and recovery (ASR) system via injection for the Roza Irrigation District (RID). The goals of this study are to replenish groundwater reservoirs and use that storage to increase water supply reliability for irrigators in the Yakima Basin during drought years. A separate report discussing the feasibility of infiltration to the basalt aquifer system is being prepared by Coho Water Resources and is not included in this report.

The study was authorized by an Interagency Agreement contract[1] between Washington State's Department of Ecology (Ecology) and Central Washington University (CWU). CWU teamed with Geosyntec Consultants, Inc. (Geosyntec), and Coho Water Resources, LLC (Coho), because of their knowledge of the hydrogeologic conditions of the Study Area and experience working on managed aquifer recharge (MAR) projects in the Yakima Basin.

1.2 Authors

The primary contributors to this report are listed in Table 1.

Table 1: Report Authors

Central Washington University	Geosyntec Consultants, Inc.
Dr. Carey Gazis	Robert Anderson, LHG
Bethany Kharrazi	Derek Holom, LHG

1.3 Report Structure

This report builds upon the work that was previously conducted and documented in an unpublished technical memorandum from 2022. The primary components of the ASR feasibility evaluation are listed below:

[1] CWU contract number 15445

- **Section 2** summarizes the background information and data available in the Study Area. This includes a description of the geographic region, climate, geology, hydrogeology, surface water and groundwater quality, and aquifer geochemistry.
- **Section 3** provides an overview of the primary phases of an ASR system with the goal of increasing groundwater storage and stabilizing long-term declining groundwater levels.
- **Section 4** summarizes the field data collected as part of this study. This includes water quality data collected along RID's main canal and a pumping test conducted in a water supply well completed in the Wanapum Aquifer.
- **Section 5** describes the conceptual hydrogeologic model in the Study Area with focus on the Wanapum Aquifer (target storage zone). This section also presents the predicted changes in groundwater levels in the target aquifer based on multiple ASR injection scenarios using a simplified analytical spreadsheet model.
- **Section 6** presents the results of the hypothetical long-term ASR operations analysis using historical source water reservoir storage data from 1981 through 2023. The ASR injection and storage volumes used in the operations analysis are based on the hydraulics analysis in Section 5.
- **Section 7** presents the geochemical model results used to predict the potential changes in groundwater quality and aquifer geochemistry based on the available source water quality data for the Yakima River and RID irrigation water. The results from this analysis can be used to guide an initial regulatory analysis and preliminary treatment design for the source water prior to injection.
- **Section 8** summarizes the feasibility evaluation for an ASR system in the Study Area using RID source water and existing and future infrastructure. We also provide recommendations for future work to advance the development of an ASR system.

2. BACKGROUND

2.1 Geographic Setting

The Study Area is focused on the RID, and generally includes the Moxee Valley to the east of the Yakima River, the Yakima Valley between Rattlesnake Hills to the north, and Horse Heaven Hills to the south (Figure 1). Ground elevations range from approximately 3,800 feet above sea level (asl) on Yakima Ridge to less than 700 feet asl near the confluence of the Yakima and Columbia Rivers.

Agriculture in the valley is a major component of the local economy. Irrigation water for the Study Area is diverted from the Yakima River at the Roza Dam in the Yakima River Canyon (Figure 1). Flows in the upper Yakima River above the Roza Dam are controlled by releases from Kachess, Keechelus, and Cle Elum reservoirs near the crest of the Cascade Mountain Range.

2.2 Climate

The Yakima region receives less than 8 inches of mean annual precipitation in the valleys to more than 40 inches in the upland areas in the foothills of the Cascade Range to the west. In the Study Area, precipitation ranges from less than 8 to about 15 inches in the surrounding hills and ridges (Vaccaro, Kahle, et al. 2015). The estimated mean annual recharge from precipitation over most of the Study Area is less than 1 inch per year (in/yr) in the valleys where precipitation is typically less than 8 in/yr (Kahle, et al. 2011). Much of the remaining water available from precipitation is either surface runoff to streams and rivers, diverted for irrigation use, or lost to evapotranspiration.

2.3 Geology

The Study Area lies within the western portion of the Columbia Plateau, in a structural region known as the Yakima Fold and Thrust Belt, which is characterized by a series of east-to-west trending anticlinal ridges and synclinal basins and associated faults (Figure 2). The regional geology has been well characterized by multiple researchers as part of a broader investigation into the groundwater availability for what the United States Geological Survey (USGS) defines as the Columbia Plateau Regional Aquifer System. The description of the geologic setting in this section is primarily based on the work done by Jones (2006), Burns (2011), and Vaccaro (2015). The primary geologic units in Study Area, from youngest to oldest, include the following:

- Quaternary sediments
- Miocene Ellensburg Formation
- Miocene Columbia River Basalts
- Pre-Miocene rocks (includes intrusives, metamorphosed intrusives, metamorphosed sedimentary, and volcanic rocks)

Figure 3 shows the regional geologic map of the Columbia Plateau presented in the USGS regional geologic framework for the Columbia Plateau Regional Aquifer System (Burns, et al. 2011). Cross-sections A-A’ and B-B’ traverse the Study Area and are shown in Figure 3. A summary of the major geologic units present within the Study Area is provided in Figure 4. The descriptions of the geologic units in the Study Area are summarized below.

2.3.1 Quaternary Sediments

Quaternary sediments consist of unconsolidated deposits of fluvial sediments, colluvium, wind-blown loess, and Missoula flood deposits. These form varying thicknesses of potential overburden, from a few feet to tens of feet, which overlies middle- to upper-Miocene stratigraphy of the Ellensburg Formation and Columbia River Basalt Group in some locations.

2.3.2 Ellensburg Formation

The Ellensburg Formation is an unconsolidated-to-consolidated sedimentary unit that is intercalated within and overlies the Columbia River basalts. This formation is composed of continental sedimentary deposits ranging from lacustrine clays and overbank fine-grained deposits to fluvial sands and gravels, sandstones and conglomerates, and interbedded volcaniclastic sediments (Burns, et al. 2011). In the western area of the Moxee Valley, the Ellensburg Formation is nearly 2,000 feet thick but thins toward the eastern half the valley against the slopes of the anticlinal basalt ridges. In the western half of the Yakima Valley, the basin-fill thickness is up to about 1,200 feet thick; whereas in the eastern half of the Yakima Valley, the basin-fill thickness of the Ellensburg Formation is less than 800 feet.

2.3.3 Columbia River Basalt Group

The flows of the Columbia River Basalt Group (CRBG) occurred over a span of more than 11 million years, from about 16.7 to 5.5 million years ago (Ma) (Reidel, Camp, et al. 2013). The CRBG formations of interest in the Study Area, from youngest (shallowest) to oldest (deepest), are the Saddle Mountains Basalt, Wanapum Basalt, and Grande Ronde Basalt. Each basalt formation is grouped into named members, which may contain multiple flow sequences with a variety of internal structures (Figure 5). Below is a summary of key information on each basalt and major interbed formation:

- The Saddle Mountains Basalt is the shallowest basalt unit and generally consists of three basalt flow sequences, named the Elephant Mountain, Pomona, and Umatilla. The Elephant Mountain sequence is the youngest and is approximately 30 to 100 feet thick. It consists of at least two flows with distinct basaltic flow structures. The Pomona Member is the dominant outcrop near Konnowac Pass and along the crest of Rattlesnake Hills. The Umatilla Member is poorly exposed in outcrop but present at depth in the Study Area.
- The Mabton Interbed is a member of the Ellensburg Formation that separates the Saddle Mountains Basalt from the underlying Wanapum Basalt. The Mabton Interbed is not well exposed in the Study Area but is a regionally extensive silty sandstone and clay unit that was deposited during a hiatus at the end of the emplacement of the Wanapum Basalt. The Mabton Interbed has a maximum estimated thickness of 250 feet and averages 70 feet thick in the Study Area. It is often characterized in well logs by its greenish-grey color and notable clay content.
- The Wanapum Basalts are not well exposed in the Study Area but are exposed on topographic ridges north of the Study Area. The depth of the top of the Wanapum ranges from 475 to 2,610 feet below ground surface (bgs), with greater depths in the middle of

synclinal valleys. From the 126 wells logs of deep wells that were examined in the Study Area, 83 were interpreted to be completed in the Wanapum Basalt.

- The Vantage Interbed separates the Wanapum Basalt from the underlying Grande Ronde Basalt. The Vantage is a regionally extensive silty sandstone formation that was deposited during a significant hiatus at the end of the emplacement of the Grande Ronde Basalt.
- The Grande Ronde Basalt accounts for approximately 72% of the volume of the CRBG in the Columbia Plateau (Reidel and Tolan 2013). Like the Wanapum, the Grande Ronde Basalt is not well exposed in the Study Area but is exposed on topographic ridges north of the Study Area. In the Study Area, it is typically 2,000–2,600 feet bgs.

2.3.4 Geologic Structure

The Yakima Fold Belt began to develop approximately 5 Ma ago, forming the series of northwest- to west-trending ridges and valleys that characterize the current major landforms in the Yakima Basin. The prominent anticlinal structures in the Study Area include the Rattlesnake Hills, Ahtanum Ridge, and Yakima Ridge to the north and the Toppenish Ridge and Horse Heaven Hills to the south (Vaccaro, Kahle, et al. 2015). These anticlinal structures are asymmetrical with a steep north limb and a relatively shallow south limb. Both low-angle (near-horizontal) compressive thrust faults and high-angle (near-vertical) compressive reverse faults occur in the Study Area and are typically associated with the axis of the fold structures. The Study Area includes additional major faults that may not be directly associated with folds.

Three cross sections shown in Figures 6 through 8 depict both the structural and stratigraphic controls both within and around the Study Area. Cross-sections A-A’ and B-B’ (Figures 6 and 7) are regional in nature, defined by the data in Burns et al. (2011); and cross section C-C’ is from Kharazzi (2023)[2] (Figure 8) and is based on well logs within the study area. Cross section A-A’ shows the fault-bounded anticlinal structures on the western boundary of the Study Area that characterize the western portion of Rattlesnake Hills and Toppenish Ridge. Cross section B-B’ shows the fault-bounded anticlinal structures on the eastern boundary of the Study Area that characterize the eastern portion of Rattlesnake Hills and Umtanum Ridge. Cross section C-C’ generally follows the length of the RID canal along the southern flank of the Rattlesnake Hills and shows the overall thickness of the various basalt flows and interbed members in the Study Area. The key points relevant to the ASR evaluation that are shown in the cross sections include the following:

- The Saddle Mountains Basalt is better exposed at the ground surface and therefore more capable of receiving and infiltrating precipitation to form groundwater recharge.
- A significant accumulation of “overburden” overlies the basalts, including the Ellensburg Formation.
- A significant discontinuity along Rattlesnake Hills resulted from high-angle faulting and separated the Yakima Valley from the Moxee Valley (Figure 6).

[2] Kharazzi’s study was funded by Groundwater Subcommittee of the YBIP.

- A significant discontinuity south of the Study Area boundary resulted from high-angle faulting along the Toppenish Ridge.

For the objectives of this study, the geologic setting can be characterized as a well-defined sequence of basalt flows and interbeds with significant structural discontinuities on the northern and southern boundaries of the Study Area that are likely to act as barriers to groundwater flow. The major basalt flow sequences (Saddle Mountains, Wanapum, and Grande Ronde Basalts) and the interbeds that separate them (Mabton and Vantage) are generally recognizable in well logs and provide reasonable definition of the boundaries and targeted recharge zones for an ASR system. Smaller scale structures and discontinuities are likely present within the Study Area, but a conceptual model based on the bounding structures along Rattlesnake Hills and Toppenish Ridge is more relevant at this phase of the study for evaluating the feasibility of ASR in the Study Area.

2.4 Hydrogeology

The geology described in Section 2.3 provides the setting for groundwater movement and occurrence within the Study Area. The regional hydrogeologic framework for the Yakima Basin is described in more detail by Vaccaro (2009), which describes the hydrogeologic units within the basin, the lateral and vertical extent of aquifers, the hydraulic characteristics of the aquifer units, hydrogeochemistry, groundwater flow patterns, water level trends, and groundwater use.

The key elements of the hydrogeology relevant for evaluating the feasibility of ASR in the Study Area are summarized below. The main topics include the following:

- Definition of aquifer units and their hydraulic properties
- Groundwater recharge and discharge
- Groundwater flow directions and trends in groundwater levels

2.4.1 Aquifer and Aquitard Units

The following hydrogeologic units, described generally from youngest (shallowest) to oldest (deepest), are found in the vicinity of the Study Area.

Upper Sedimentary Aquifer
The shallowest quaternary sediments are loose sands and gravels mostly along river channels and alluvial fans as reported by Jones (2006). These sediment deposits are typically well connected to ephemeral streams that emanate from steep uplands into flat lowlands and are generally less than 100 feet thick. While these sediment deposits may have significant storage capacity because of relatively high porosity, they receive and drain water quickly, which limits their ability to store water long term and are not considered feasible candidates for ASR.

The Ellensburg Formation is a semiconsolidated volcaniclastic sandstone aquifer that is an important drinking water source throughout the Yakima Basin. This aquifer is often in hydraulic continuity with surface waters in the Study Area, which makes it a possible candidate for surface aquifer recharge. ASR via injection in the Ellensburg Formation is also being evaluated as a water supply source for the City of Moxee. Within the Study Area, the Ellensburg Formation is not considered a viable candidate for ASR because the thickness and extent of the formation are variable, and the hydraulic properties and groundwater occurrence are not well understood.

Saddle Mountains Basalt Aquifer
The Saddle Mountains Basalt Aquifer contains multiple water-bearing and confining zones. Transmissive zones occur primarily within the fractured and brecciated flow tops and bottoms of individual basalt flows. The dense competent basalt interior zones between the flow tops and bottoms serve as confining units within the basalt, though flow may occur through major joints or fractures within the dense interior. In some areas, aquifers characterized as Saddle Mountains are contiguous with the Ellensburg Formation where it is interbedded with basalts. For example, in the Moxee area (north of the Study Area) Kirk and Mackie (1993) described an upper and lower aquifer zone in Saddle Mountains Basalt that included interbedded zones of sands and gravels.

Within the Study Area along Rattlesnake Hills, wells are completed within and often across all members of the Saddle Mountains basalt sequence (Elephant Mountain, Pomona and Umatilla). The upper basalt flow sequences of the Elephant Mountain and Pomona members are important sources of domestic water supply, while the deeper basalt flow sequence (Umatilla member) is often tapped for agricultural use. The Saddle Mountains Basalt is considered less viable for ASR in the Study Area. The hydrogeologic conditions in the Saddle Mountains Basalt are more complex due to the interbedded sequences of Ellensburg Formation, higher potential connectivity to surface drainages, and higher domestic groundwater use.

Wanapum Basalt Aquifer
The Wanapum Basalt Aquifer contains multiple water-bearing and confining zones. Transmissive zones occur primarily within the fractured and brecciated flow tops and bottoms of individual basalt flows. The dense competent basalt interior zones between the flow tops and bottoms serve as confining units within the basalt, though flow may occur through vertical joints or fractures. Within the Study Area, some wells are completed across all members of the Wanapum basalt sequence, and a few wells appear to be completed across both the Wanapum and lower section of the Saddle Mountains basalt. Interbedding of sedimentary units within the Wanapum is less extensive, and there are few, if any, locations where the Wanapum is able to discharge directly to surface waters.

The Wanapum Basalt Aquifer is primarily used for irrigation. A review of 93 well logs within the Study Area that were completed in the Wanapum Aquifer indicated that over 90% of the wells were drilled for irrigation or industrial use, and only 4% of the wells were drilled for domestic purposes. The uniform nature of the basalt, combined with a lack of surface discharge and a high percentage of agricultural use makes the Wanapum a preferred target for ASR injection and recovery for agricultural purposes.

Grande Ronde Basalt Aquifer
The lowermost basalt formation present in the Study Area is the Grande Ronde Basalt. Like the shallower formations, the Grande Ronde Basalt Aquifer contains multiple water-bearing and confining zones. The top of the Grande Ronde is about 2,000 feet bgs (Vaccaro, Jones, et al. 2009). The total thickness of the Grande Ronde is not well defined in the Study Area, as only one well was identified in the Study Area that was completed in this unit. The Grande Ronde Basalt Aquifer is a potential candidate for ASR but is less preferable than the Wanapum Basalt Aquifer because of the required depth to complete an ASR well (i.e., greater than 2,000 feet bgs).

2.4.2 Hydraulic Properties of the Basalt Aquifers

A wide range of hydraulic properties for the CRBG basalt aquifers is reported in several published technical reports by USGS and others. Due to the naturally complex structure of individual basalt flows (e.g., flow tops, dense colonnades, entablatures, flow bottoms, pillow zones), the estimated hydraulic properties are typically lumped into two categories: (1) flow tops and bottoms and (2) dense interior and entablature. In general, the dominate groundwater occurrence and flow is through the rubbly and/or brecciated flow tops and bottoms; whereas the dense flow interiors and entablatures are much less porous and much less transmissive (both vertically and laterally) compared to the basalt flow tops and bottoms.

Hydraulic properties estimated from well testing depend on the effective thickness of groundwater flow intervals intercepted by the well. The hydraulic conductivity of flow tops and bottoms, pillow zones, or other brecciated structures can be many orders of magnitude higher than in flow interiors and entablatures (Strait and Mercer 1987, Reidel, Johnson and Spane 2002). Transmissivity, which is the product of hydraulic conductivity and aquifer thickness, is typically estimated from pumping tests conducted in water supply wells. Determining the effective hydraulic conductivity from these tests can be challenging in basalts and often varies widely among different analysts. For example, an analyst may estimate hydraulic conductivity by assuming the entire thickness of the basalt formation (i.e., combined flow tops, dense interiors, and flow bottoms) that is open or screened in the well is equal to the aquifer thickness, which yields a smaller estimate of hydraulic conductivity compared to using only the combined thickness the flow tops or flow bottoms to estimate hydraulic conductivity.

USGS summarized the lateral and vertical hydraulic conductivities for the CRBG basalt and sedimentary units based on calibrated results from regional groundwater modeling in the Columbia Plateau (Vaccaro, Kahle, et al. 2015). Table 2 summarizes the hydraulic conductivities from the calibrated groundwater flow model developed for the Yakima River Basin Aquifer System (YRBAS).

Table 2: Hydraulic Conductivity of Primary Hydrogeologic Units in the Yakima River Basin

Lateral Hydraulic Conductivity, ft/d			
Hydrogeologic Unit	**Minimum**	**Maximum**	**Mean**
Saddle Mts, interflow zones	35.8	261	119
Saddle Mts, flow interiors	0.0005	0.0036	0.0017
Saddle Mts, effective value			**10**
Mabton Interbed	0.36	1.57	0.88
Wanapum, interflow zones	25.7	278	130
Wanapum, flow interiors	0.00007	0.00075	0.00035
Wanapum, effective value			**13**
Grande Ronde, interflow zones	4.28	91	23
Grande Ronde, flow interiors	0.00008	0.0015	0.0004
Grande Ronde, effective value			**2.3**
Vertical Hydraulic Conductivity, ft/d			
Hydrogeologic Unit	**Minimum**	**Maximum**	**Mean**
Saddle Mts, interflow zones	0.008	0.06	0.03
Saddle Mts, flow interiors	0.003	0.02	0.009
Saddle Mts, effective value			**0.01**
Mabton Interbed	0.002	0.01	0.006
Wanapum, interflow zones	0.05	0.5	0.25
Wanapum, flow interiors	0.00004	0.0005	0.0002
Wanapum, effective value			**0.025**
Grande Ronde, interflow zones	0.002	0.04	0.01
Grande Ronde, flow interiors	0.0002	0.005	0.001
Grande Ronde, effective value			**0.002**

Storativity estimates for Wanapum Basalt were summarized by Kahle (2011) based on previously reported values, with an overall range of 1.8×10^{-6} to 2.3×10^{-4} and a median value of 3.5×10^{-5}.

Influence of Basalt Flow Structures

As described previously, the flow structures within an individual basalt flow vary in thickness, extent, and hydrogeologic properties. Generally, the highest storage potential is in the interflow zones between basalt flows where vesicular flow tops or flow bottoms can be broken and rubbly, creating increased permeability and porosity. Flow bottoms can also consist of pillow structures which are often permeable. Although the basalt interiors are saturated, there is little storage volume in these portions of the basalt flows because of their low porosity which can be as low as 0.1%.

Faults and folds can also create hydrogeologic compartments within geologic units. At a basin-wide scale for the Study Area, the anticlinal structures along Rattlesnake Hills and Toppenish Ridge, combined with high angle faulting at the anticlines conceptually produces a "compartment" or "block" that likely laterally confines the groundwater within an area of approximately 620 square miles (Figure 9). Smaller compartments or blocks may exist within this regional structure from other smaller scale faults or structures.

Groundwater Recharge

Groundwater in the basalts of the Yakima Basin is recharged directly by infiltration from precipitation or snowmelt along the anticlinal ridges and from surface water along losing reaches of rivers where the basalt is exposed at the surface. The basalt aquifers are also recharged by downward leakage from the upper sedimentary and overburden aquifers. The estimated total mean annual recharge from precipitation and return flows from irrigation range from less than 5 to more than 20 in/yr in the Study Area (Kahle, et al. 2011). Higher recharge rates from irrigation are typically a result of inefficient irrigation methods or leakage from unlined irrigation canals.

Most recharge (from both irrigation and precipitation) enters the shallow Overburden, Ellensburg Formation, and near-surface exposures of the Saddle Mountains Basalt Aquifer. Therefore, with the exception of areas where the Wanapum is exposed at the ground surface, recharge does not typically produce direct deep percolation to the Wanapum Basalt Aquifer. Leakage from overlying aquifers is an indirect source of recharge to the Wanapum and is controlled by head differences between the Saddle Mountains and Wanapum aquifers.

Groundwater Discharge

Groundwater discharge from the basalts to the ground surface or surface waters can occur naturally at seeps or springs where basalt aquifers daylight at the ground surface. In the Study area, this form of direct groundwater discharge primarily occurs from the shallow overburden aquifers and the Saddle Mountains aquifers (particularly the shallowest flow members).

The Yakima River is an important regional groundwater discharge area. Because there are multiple aquifers (shallow overburden, Saddle Mountains, and Wanapum), the total amount of groundwater discharge is a complex function of hydraulic gradients and vertical hydraulic conductivities between each aquifer zone and between the shallowest aquifers and the Yakima River. The shallow overburden in the Yakima floodplain is in direct hydraulic continuity with the Yakima River. Shallow processes that affect baseflow discharge to the Yakima River are related to local recharge patterns, the structure and layering of the floodplain sediments, and hyporheic processes near or within the riverbed. The deeper basalt aquifers are in indirect continuity but provide inflow to the overlying aquifers and floodplain where there is an upward hydraulic gradient. The volume of this inflow is proportional to the magnitude of the hydraulic gradient between the two aquifers and the hydraulic conductance of the intervening aquitard. Even if this inflow volume is low, the maintenance of an upward hydraulic gradient can be a significant second-order process that ultimately affects the magnitude of baseflow discharge to the Yakima River from the shallower aquifer.

USGS conducted a comprehensive study of river-to-aquifer exchanges on the Yakima River (Vaccaro 2011) and estimated that the reach of the Yakima River on the southern boundary of the Study Area showed streamflow gains of as much as 30 cubic feet per second (cfs) per mile. This is consistent with the conceptual hydrogeologic model of both the basalt and sedimentary aquifers being bounded along Toppenish Ridge to the south by the associated high-angle faulting. Groundwater flow from the higher elevations along the Rattlesnake Hills toward the Yakima River would cause upward hydraulic gradients from the basalt aquifers to the floodplain, resulting in a higher rate of seepage compared to other portions of the Yakima River Basin where there is less confinement of the basalts along the Yakima River and a stronger component of eastward down-valley flow toward the Columbia River. The USGS study did not investigate the source of the higher streamflow gains in this reach, and it is likely a combination of basalt "upwelling" and other factors within the floodplain in this area.

Groundwater is also discharged via pumping from water supply wells, which is the primary cause for long-term declines in regional groundwater levels. Declining water levels in the Wanapum have reduced upward flow to the Saddle Mountains Basalt Aquifer (Vaccaro, Jones, et al. 2009), which may have reduced steady-state baseflow groundwater discharge to the Yakima River. In this regard, artificial recharge to the Wanapum and the associated recovery of groundwater levels would be expected to improve baseflow groundwater discharge to the Yakima River.

Groundwater Flow Patterns and Trends in Groundwater Levels

Groundwater levels have been monitored in numerous wells within the Study Area since the 1970s; many of these wells have records of more than 30 years. The discussion below is based on a review of data provided by the Washington State Department of Ecology (Ecology) for over 50 wells on the southern flank of Rattlesnake Hills (Figure 10).

Since 1964, groundwater elevations in the Saddle Mountains Aquifer ranged from 620 to 1,150 feet asl. Most wells in the Saddle Mountains and Wanapum aquifers evaluated for this study (80% to 85%) exhibit a long-term decline in water level in the range of about 1 to 3 feet per year (on average) with up to 260 feet of total decline over the past 30 years.

In the Wanapum Aquifer, groundwater elevations ranged from about 500 to 1,260 feet asl. Basin-wide, groundwater elevations are higher along Rattlesnake Hills and lower to the southeast toward the Yakima River. Figure 11 is a plot of groundwater elevations versus longitude for the Wanapum and Saddle Mountains aquifers. This plot is not synoptic and contains measurements from 2000 to 2019. The figure shows a generalized west to east regional hydraulic gradient from Rattlesnake Hills towards the Yakima River. In general, groundwater elevations decrease from about 1,000 feet asl in the west-northwest to 800 feet asl to the east-southeast in the Saddle Mountains Basalt; while groundwater elevations in the Wanapum Basalt generally decrease from about 900 feet asl in the west-northwest to about 550 feet asl in the east-southeast. Considering the discussion of vertical hydraulic gradients above, there is generally a modest downward gradient (100 feet) toward the Wanapum in the west-northwest and a stronger downward gradient (250 feet) in the east-southeast (nearest the Yakima River). This pattern suggests that there is downward leakage from the Saddle Mountains Aquifer to the Wanapum Aquifer in the east-southeast portion of the Study Area, which may be a cumulative result of groundwater levels lowering in the Wanapum Aquifer. Recovery of water levels in the Wanapum through ASR could reduce this gradient and potentially improve discharge from the Saddle Mountains Aquifer to the Yakima River.

2.5 Groundwater Balance for the Study Area

The historical declines in groundwater levels in the Yakima Basin are predominantly related to groundwater pumping, with the Rattlesnake Hills area experiencing some of the largest water level declines (Vaccaro, Jones, et al. 2009). The water-level decline in the Wanapum Aquifer within the Study Area is due to groundwater pumping exceeding the groundwater recharge to the Wanapum (which originates outside the Study Area) plus leakage from the Saddle Mountains Aquifer to the Wanapum Aquifer. The observed water level decline of 3 feet per year represents the loss of aquifer storage within the Wanapum Aquifer. The total loss of aquifer storage (as much as 150 feet of cumulative water level decline) is not reversible without artificial recharge. Similarly, the current rate of storage loss will not stabilize to a lower rate of decline without a reduction in pumping and/or an increase in artificial recharge.

The estimated total annual pumping in the Study Area is 54,000 acre-feet (AF). This is based on the water rights analysis presented in the USGS regional hydrogeologic framework for the Yakima Basin (Vacarro et al, 2006). This study estimated pumping based on water rights across the entire Yakima Basin (Figure 22 in Vaccaro, 2009). The total pumping estimates for each quarter township within the study were summed to arrive at the estimated annual pumping. The USGS pumping estimate did not distinguish which aquifer was being pumped. For planning purposes, we assumed that about one-third (20,000 AF) of the total annual pumping in the Study Area originates from the Wanapum Aquifer; therefore, an ASR system that could deliver at least 20,000 AF per year (AF/yr) on average could stabilize long-term groundwater decline in the aquifer and result in recovery (increase) in groundwater levels. It could also provide a “storage pool” of artificial storage that could be allocated on a year-to-year basis for consumptive use in conjunction with surface water deliveries. This allocation could also be conditioned on water-level targets (or storage levels) in the Wanapum Aquifer to stabilize leakage to or from the Saddle Mountains Aquifer. As described earlier, this could, in turn, provide benefits to streamflows in the Yakima River by reducing downward leakage from the Saddle Mountains Aquifer.

Further evaluation of regional groundwater level response to ASR injection/recovery will be needed to explore these effects. However, a design-level injection/recharge capacity from a system of ASR wells in the Wanapum Aquifer is needed, in addition to further characterization of hydraulic properties and structures within the basalt aquifer system. As described in Section 4, a reliable field study of ASR injection capacity and hydraulic response is not feasible with the current well infrastructure along Rattlesnake Hills. A well designed specifically for ASR is needed in the area to determine injection capacity and provide a foundation for further analysis of hydraulic responses. However, in the absence of site-specific data, an analysis of injection capacity and associated recovery scenarios using analytical models (see Section 3) provides a useful test of the current conceptual model and demonstrates some of the operating constraints of an ASR wellfield (i.e., well interference effects).

2.6 Geochemistry and Water Quality

2.6.1 Receiving Aquifer Matrix Geochemistry

The geochemistry of the receiving aquifer and the water quality characteristics of the source water and native groundwater in the receiving aquifer can affect both the operational and regulatory feasibility of MAR. The geochemistry of CRBG units have been well characterized by previous studies and are summarized in Tables A-1 and A-2 in Appendix A.

2.6.2 Receiving Aquifer and Groundwater Quality

Differences in groundwater geochemistry are the result of different residence times of water rather than the specific basalt unit in which they reside. Several studies have examined the chemical evolution of basalt groundwaters (Steinkampf 1989; Steinkampf and Hearns 1996). Typically oxygenated, acidic, carbon dioxide-charged precipitation and surface waters with a dilute calcium-magnesium-bicarbonate (Ca-Mg-HCO_3) signature enter the basalt. The main chemical reactions that impact the evolution of groundwater in CRBG aquifers are dissolution of basalt by carbonic acid and silicate hydrolysis, which leads to an increase in pH and silica (Vlassopoulos et al. 2009). Native groundwater concentrations are relatively high in dissolved silica because most of the active hydrologic system contains volcanic glass, a more soluble form of silica relative to other crystalline forms of silica (e.g., quartz and silicate minerals). Over time, precipitation and ion-exchange reactions remove Ca and Mg from the groundwater, replacing these cations with sodium (Na). Chemically evolved waters in the basalts are usually $Na\text{-}HCO_3$ type waters and are indicative of longer residence times, which are typically found in deeper aquifers and/or in downgradient areas of the Columbia Basin Plateau (Steinkampf 1989). Chemically evolved waters in the Grande Ronde formation also tend to have elevated fluoride concentrations due to leaching from the basalt matrix (Vlassopoulos et al. 2009).

Groundwaters in the Yakima Basin aquifer system, including in the CRBG, typically exhibit anoxic, aerobic conditions, which may contain nitrate. Anoxic, anaerobic conditions—indicated by the absence of nitrate and the presence of iron, manganese, and sulfate—are present in deep portions of the Yakima Aquifer system. Nitrate in shallow groundwater, particularly in the upper Ellensburg Formation, is a concern in the Lower Yakima Valley. Elevated nitrate levels have not been observed in Yakima basin basalts or in the Yakima River upstream of the diversion points at the Roza Dam. The primary source of nitrate is commercial agriculture, both fertilizer application for crops and animal waste from Concentrated Animal Feedlot Operations. Yakima County has created a Groundwater Management Area (GWMA) in the Lower Yakima Valley to address this issue in the shallower aquifer. This GWMA encompasses most of the Roza Irrigation District south of Rattlesnake Hills (Ecology 2010).

2.6.3 Yakima River Water Quality

The Yakima River upstream of the Roza Dam is characterized as a $Ca\text{-}Mg\text{-}HCO_3$ type water (USGS 2020). Ecology conducted a study of the water quality of the Yakima River above Selah, which included continuous monitoring for dissolved oxygen (DO), pH, specific conductance, and total suspended solids (TSS) at the Selah-Moxee Diversion (Urmos-Berry et al. 2021). Ecology also measured alkalinity, total organic carbon (TOC), ammonia, orthophosphate, total phosphorus, nitrate/nitrite as nitrogen (N), and total persulfate nitrogen. This work provided an initial baseline for the potential range of these water quality parameters at the diversion point for the Roza Canal. Near the Roza diversion dam, DO values fluctuated from around 11 milligrams per liter (mg/L) in the spring to around 8.0 mg/L in summer, and then up to about 12 mg/l in the fall. River pH was somewhat alkaline, with daily median values ranging from 8.0 to 8.5 (ranging between 7.3 and 9.2). Higher pH was associated with afternoon measurements during the summer and may be the result of increased photosynthetic activity from aquatic plants. Turbidity was generally less than 10 nephelometric units (NTU). Water quality graphs from the Ecology water quality studies are included in Appendix B.

Yakima River water quality has also been studied and monitored by USGS as part of its National Water Quality Assessment (NAQWA) project (Fuhrer et al. 2004) and by Ecology (Johnson and others 2010). The NAQWA study focused on evaluating the effects of agricultural activity on surface water quality from constituents of concern such as nitrate, phosphorous, fecal coliform, and pesticides. The Ecology study focused on pesticides and polychlorinated biphenyls (PCBs) that exceeded the total daily maximum load for the Yakima River in 2007 and 2008. Both studies concluded that irrigation returns have the largest impact on water quality in the Yakima River due to elevated levels of suspended solids, which in turn lead to increases in turbidity and concentrations of pesticides and PCBs.

2.6.4 RID Canal Water Quality

The water quality in the RID canal is essentially the same as that of the Yakima River. There is limited water quality data along the RID canal for conventional anions/cations and trace metals. The RID manages aquatic plants, including algae, in the main canal with regular application of the herbicides acrolein, endothall, and copper. The application is publicly posted ahead of time and dyes are released into the water immediately before and after to signal the presence of the herbicides in the water. The RID compiles annual reports, in which the treatment events and locations are given along with the target herbicide concentration and total amount of product used. Reports from 2012 to present are available.

Regulatory Criteria for Water Quality

Groundwater quality reported by Steinkampf (1989) for aquifers present in the Wanapum basalts is summarized in Table A-3 in Appendix A. Comprehensive groundwater quality samples were also collected as part of ASR feasibility study for the Kennewick ASR-1 Well (Tables A-4). Based on the results from these studies, the native groundwater quality in the Wanapum is expected to meet the Groundwater Criteria in the Washington Administrative Code (WAC) 173-200 with the exception of arsenic and pH. For arsenic, most reported values were non-detect (i.e., less than 0.01 or 0.0005 mg/L), but the detection limit was above the criterion of 0.00005 mg/L. One sample reported for Kennewick ASR-1 was reported at 0.0004 mg/L. Based on Steinkampf (1989), the overall range in pH for 410 samples collected from the Wanapum was 6.1 to 9.4 standard units with a mean pH value of 7.4. The mean value was within the pH limits, but the overall range in pH was both below and above the Groundwater Criterion of 6.5 to 8.5 standard units.

3. ASR CONCEPTS AND TERMINOLOGY

This section describes basic terminology used to describe ASR operations and the anticipated response in the aquifer.

3.1 ASR Phases

ASR typically has three phases that make up one cycle, which are described below.

3.1.1 Recharge (Injection) Phase

The recharge (or injection) phase is the period when water is pumped into the aquifer through a well. During recharge, water levels in the injection well rise as water enters the aquifer via the screened, perforated, or open-hole portions of the well. Water levels in wells surrounding the injection well increase in response, which is governed by the hydraulic properties of the aquifer (i.e., transmissivity and storativity). Changes in water quality require mixing of water molecules, so there is a different radius-of-influence for water quality effects (which can be governed by advective, dispersive, and diffusive movement) compared to water level effects (i.e., pressure response) from recharge.

3.1.2 Storage Phase

The storage phase is the period when the recharged water resides in the aquifer until it is pumped out. After recharge, the increased water level near the well will subside as the water spreads laterally and stabilizes at a new equilibrium water level. The equilibrium water level during the storage phase will depend on regional hydraulic gradients and aquifer properties and is expected to be higher than the "static" water level at the start of the ASR cycle. With respect to water quality, the recharged water (injectate) does not immediately mix completely with the native groundwater, but rather forms a "bubble" that displaces the native groundwater with the injected surface water. Mixing of the native and injected water occurs initially at the margins of the bubble, which then continues to interact with the native groundwater and surrounding aquifer material over time. Full mixing of the bubble with native groundwater may or may not occur, depending on when and where ASR recovery occurs and the hydraulic characteristics of the aquifer. In this regard, water quality impacts from ASR injection are to some degree reversible if the injected water is recovered before full mixing occurs, providing a level of risk management as long as there is adequate monitoring to determine if negative impacts are occurring. Over long periods of time, some aquifers have been shown to become "re-conditioned" such that water quality and geochemical interactions reach a new steady state condition that is improved compared to the original condition (Pyne 1994; Federal Emergency Management Agency 2017).

3.1.3 Recovery Phase

The recovery phase is the period when stored water is pumped for beneficial use. Stored recharge water can be recovered from the ASR well or can be recovered from a different well completed within the zone of groundwater storage. During recovery, water levels in the ASR well and surrounding wells will decrease to a level that is governed by the pumping rate and hydraulic properties of the aquifer. The resulting water level at the end of an ASR cycle depends on how much water is recovered. ASR systems are typically operated so that recovery does not exceed the amount of water injected and may be less than what is injected to ensure that water levels do not decline below the original static water level at the start of the ASR cycle. The volume of water left in the aquifer at the end of an ASR cycle is sometimes called a “leave behind.” If no recovery occurs over multiple injection cycles, the concept of “carry-over” is introduced. Carry-over allows for the volume of injected water from previous ASR cycles to be recovered during future cycles. For an ASR system that is operated over multiple cycles of injection and recovery, the volumes of “leave-behind” and “carry-over” become part of an accounting mechanism that is designed to protect beneficial uses. From a water quality perspective, if the water is recovered after a short period of storage, the recovered water quality will largely represent the surface water that was injected initially. The longer the injected water remains in storage, the more fully mixed the recovered water will be. The term “co-mingled” in this report is used to describe water that has been recharged and then mixed with native groundwater.

3.2 Primary Factors that Influence ASR Feasibility

The feasibility of an ASR system with the goal of increasing groundwater storage and stabilizing groundwater levels are primarily dependent on (1) source water availability and infrastructure; (2) the hydrogeologic conditions of the target aquifer; (3) the hydraulic performance of the well or wellfield; and (4) hydrogeochemistry, such as the compatibility of the source water with native groundwater and geochemical compatibility with the aquifer matrix.

3.2.1 Source Water Availability and Infrastructure

The Kachess/Keechelus/Cle Elum reservoir system is part of the Yakima Project operated by the United States Bureau of Reclamation and is the primary source of surface water contemplated for this ASR concept. The combined storage capacity of this reservoir system is 833,700 AF; individual storage capacity of each lake is listed below:

- Kachess Lake: 239,000 AF
- Keechelus Lake: 157,800 AF
- Cle Elum Lake: 436,900 AF

Water from the Yakima Project is diverted to RID’s main canal system at the Roza Diversion Dam, located on the Yakima River approximately 10 miles north of Yakima. The RID distribution system provides a practical means of delivering water to prospective ASR wells in the Study Area. The irrigation season is from April 15 to October 15. After the irrigation season, the canal is drained for the remainder of the year for maintenance and to protect the canal from freeze damage. The RID’s main canal has a maximum capacity of 1,300 cfs, which is typically not needed until the middle of June (Figure 12). Therefore, the RID’s main canal has adequate excess capacity for delivery of at least 20,000 AF per month (AF/month) (112 cfs) before the beginning of peak irrigation operations in June. Conceivably, other irrigation distribution systems, such as the Sunnyside canal, could also provide delivery capacity if ASR operations were considered adjacent to these canals.

3.2.2 Hydrogeologic Conditions of the Target Aquifer

The hydrogeologic conditions of the target aquifer that influence the feasibility of ASR include the following:

- Aquifer type (unconfined, semiconfined, or confined)

- Effective hydraulic parameters (i.e., transmissivity and storativity), which will govern the radius-of-influence of the ASR well(s) for the volume and duration of injected water
- Groundwater levels and hydraulic gradients
- Aquifer boundaries (e.g., low-flow boundaries from geologic structures or changes in lithology, or recharge boundaries associated with continuity with surface waters or leakage from adjacent water bearing zones)

Generally, the water level response in a confined aquifer (typically with low storativity) will have a larger radius-of-influence compared to an unconfined aquifer (typically with high storativity). Bounded aquifers are typically more favorable for ASR when the goal is to increase late-season water supply and stabilize groundwater levels due to the compartmentalization of the aquifer; this allows for high efficiency in recovery of injected and stored water because the injected groundwater is less likely to flow out of the targeted aquifer.

3.2.3 Hydraulic Performance of the ASR Well or Wellfield

The amount of head build-up during injection can be a limiting factor for an ASR well or wellfield. If the build-up of head in the injection well is too high (i.e., above the top of the well casing) then additional engineering requirements are required to allow for a pressurized injection system to maintain higher heads. A gravity-driven injection system is preferable, so for initial conceptual design, the peak head build-up in an injection well should be below the ground surface. For this reason, wells with deep groundwater levels are typically preferable to wells with shallow groundwater levels. The amount of head build-up in an injection well is proportional to the hydraulic properties of the aquifer and the injection rate, and also depends on well construction, operation, and maintenance. Wells with lower efficiency produce higher build-up of head for the same injection rate compared to higher efficiency wells. Well inefficiency can result from poor well design or from suspended solids or other water quality factors that cause clogging of the screened or open interval of the well during injection. The hydraulic performance of a well can be evaluated through step-rate pumping tests by incrementally increasing the pumping rate for set duration of time and analyzing the changes in drawdown during each step. Head build-up can also be predicted for a hypothetical ASR well using analytical methods that incorporate aquifer properties, injection rates, and well efficiency factors.

3.2.4 Hydrogeochemistry

Water quality can change in and around the injection well resulting from ASR. When water with a different chemical composition is mixed with native groundwater, chemical reactions can occur that cause either precipitation and/or dissolution of minerals in the aquifer matrix. This can result in precipitates forming in the well bore that can clog the well and/or result in changes to dissolved concentrations of regulated constituents (particularly metals) in the mixing zone between injected water and native groundwater. Chemical reactions caused by injection water mixing with native groundwater occur initially within the radius-of-influence, which is conceptualized as the "bubble" of injected water around the injection well during the storage phase of ASR. The size of the bubble (i.e., its radius-of-influence around the injection well) is based on how far water molecules of injected water move away from the injection well; this radius is not the same as the pressure response and is typically much smaller, as it is a function of the total volume of injected water, aquifer properties (primarily porosity), preferential pathways of flow, and regional hydraulic gradients in the aquifer. The bubble will tend towards a geochemical equilibrium over time as it mixes with native groundwater during the storage phase. Similar to the hydraulic performance of the well, geochemical equilibrium can be evaluated through pumping tests and geochemical modeling.

4. FIELD INVESTIGATIONS

Three field investigation programs were initiated as part of this project:

- The first field study was a reconnaissance and mapping study that was carried out and documented as part of Task 2. This field work is summarized in Section 4.1 and the Task 2 report.
- The second field study was focused on field testing of wells to evaluate the hydraulic properties of the Wanapum Basalt within the Study Area. This field work is summarized in Section 4.2
- The third field study was focused on water quality in both the Roza Canal and selected wells within the Study Area. This field work is summarized in Section 4.3

4.1 Field Reconnaissance

A two-day field reconnaissance was conducted that included a tour by RID of the RID's main canal. As part of the reconnaissance task, the field team examined bedrock outcrops and field relationships of basalt flows and associated structures.

Following the field reconnaissance, an interim report (Task 2 Report) was developed that summarized the regional hydrogeologic setting, opportunities for groundwater storage (surface infiltration and direct injection), and a proposed work plan for additional field investigation, which was originally focused on field testing of existing wells completed in the basalt and water quality relevant to groundwater storage.

4.2 Well Hydraulic Testing

Hydraulic properties of the Wanapum Basalt vary across the Columbia Plateau, and measuring them through a pumping test in the Study Area was an objective of this project. Pumping test data and the resulting calculations of hydraulic properties are affected by a variety of specific details regarding which wells are tested, the completion parameters for individual wells, and the testing procedures used. The first element of this task was to identify existing wells in the Study Area that were completed in the Wanapum and request permission from landowners to conduct pumping tests to calculate hydraulic properties. It was also hoped that involvement of local landowners in the testing would further promote the concept of managed aquifer recharge and engage them more meaningfully in solutions to water-level declines in the study area.

Well logs from Ecology's Well Report Viewer and the USGS stratigraphic well compilation (Burns and others 2013) were screened for the deepest wells within the RID (126 wells). Logs were located for these wells where possible and reviewed for information on stratigraphy and well ownership. An email was then prepared and sent to all landowners in the RID to explain the goals of this study and to ask landowners if they would offer their wells for testing purposes. The email was sent by the RID. A total of eight landowners with one or more wells responded favorably and several meetings were then held with each landowner (in person) to further describe the project and perform field inspections of their wells. The minimum requirements for testing were described to them: a flow meter, access port, and (preferably) a sounding tube. A summary of each landowner and associated well inspection is provided below.

- **Landowner 1:** This landowner offered five wells for inspection. The wells ranged in depth from 1,200 to over 2,000 feet, and completion in the Wanapum was confirmed from the well logs provided. Only one well had a flow meter. Access ports were present on three of the wells, but one of them was blocked at the top of the access port. A water-level measurement was attempted in the other two wells with access ports, but one of them caused extreme fouling of the sounding tape, and the other caused tangling of the tape so no water level could be measured. After consulting the landowner, the remaining two viable wells ("Greenhouse" and "Nillson") were selected for testing, and the landowner agreed to make well modifications to the Greenhouse well, including a new flow meter and removal of the access port blockage. The Nillson Well had both an access port (but no sounding tube) and a flow meter. Communication with the landowner continued during the installation of the flow meter and access port in the Greenhouse well. However, when the field testing was scheduled and the well was visited to install a pressure transducer, only the flow meter had been installed and the access port was still blocked. By this time, the irrigation season was about to begin and it was not possible to fix the access port, so the Greenhouse well was eliminated from the testing program.
- **Landowner 2:** This landowner offered two wells for inspection. The wells were 1,100 and 2,100 feet deep, and completion in the Wanapum was confirmed for the deeper well. Neither well had a flow meter, and the shallower well had no pump as it was a back-up well. The landowner was willing to consider installing a flow meter on the primary well, but the configuration of the piping would have required extensive modification to allow proper pipe runs for an inline flow meter. After further consultation with the landowner, the back-up well was offered for use as a monitoring well during pumping of the Greenhouse and Nillson wells. A water level was obtained from the backup well; an agreement was signed with the landowner for monitoring in this well; and a pressure transducer was purchased for installation. The pressure transducer was installed and began taking readings, but the readings were not consistent with the hand-measured water level. Attempts to retrieve the pressure transducer were unsuccessful, and the cable to the transducer broke. The well owner then withdrew the well monitoring agreement.
- **Landowner 3:** This landowner offered three wells for inspection. The wells ranged in depth from 1,200 to over 2,000 feet, and completion in the Wanapum was confirmed from the well logs provided. One well had a flow meter and an access port that was inaccessible for a water-level sounder but not a pressure transducer. The landowner was willing to consider modification of the access port. The second well had no flow meter or access port, and the third well was located beyond standard electrical service and would require a significant service fee to start the pump. An agreement to install a transducer and test the first well was offered to the landowner, with the condition of modifying access port. After several weeks, the landowner withdrew support for the testing, based on advice from legal counsel.
- **Landowner 4:** This landowner offered four wells for inspection. The wells ranged in depth from 1,000 to over 3,000 feet, and completion in the Wanapum was confirmed for two of the wells from the well logs provided. The deepest well was completed in the Grande Ronde and the shallowest well was completed in the Saddle Mountains. Neither Wanapum well had a flow meter and only one of them had an access port. An agreement to install a transducer and test the well with the access port was offered to the landowner,

with the condition of installing a flow meter. After several weeks, the landowner withdrew support for the testing, based on further consultation with farm partners.

- **Landowner 5:** This landowner offered one well for inspection. The well was 2,000 feet deep; completed in the Wanapum; and pumping was generator-operated. The well had a flow meter and an access port with a sounding tube. An agreement to install a transducer and test the well was offered to the landowner. After several weeks, the landowner withdrew support for the testing, based on advice from legal counsel.
- **Landowner 6:** This landowner offered one well for inspection. The well did not have a flow meter and there was no access port. After further consultation, this landowner was not willing to make well improvements to allow testing.
- **Landowner 7:** This location was a Washington State Department of Natural Resources' (DNR) lease property and had one well that was completed in the Wanapum. The well had a flow meter and an access port. Discussions were initiated with DNR, and a special permit was initiated to conduct the testing. However, the DNR permit required information and approval from the leasee, who was contacted several times by DNR. The leasee never responded, so the well was removed from consideration.
- **Landowner 8:** This location was also a DNR lease property and had one well that was completed in the Wanapum. The well had a flow meter but no access port. Discussions were initiated with DNR, but the leasee never responded, so the well was removed from consideration.

After the disappointing results related to landowner cooperation, well modification mishaps, and general difficulties with accessing the wells, the well testing program was essentially abandoned with the exception of testing the Nilsson well. As Murphy's law would have it, this test was also unsuccessful. During testing, controlling the Nilsson butterfly valve, which controls the flow rate, was exceptionally difficult, and a constant flow rate could not be established for any length of time. Furthermore, the observed drawdown in the well was very high, which appeared to be predominantly related to well completion history and modifications, and not the hydraulic properties of the Wanapum formation. And as a final nod to bad luck, after the testing, the pressure transducer could not be removed from the well and the cable to the transducer broke.

Although the well testing program did not yield any useful hydraulic testing data, it clearly demonstrated two key points for consideration of a regional ASR program in the Study Area:

1. First and foremost, it will not be possible to use an existing well to conduct even a preliminary site-specific hydraulic analysis of ASR in the Study Area. A new well, specifically designed for ASR, is needed to advance this concept. This limitation also applies to installing monitoring wells. The access port and transducer difficulties indicate that specifically designed monitoring wells would be much more reliable and less risky than using existing wells for continuous monitoring.
2. Despite initial enthusiasm from the landowners contacted for this study, it is unlikely that landowners in the study area would allow a new ASR test well, or any future ASR wellfield wells, to be installed on their property. There are a variety of reasons for this, ranging from landowner technical capability, trust, and legal uncertainty surrounding the ASR concept and its implications, and (put simply) landowners have many other higher priorities to operate their lands. The most feasible owner for an ASR test well or any

subsequent future ASR wellfield would be the RID or some form of viable partnership with RID so that wells can be installed along the RID canal access road or on easements with landowners adjacent to the RID canal.

Although site-specific data on hydraulic properties within the Study Area was not obtained, existing information is still sufficient to describe and evaluate the feasibility of a regional ASR system and its potential effects. Although the analysis presented in Section 5 is based on regional data, it incorporates a range of hydraulic properties and is still sufficiently robust to decide whether to advance the ASR concept to a pilot testing phase whereby an ASR test well would be installed and tested; first for hydraulic response through pumping only, and then for hydraulic and water quality response through injection.

4.3 Water Quality

The sampling and laboratory methods for obtaining water quality data are described briefly in this section. A more detailed description of the field and laboratory methods including quality assurance/quality control protocols is given in the project's quality assurance project plan (QAPP) (Ecology 2023).

Water sampling sites are shown in Figure 13. Surface water samples were collected from five sites: the Yakima River just upstream of the Roza diversion (the input water to the Roza Canal), and then four locations along the Roza Canal to characterize overall water quality of MAR source water and to document any changes in water quality that might occur as the water moves through the canal. The five surface water sampling sites are as follows:

1. Yakima River (YR) at Roza Campground, river mile (RM) 129
2. Roza Canal (RC1): ramp near Deeringhoff Road, mile post (MP) 21.8
3. Roza Canal (RC2): Highland Drive Bridge, MP 39.3
4. Roza Canal (RC3): N. Outlook Road Bridge, MP 49.2
5. Roza Canal (RC4): N. County Line Road Bridge, MP 69.8

Samples were collected from these five sites on April 6, July 7, and October 5, 2023.

Additional samples were collected for suspended solids analysis on May 6 and May 22, 2023, from Yakima River and the first two Roza Canal sites (RC1 and RC2).

Groundwater from the Wanapum Basalt aquifer was sampled from the Nillson Well, a 1,270-foot deep well on the northern slope of Rattlesnake Hills, on March 17 and August 30, 2023. The March sampling occurred immediately after the attempted pumping test at this well but before the well was in use for irrigation. In contrast, the well was in full operation for irrigation at the time of the August sampling.

Surface water samples were collected from bridges using a Wildco horizontal water sampler at three sites (RC2, RC3, RC4) and from ramps at the YR and RC1 sites. The Nillson Well groundwater sample was collected from a spigot located approximately 20 feet away from the wellhead. Field measurements of pH, oxidation reduction potential (ORP), temperature, electrical conductivity, and DO concentration were made with standard meters at the time of sampling. For the groundwater sample, these measurements were made several times to reach stable readings. Further details on sampling protocol, including containers used, holding times, chain of custody procedures, etc., are given in the project QAPP (Ecology 2023).

In addition to the field measurements, which were made on all samples at the time of collection, water samples were analyzed in the laboratory for a suite of water quality and water chemistry parameters. Some measurements were made in the Murdock Research Laboratory at CWU, while others were performed at accredited laboratories in Washington. A list of the parameters, the laboratory, and method/instrument used for each parameter is given in Table 3. General chemistry parameters were measured on all samples. Solids, nutrients, and bacteriological measurements were made on all surface water samples. Nutrients were also measured on the March groundwater sample. Pesticide measurements were made on two of the October Roza Canal samples (RC1 and RC3). Details of the laboratory measurements including detection limits, quality assurance/quality control protocols, data management, etc., are given in the project QAPP (Ecology 2023).

Table 3: Water Quality Parameter List and Laboratory Methods/Instruments

Water Quality Parameter	Laboratory[1], Method/Instrument
Field Measurements	
pH, temperature, ORP	Hanna Instruments multimeter
Electrical conductivity	Orion 135 conductivity meter
DO	YSI DO meter
General Chemistry	
Alkalinity	CWU, Titration, USEPA 310.1
Major Anions: bromide, chloride, fluoride, nitrate-N, sulfate	CWU, Metrohm Ion Chromatograph, USEPA 300.0
Major Cations: calcium, magnesium, potassium, sodium	
Dissolved silica	CWU, Agilent 5110 Inductively Coupled Plasma Optical Emission Spectrometer, USEPA 6010D
Trace Elements: aluminum, arsenic, barium, cadmium, chromium, cobalt, copper, iron, lead, manganese, molybdenum, nickel, selenium, uranium, vanadium, zinc	CWU, Agilent 8900 Triple Quadrupole Inductively Coupled Mass Spectrometer, USEPA 200.8
Stable isotopes: oxygen-18, deuterium	CWU, Picarro L2130-I Isotopic H_2O Analyzer
Other Water Quality	
Solids: total suspended solids, turbidity	AmTest Laboratories, SM2540D, USEPA 180.1
Sediment size distribution	CWU, Malvern Mastersizer 3000
Nutrients: TOC, dissolved organic carbon, ammonia-N, total Kjelstad nitrogen, nitrate + nitrite, total phosphorus	AmTest Laboratories, SM5310B, USEPA 350.1, USEPA 351.2, USEPA 353.2, SM 4500PF
Bacteriological: E. coli, fecal coliform	LabTest, SM9222D, 9222G
Pesticides: Endothall, Acrolein	AmTest Laboratories, USEPA 548.1, USEPA 624.1

1. Laboratories used are Murdock Research Laboratory at Central Washington University (CWU, www.cwu.edu/academics/geology/facilities/murdocklab/index.php); AmTest Laboratories in Kirkland, Washington (amtestlab.com); and LabTest in Yakima, Washington (labtestwa.com).
USEPA: United States Environmental Protection Agency

5. HYDROGEOLOGIC ANALYSIS AND MODELING

An overall hydrogeologic conceptual model for the Study Area was prepared using available hydrogeologic data described in Section 2.4 in conjunction with additional field investigations described in Section 4. Based on the conceptual model, the feasibility of a large-scale ASR system in the Study Area was evaluated using a spreadsheet model to predict the head build-up and drawdown during injection, storage, and withdrawal from a multiwell ASR system. Results from this analysis are included in Appendix C. A hypothetical assessment of long-term ASR operations was also prepared based on the results of the hydraulic analysis and historical data (Section 6).

Further details of each component of the conceptual hydrogeologic model and hydraulic analysis are described in the subsections below.

5.1 Conceptual Hydrogeologic Model

The conceptual hydrogeologic model for ASR in the Study Area considers the regional hydrogeology, specific well and aquifer parameters in the vicinity of an ASR well, and the overall groundwater balance within the Study Area. Key aspects of the regional hydrogeology with respect to the ASR conceptual model for the Wanapum Aquifer in the Study Area include the following:

- Aquifer type and domain
- Groundwater occurrence
- Hydraulic gradients
- Hydraulic parameters

5.1.1 Aquifer Type and Domain

The Wanapum Aquifer target area is confined to an aerial extent bounded to the north by the Ahtanum Ridge and Rattlesnake Hills and to the south by Toppenish Ridge and Horse Heaven Hills; these boundaries generally trend west to east. The western end of the aquifer is bounded by the topographic highs west of White Swan and to the east by the Yakima River near Benton City (a total length of approximately 60 miles). The overall average thickness of the Wanapum Basalt in the Study Area is 600 feet, which includes a combination of 8 to 10 flow tops/bottoms or interflow zones, and dense flow interiors (Steinkampf 1985). The range of thickness of the more permeable flow top/bottom and interflow zones is assumed to be 75 to 150 feet.

5.1.2 Groundwater Occurrence and Hydraulic Gradients

Groundwater elevations are locally higher along the margins of the boundaries to the north and south and lower toward the axis of the valley. Generally, groundwater elevations are higher in the west (average of about 800 feet asl) and lower in the east (average of about 600 feet asl) toward the Benton City; thus, the overall direction of groundwater flow in the Wanapum Aquifer is to the east-southeast.

Vertical hydraulic gradients are generally downward in the Study Area, where a portion of groundwater flow is from the overlying Saddle Mountains Aquifer to the Wanapum Aquifer (Figure 11).

5.1.3 Hydraulic Parameters

Hydraulic conductivity (K) of the flow tops in Wanapum Aquifer in the Study Area is assumed to range between 25 to 280 ft/day with an average of 130 ft/day (Table 2). The overall "effective" K of the entire thickness of the Wanapum Basalt is 13 ft/day based on a weighted-average of the flow tops and dense flow interiors (Vacarro 2015).

Storativity of the Wanapum Aquifer ranges from 1×10^{-3} to 1×10^{-5}. Porosity is estimated to be 5% for the flow tops and interflow zones, and 0.1% for the dense flow interior portions of the basalt flow.

5.2 ASR Wellfield Hydraulics Analysis

The hydraulic response of a well or wellfield and the surrounding aquifer to ASR injection is a key factor for the feasibility of ASR because it determines the maximum injection rate that can be sustained in an ASR well or wellfield. During injection, the water level in the well will rise and ideally not reach the ground surface. The maximum injection water level is a function of the injection rate, the well construction, and the hydraulic properties of the aquifer.

An analytical spreadsheet model was developed to evaluate a multiwell ASR system in the Study Area. The mathematical approach is based on the principal of superposition, which calculates the arithmetic summation of the Theis (1935) solution for 20 individual injection wells to simulate an ASR wellfield. A depiction of the Theis superposition method is shown in Figure 14. The analytical solution includes the following simplifying assumptions:

- The Wanapum Aquifer is confined, homogenous, isotropic, and of infinite aerial extent (i.e., no boundary conditions).
- Groundwater flow to the wells is horizontal.

The model assumed the injection wells had a 16-inch diameter and were evenly spaced 10,000 feet apart in a linear pattern over about 38 miles. The line of injection wells was intended to evaluate an ASR system that generally follows the RID's main canal from Konnowac Pass toward Benton City.

Three cases were simulated for a range of hydraulic parameters, as summarized in Table 4. For each case, the model simulated a recharge period of 120 days with each well injecting 1,900 gallons per minute (gpm) for a total pumping volume of about 20,000 AF for one ASR cycle. The static groundwater elevation (or potentiometric surface elevation because of confined conditions) at each well was assumed to be 700 feet asl (average of 800 and 600 feet asl). The average ground surface elevation along the RID main canal was assumed to be 1,100 feet asl, resulting in a maximum head build-up target of 400 feet.

Table 4: ASR Wellfield Analytical Model Inputs

Model Input	Case 1 Low S Low T	Case 2 High S High T	Case 3 Effective S and T
Aquifer transmissivity, T (ft^2/day)	10,000	20,000	7,800
Storativity, S (dimensionless)	1×10^{-5}	1×10^{-3}	5×10^{-5}

ft^2: feet squared
S: storativity
T: transmissivity

Case 1 represents the "worst case" with conservative hydraulic parameters (low transmissivity and low storativity). Transmissivity (9,750 ft^2 per day) was based on a mean K of 130 feet per day for flow tops/bottoms and interflows zones with an aquifer thickness of 75 feet (low range of combined thickness of flow tops/bottoms/interflows).

Case 2 represents "best case" hydraulic parameters high transmissivity and high storativity. Transmissivity (19,500 ft^2 per day) was based on a mean K of 130 feet per day and aquifer thickness of 150 feet (high range of combined thickness of flow tops/bottoms and interflow zones).

Case 3 represents the "planning level case" using effective hydraulic parameters reported by Vaccaro (2015) which assumes an aquifer thickness of 600 feet (i.e., equal to the total average thickness of Wanapum Basalt) and a thickness-weighted K of 13 feet per day. This is equal to a T of 7,800 ft^2 per day. The hydraulic responses to injection of water is more sensitive to storativity than any other input parameter. Although the T for Case 3 is less than Case 1, the storativity is higher by a larger degree, resulting in more storage capacity (and therefore less hydraulic head build-up) than Case 1.

Figures C-1 to C-3 in Appendix C present the predicted potentiometric surface elevations in the Wanapum Basalt based on the analytical model results for the three cases. These results assume one recharge (injection) period of 20,000 AF. Each case also simulated the theoretical head build-up in each well assuming a well efficiency of 100% and 50%.

For all cases, the predicted head build-up remained below 400 feet bgs after 120 days of injection and assuming 100% well efficiency.

For Case 1, a 20-well ASR system, with wells spacings of 10,000 feet apart, produces predicted build-up of head at individual wells within 10 feet of ground surface (almost 400 feet of head build-up) assuming a well efficiency of 50%. Less head build-up (which would be more favorable) would occur with higher well efficiency, larger well spacings, or lower injection rates. A well efficiency of greater than 50% would be expected for a properly designed ASR well.

For Case 2, a 20-well ASR system, with wells spacings of 10,000 feet apart, produces predicted build-up of head at individual wells of about 100 feet (300 feet bgs), assuming a well efficiency of 50%. Higher head build-up would be possible for this scenario, which could reduce well spacings or increase injection rates at each well and reduce construction and operation costs. A well efficiency of greater than 50% would be expected for a properly designed ASR well, which could allow further reduction in well spacings or increases in injection rates.

For Case 3 (effective aquifer parameters), a 20-well ASR system, with wells spacings of 10,000 feet apart, produces predicted build-up of head at individual wells of about 360 feet (40 feet bgs), assuming a well efficiency of 50%. The general potentiometric surface elevation is about 950 feet asl in response to one ASR cycle, with a maximum predicted head build-up about 40 feet below ground surface.

Based on this analysis, injection of 20,000 AF over a 3-month period from a 20-well ASR system appears feasible. However, for “worst case” hydraulic properties, head build-up may approach the ground surface and optimization of the number, efficiency, and spacing of injection wells will need to be carefully considered. For the “best case” hydraulic properties, head build-up is low enough that a system of fewer wells, closer well spacings, and higher injection rates could be considered. The configuration of wells and associated injection rates should be analyzed further after testing of an ASR pilot well.

6. OPERATIONS ANALYSIS AND MODELING

This section describes a hypothetical time history of how an ASR system might operate year-after-year and provides a first approximation of potential total volumes of water that could be managed via ASR over a long period of time. The generalized approach to the exercise was to combine the injection and withdrawal capacity of a theoretical ASR wellfield with potential constraints on the availability of surface water and demand for ASR recovery during dry years. A hypothetical long-term (40+ years) water budget of ASR operations was prepared to illustrate how 20,000 AF/yr of surface reservoir water, conveyed during the spring (March-May) to an ASR wellfield, could be stored in, and selectively recovered from, the Wanapum Aquifer within the area of the RID main canal. The intent was to demonstrate that a regulated ASR program using a modest but consistent late winter delivery of surface water from the Yakima River can restore storage volumes to the Wanapum Aquifer while also providing valuable beneficial use for agriculture during dry years.

The water balance analysis is based on historical monthly storage volumes from 1981 to 2023 in the Kachess, Keechelus, and Cle Elum reservoirs to account for (in general) past year-to-year variability in surface water availability and historical delivery patterns from the reservoirs. There are numerous simplifying assumptions that are necessary to produce this analysis. The intent of the analysis is not to propose specific ASR operations scenarios, but to provide an example for demonstration and discussion with potential stakeholders or project sponsors for an ASR pilot study.

The water balance model was developed in an Excel spreadsheet and uses simplified rules for when surface water is available for injection and when ASR storage is made available for recovery. The model does not incorporate water rights, pro-rationing levels, reservoir "flip-flop," any other specific reservoir operational considerations, nor does it incorporate climate change predictions. The model also does not simulate water-level responses in the aquifer or any other aquifer characteristics that might constrain injection, storage, and recovery volumes. Essentially, the analysis produces a high-level "what-if" example of what a surface water delivery and ASR system might have "looked like" had it been in operation from 1981 to 2023. To use the common Chinese proverb that "*the best time to plant a tree was 20 years ago,*" this demonstration is intended to show how much ASR injection, storage, and recovery might have accrued, had an ASR program been established in 1981.

6.1 Hypothetical ASR Injection Operation (1981 to 2023)

Source water for ASR injection operations would originate from the Kachess/Keechelus/Cle Elum reservoir system via the Yakima River and RID canal. The model applies simplified operating assumptions for delivery of water for ASR injection. The model does not distinguish between the waters from the Kachess, Keechelus, and Cle Elum reservoirs for ASR delivery (i.e., the three reservoirs are treated as one source). The model also assumes no canal capacity limitations for conveyance of surface water for ASR injection.

Surface water is available for ASR during the months of March, April, and May. The maximum amount of surface water delivered is about 6,700 AF per month. This is equivalent to about 167 AF per day or 112 cfs in one or more delivery canals and a total annual delivery of 20,000 AF per yr. The 6,700 AF per month target delivery also corresponds to an ASR wellfield of 20 wells, with an average injection capacity of 1,900 gpm (8.3 AF per day) per well. As described in

Section 5, this injection rate appears feasible, but additional testing in a well designed specifically for ASR is necessary to confirm single well injection capacity.

Surface water is only available if the ASR monthly delivery amount (6,700 AF) is less than 2.5% of the total reservoir capacity during that month. The selection of a 2.5% threshold was arbitrary and intended to introduce some variability in the year-to-year availability of surface water for delivery (i.e. it produces some years or months when no ASR injection would occur). Based on historical reservoir volumes, at an injection capacity of 6,700 AF per month, any threshold value greater than 4% results in availability every month over the simulation period. In other words, the maximum impact on total reservoir storage from delivery of 6,700 AF per month for ASR is no more than 4%.

The model calculates "in-year" and cumulative surface water delivery and ASR injection volumes as shown on Figure 15. Figure 15a shows that the full 20,000-AF-per-year maximum capacity is delivered on most years, but in 1987, 1988, 1993, 1994, and 2006 delivery volumes would be less than the 20,000-AF-per-year maximum injection capacity due to low reservoir storage. Figure 15b shows that, after 42 years of operation, a total of 790,860 AF of water would have been delivered and injected into the Wanapum Aquifer. The cumulative volume is equivalent to 18,800 AF per year, which is equal to the estimated historical groundwater pumping from the Wanapum.

Note that, although different surface water delivery rules would produce different injection volumes, the total injection in any given month will always be limited by the injection capacity of the wellfield. As described in Section 5, the maximum feasible injection capacity is currently estimated to be 1,900 gpm per well for 20-well ASR system, which is equivalent to 20,000 AF per year. The cumulative injection volume could be higher if the reservoir threshold is greater than 2.5%, or if delivery/injection occurs in months outside the March-May window. From an operations standpoint, it is desirable to only have one continuous injection period per year.

6.2 Hypothetical ASR Storage and Recovery Operation (1981 to 2023)

The model then applies a second set of assumptions to evaluate how ASR injection volumes would accumulate and made available for recovery. The concept of an "ASR storage pool" is introduced to describe the volume of ASR surface water present in the Wanapum Aquifer at any point in time, less any withdrawals from the storage pool recovered for beneficial use. This ASR storage pool is not intended to have a technical or regulatory meaning and is essentially an accounting term to keep track of artificial recharge and withdrawals. In reality, ASR would result in a co-mingling of injected water and native groundwater, from both a physical and regulatory perspective. The hypothetical storage and recovery volumes are calculated in the model based on the following criteria:

- A minimum ASR storage pool of 100,000 AF. No recovery occurs if the storage pool is less than this value, which ensures a minimum volume of injected water remains in the aquifer. This minimum storage pool can also be considered a minimum ASR volume dedicated to the aquifer and its role in supporting baseflows the Yakima River. The value of 100,000 AF is arbitrary but remains constant throughout the model simulation. Higher or variable minimum storage pool values could be incorporated.

- Stored groundwater is only available for recovery in July, August, and September when the combined surface water reservoir volumes are less than the following thresholds: 600,000 AF in July; 500,000 AF in August; and 300,000 AF in September.
- ASR recovery always occurs at a maximum withdrawal capacity of 6,700 AF per month (equal to the maximum injection capacity).
- No accounting for avoided surface water diversion is included. In other words, reservoir volumes are not adjusted to reflect water that might not be released due to the availability of ASR storage.

These criteria introduce a set of simplified conjunctive use rules that prioritize the surface water supply over artificially stored groundwater and ties both the delivery and recovery of the ASR storage pool to the amount of surface water available in any given month. When reservoir levels are greater than the levels set below, no ASR recovery occurs. This type of withdrawal constraint can become highly complex (both from a water balance perspective and a water rights or instream flow perspective).

The model produces a hypothetical “in-year” ASR withdrawal volume and cumulative ASR withdrawal volume shown on Figure 15. Figure 15c shows that the full 20,000 AF recovery capacity is exercised 11 times. Recovery capacity is less than 20,000 AF in 19 years, and there is no recovery in 14 years. Figure 15b shows that, after 42 years of operation, a total of 435,500 AF of water could have been delivered for consumptive use from the ASR storage pool based on the operating criteria.

Figure 15e shows the ASR storage pool volume that results from the injection and withdrawal scenarios. This is the ASR water that “stays” in the aquifer during any given year. The ASR storage pool fluctuates from year to year based on the injection and recovery thresholds, but never declines below 100,000 AF. Using these simplified operating rules, the storage pool increases to a maximum volume of 355,100 AF at the end of the simulation. Conceptually, adjustments to the recovery criteria for ASR storage pool could be implemented as the ASR pool increases, allowing higher or lower recovery volumes based on other criteria. In addition, with a refined groundwater model, the volume of the ASR pool could be converted to groundwater levels, and the storage pool could be managed based on target water levels to produce hydraulic gradients that maintain a desired dynamic equilibrium, particularly with respect to baseflow discharge to the Yakima River.

There are no quantitative conclusions to be drawn from this analysis, because it is a hypothetical and highly simplified example from both an operational and regulatory perspective. However, it does demonstrate that a regulated ASR program using a modest but consistent spring delivery of surface water can restore storage volumes to the Wanapum Aquifer, while also providing valuable beneficial use for agriculture during dry years when surface water is limited.

These water supply benefits from a large-scale ASR system will require further quantification and refinement, both in terms of the injection/withdrawal capacity of an ASR wellfield and the rules that would be needed to integrate an ASR wellfield with reservoir releases and subsequent delivery via the canal systems. A pilot test would allow for this model refinement. Water quality is an important additional consideration and also requires careful analysis. This is discussed further in Section 7 below.

7. WATER QUALITY ANALYSIS AND MODELING

This section presents the major ion, trace element, and stable isotope geochemistry for the surface water and groundwater samples (data given in Appendix E) and compare them to data from three other nearby studies:

1. A study of groundwater geochemistry in the Kennewick Irrigation District (KID) area, approximately 50 miles southeast of Konnowac Pass (KID 2023).
2. Groundwater monitoring in deep wells (547 to 555 feet) at the Cheyne Landfill, approximately 1.5 miles north of MP 35.2 on the Roza Canal (Environmental Information Management [EIM] Cheyne 2023).
3. A comprehensive study of groundwater geochemistry for CRBG aquifers in the Columbia Basin Ground Water Management Area (GWMA) of Adams, Franklin, Grant, and Lincoln County (Vlassopoulos et al. 2009). This four-county area is centered approximately 90 miles northeast of the Konnowac Pass area.

7.1 Groundwater Quality

7.1.1 Major Ion Chemistry

The geochemistry of Columbia River basalt groundwaters has been measured and analyzed in numerous previous studies (e.g., Steinkampf and Hearns 1996; Vlassopoulos et al. 2009). In general, as described in Section 2.6, there is a systematic shift in cation ratios, from Ca-Mg dominant (similar to surface water) to Na-dominant the longer that the groundwater resides in the basalt aquifer. This is a general trend, characteristic of water-rock interaction for a range of lithologies. The cation ratio (Na+K)/(Na+K+Ca+Mg) is used as an indicator of the degree of chemical evolution of groundwater (Chebotarev 1955). Figure 16 is a Piper diagram that compares the major ion chemistry of the groundwater and surface water samples with basalt geochemistry from the three nearby studies (KID 2023; Vlassopoulos et al. 2009; EIM Cheyne 2023). In Figure 16, the basalt wells in the KID area (plus signs) have been divided based on depth where 400 feet is chosen to represent the division between Saddle Mountains and Wanapum aquifers, based on basalt unit depths in Jones and Vaccaro (2008). The two Cheyne landfill wells are completed in the Saddle Mountains basalt; an example well log is included in Appendix F. The four data points from Vlassopoulos et al. (2009) represent medians for four groups of samples from Wanapum wells in the Columbia Basin GWMA. The groups were derived from principal component and hierarchical cluster analyses of all basalt groundwaters (Vlassopoulos et al. 2009) and represent the most evolved (purple circle), intermediate (green circle), and least-evolved (grey circle) Wanapum groundwaters.

The typical groundwater cation evolution path is illustrated by the red arrows in Figure 16. The March 2023 sample collected from the Nillson Well, before the well was regularly used for irrigation, appears on the evolved end of the spectrum, with a cation ratio of 0.90, which is similar to the evolved Wanapum end-member identified by Vlassopoulos et al. (2009). This sample likely represents the ambient groundwater in the Wanapum Aquifer when the potentiometric surface is at its static level. The August 2023 sample from the Nillson Well is distinctly different in major ion concentration, with a lower cation ratio of 0.83; on a Piper diagram, this value falls in the direction of three potential mixing end members: Roza Canal water average value (pink circle); nearby Saddle Mountains groundwater (Cheyne wells), or the intermediate Wanapum groundwater of Vlassopoulos et al. (2009). The August sample from the Nillson Well represents water extracted during a dynamic period when the well is pumping near its maximum capacity. An interpretation of the shift in chemistry is discussed below with the stable isotope data.

Anion concentration proportions (lower right triangle on the Piper diagram) do not follow a straightforward evolutionary path like cations but are dependent on both the progressive dissolution of basaltic glass and minerals in the sedimentary interbeds and infiltration of surface waters containing elevated nitrate (NO_3), chloride (Cl), and sulfate (SO_4). The basalt wells shown in Figure 16 reflect this variability in anion concentration, particularly in SO_4 concentration. In general, the variation in anion composition is less for more evolved waters, which also tend to come from deeper wells and have less surface water influence (Vlassopoulos et al. 2009). Notably, groundwater from the Nillson Well and the nearby Cheyne wells have much lower proportions of SO_4 than basalt groundwaters from the KID area. Wanapum waters from the Columbia Basin GWMA are intermediate in SO_4 percentage. Potential sources for the higher SO_4 concentrations may be attributed to 1) dissolution of primary sulfide minerals such as pyrite by oxygenated recharge water; 2) dissolution of sulfate minerals in basalt interbeds; or 3) infiltration of sulfate-rich surface waters, presumably from agricultural chemicals. The low SO_4 proportions in the groundwaters from the Nillson and Cheyne wells suggest none of these mechanisms are dominant in this region.

7.1.2 Trace Element Concentrations

Trace element data add some context to the major ions data. All major and trace element data are provided in Appendix E. Table 5 shows selected major ion and trace element concentrations, which are color-coded so that

- dark red cells represent the highest measured concentrations for a given element or ion;
- dark blue cells are the lowest measured concentrations above the detection limit;
- light shades of red and blue represent intermediate concentrations; and
- pale green cells are measurements below the detection limit.

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Table 5: Selected Major Ion and Trace Element Concentrations for Surface Water and Groundwater Samples

Sample ID	Na	Mg	K	Ca	NO_3-N	SO_4	Al	V	Fe	Cu	Zn	Ba	Pb
	ppm	ppm	ppm	ppm	ppm	ppm	ppb	ppb	ppb	ppb	ppb	ppb	ppb
Detection Limits:	0.2	0.05	0.04	0.05	0.1	0.1	1.39	0.22	0.61	0.35	1.08	0.07	0.05
April 6 Surface Water													
RR-YRA	5.41	4.79	0.78	12.2	0.07	2.89	<1.39	1.72	0.91	0.44	<1.08	9.5	<0.05
RR-RC-1A	5.42	4.71	0.75	11.8	<0.1	2.48	<1.39	1.27	0.87	0.41	<1.08	4.88	<0.05
RR-RC-2A	5.52	4.82	0.77	12.3	<0.1	2.81	<1.39	1.46	<0.61	<0.35	<1.08	9.08	<0.05
RR-RC-3A	5.5	4.71	0.8	12.1	0.05	2.82	<1.39	1.5	0.98	0.4	<1.08	5.63	<0.05
RR-RC-4A	5.5	4.57	0.78	11.9	<0.1	2.82	1.9	2.49	2.5	0.47	<1.08	7.17	<0.05
July 7 Surface Water													
RR-YRB	4.77	4.36	0.8	11.5	<0.1	2.54	<1.39	1.58	0.98	<0.35	<1.08	7.77	<0.05
RR-RC-1B	4.9	4.38	0.84	11.8	<0.1	2.4	<1.39	1.94	0.96	0.47	<1.08	8.07	<0.05
RR-RC-2B	4.8	4.36	0.77	11.6	<0.1	2.52	<1.39	1.88	0.97	<0.35	<1.08	8.57	<0.05
RR-RC-3B	4.83	4.4	0.79	11.6	<0.1	2.53	<1.39	1.9	1.01	<0.35	<1.08	7.55	<0.05
RR-RC-4B	4.81	4.39	0.8	11.7	<0.1	2.57	1.57	2.47	1.34	0.37	<1.08	8.34	<0.05
October 5 Surface Water													
RR-YRC	5.51	5.23	1.3	12.6	0.24	3.57	<1.39	3.7	1.51	1.41	1.49	11.8	<0.05
RR-RC-1C	5.61	5.22	1.25	12.5	0.29	3.62	<1.39	4.41	2.25	0.94	1.2	10.9	<0.05
RR-RC-2C	5.82	5.38	1.29	12.6	0.32	3.67	<1.39	3.93	1.98	1.03	2.54	11.7	<0.05
RR-RC-3C	5.93	5.27	1.62	12.5	0.85	3.75	<1.39	4.13	1.98	2.3	4.89	10.9	<0.05
RR-RC-4C	5.89	5.19	1.17	12.4	0.32	3.8	<1.39	3.43	1.48	0.65	2.21	9.98	<0.05
Groundwater													
RR-G1A (Mar)	52.5	0.69	6.72	4.31	<0.1	0.22	3.34	0.12	8.96	6.04	19.4	6.28	4.01
RR-G1B (Aug)	32.9	1.05	5.67	4.56	<0.1	1.11	7.69	0.24	71.3	181	21.4	5.6	4.83

1. Dark Red = highest values; Dark Blue = lowest detectable values; Green = measurements below method detection limits
Al: aluminum; Ba: barium; Cu: copper; Fe: iron; Pb: lead; ppb: parts per billion; ppm: parts per million V: vanadium; Zn: zinc

Trace element concentrations for all measurements are below primary and secondary drinking water standards maximum contaminant levels (MCLs). Cobalt, arsenic, selenium, cadmium, and uranium were below the detection limit for all samples. Other trace elements that are not shown in Table 5 have similar trends to elements in the table. For example, manganese and vanadium behave similarly to iron, with the highest surface water concentrations measured from the sample on October 5, 2023, and the highest overall concentrations measured in the August 2023 groundwater sample.

The color coding in Table 5 highlights the similarity between the Roza Canal water and the Yakima River water from which it is derived. The surface water samples from October 5, 2023, have consistently higher concentrations for all elements that are above detection limits; this is likely in part the result of increased groundwater baseflow input to the Yakima River as well as evaporation over the course of the summer. However, measurable NO_3 concentrations in October suggest increased agricultural inputs to both the Yakima River and the Roza Canal and disproportionately high copper concentrations may be the result of herbicide application along the canal. These concentrations are still well below the primary drinking water MCL of 1,000 parts per billion (ppb) and below values measured by the Roza Sunnyside Board of Joint Control (RSBOJC) water quality program, described in Section 7.2.

Table 5 also highlights the different geochemical signatures of the March 2023 and August 2023 Nillson Well groundwater samples. In addition to being less evolved than the March sample, the August sample also has higher concentrations of trace metals, notably aluminum, iron, and copper. These higher concentrations in the August sample may be the result of increased mineral dissolution perhaps due to changes in oxidation potential; mixing with another water that has high concentrations of these metals; or increased inputs from humans or human infrastructure, such as piping.

7.1.3 Stable Isotope Ratios

Stable isotopes of oxygen and hydrogen are useful for identifying areas of surface water infiltration and more generally mixing between isotopically distinct water. Conversely, if two waters are isotopically distinct, this is evidence that they have not mixed and there may be a barrier to flow, such as a confining layer between them. Stable isotopes are measured as ratios and described using the δ-notation,[3] which compares the ratio in a sample to an ocean water standard.

Figure 17 shows the hydrogen and oxygen isotopic composition (δD and $\delta^{18}O$, respectively) for the Nillson Well samples collected in March and August 2023; all Roza Canal and Yakima River samples; and basalt groundwater samples from the KID area (KID 2023). The KID samples are divided between probable Saddle Mountains (grey) and Wanapum (light brown) groundwaters. Once again, the August Nillson Well sample is geochemically distinct from the March sample. Isotopically, the August sample from the Nillson Well appears to be a mixture between the groundwater sample collected in March and either surface water or a groundwater that is isotopically similar to surface water. Given the well seal, which extends 30 feet below the top of

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[3] $\delta = \frac{(R_{smp} - R_{std})}{R_{std}} \times 1000$, where smp is the sample, std is a standard and R is the isotope ratio, $\frac{^{18}O}{^{16}O}$ for $\delta^{18}O$ and $\frac{D}{H}$ for δD. The standard for water analyses is Vienna Standard Mean Ocean Water (V-SMOW).

the basalt, and the large volume of water that was being pumped in August 2023, it is difficult to find a feasible scenario in which enough surface water entered the aquifer or well to cause the observed shift in the isotopic signature. Therefore, we favor an explanation in which the well draws from two isotopically distinct aquifers, likely the lower part of the Saddle Mountains formation and the upper Wanapum formation. Figure 18 illustrates how the shift in isotopic composition and chemistry might occur in the Nillson Well. In March 2023, the aquifers have not been pumped for months and the potentiometric surface (pressure head) for the Wanapum Aquifer is higher than that of the Saddle Mountains Aquifer. As a result, the well predominantly draws from the Wanapum Aquifer. By August 2023, after weeks of pumping, the potentiometric surface of the Wanapum Aquifer has been drawn down to the point where groundwater from the Saddle Mountains Aquifer predominantly enters the well. The isotopic compositions of Saddle Mountains basalts in the KID area (from KID 2023) are similar to Yakima River and Roza Canal water (Figure 17), supporting the idea that the shift in the isotopic composition of Nillson Well groundwater is due to input of Saddle Mountains groundwater. Most of the other chemical differences between the two Nillson Well samples described above can be explained by simple mixing between Wanapum and Saddle Mountains end members.

7.2 Surface Water/RID Water Quality

The proposed source water for an ASR project in the Rattlesnake Ridge area is Roza Canal water, removed in the early spring. Roza Canal water quality is governed by the RSBOJC Water Quality program, who conduct regular monitoring of the combined Roza and Sunnyside Irrigation Districts, particularly focusing on the discharge points from their drainages into the Yakima River. A compilation of water quality data from the four major discharge points from the Roza and Sunnyside Irrigation Districts (Granger Drain, Sulphur Creek Wasteway, Spring Creek Wasteway, and Snipes Creek Wasteway) for 1997 to 2008 is available in Zuroske (2009). The water quality in Roza Canal itself is generally much better in all measures than the water quality at these discharge points, which have accumulated pollutants from both irrigation districts.

Roza Canal water begins in the Yakima River and is diverted into the canal at Roza Dam in the Yakima River canyon (RM 127.9). The water quality and chemistry in the canal change from that initial Yakima River composition as the water passes through the system due to evaporation; changes in temperature; inputs of sediment and chemicals from the surface (often related to agriculture or earth-moving); inputs of groundwater from nearby seeps; and chemical reactions. To characterize the water quality of the Roza Canal here, the following data sources were used:

1. This study’s measurements of water quality parameters for the Yakima River and four sites along the Roza Canal (complete results in Appendix E).
2. General water quality data for seven locations along the Roza Canal provided by RSBOJC for the years 2020 to 2022 (RSBOJC 2020–2022), including pH, dissolved oxygen, E. Coli, temperature, specific conductance, and nutrients (summary statistics given in Appendix E).
3. Annual summaries of pesticide use from RSBOJC for 2020 to 2022 (Roza 2020–2022a).
4. Monthly reports on pesticide concentration measurements from RSBOJC for 2020 to 2022 (Roza 2020–2022b).

5. Data from the USGS National Water Information System (NWIS) for the Yakima River at Umtanum (USGS NWIS, 2023).

7.2.1 Water Quality Compliance with Regulatory Standards and Criteria

Water quality data were compared to Washington primary (MCL) and secondary (SMCL) standards for drinking water (WAC 246-290-310) and Washington groundwater quality criteria (WAC 173-200-040). This comparison can be seen in the tables in Appendix E. Most parameters did not exceed the MCL/SMCL for drinking water. Parameters for which water quality standards are exceeded are summarized here.

7.2.1.1 pH

The SMCL for drinking water and the groundwater criteria specify a pH with the range of 6.5 to 8.5. The Yakima River at Umtanum is regularly within this range, but Roza Canal water frequently exceeds a pH of 8.5, particularly further down the canal system where values as high as 9.8 have been measured (RSJBOC 2020–2022). Table 6 and Figure 19a illustrate this progression downstream; from 30 out of 30 samples having pH less than 8.5 at Roza Canal MP 4.95 to 24 out of 30 samples with pH above 8.5 at MP 94.7. The data collected for this study, although it has fewer measurements, is consistent with this trend.

7.2.1.2 Turbidity

The Washington state and national criteria for turbidity in drinking water depends on the type of filtration system that is used. For systems using direct or conventional filtration, the MCL is 1 NTU; for systems using other filtration methods, the MCL is 5 NTU. Two of the data sets collected for this study (sampled in April and July 2023) did not exceed 1 NTU. However, the RSJBOC water quality program samples (RSBOJC 2020–2022) regularly exceeded the 5 NTU level, particularly at MP 59.0 and 75.1 (Table 6; Figure 19b). This suggests that there is local input of sediment or organic matter to the canal that was not captured in the sampling distribution for this study. Lower turbidity values further down in the canal (MP 94.7) indicate that there is also dilution or settling along the canal.

7.2.1.3 Bacterial Load

Both the data collected for this study and the RSJBOC water quality data (RSJBOC 2020–2022) indicate the presence of E. coli and other bacteria in nearly 100% of Roza Canal water (Table 6). Figure 19c shows the RSJBOC E. coli data by location with time. The highest values are in the late spring and MP 59.0 and 75.1 generally have higher E. coli loads than the other RSJBOC sampling locations.

Table 6: Summary of Water Quality Exceedances in Roza Canal

Water Quality Standard Exceeded*		Milepost on Roza Canal (RSBOJC, 2020-2022)					
		MP 4.95	MP 11.5	MP 32.8	MP 59.0	MP 75.1	MP 94.7
pH	*#samples > 8.5*	0			**7**	**10**	**24**
	Total samples	30			30	30	30
Turbidity (NTU)	*#samples > 5.0*	**4**	**6**	**6**	**16**	**19**	**6**
	Total samples	30	30	30	30	30	30
E. coli (cfu/100 mL)	*#samples > 0*	**30**	**30**	**30**	**30**	**30**	**30**
	Total samples	30	30	30	30	30	30

Water Quality Standard Exceeded*		Roza Canal Sampling Location (this study)			
		RC1 (MP 21.8)	RC2 (MP 39.3)	RC3 (MP 49.2)	RC4 (MP 69.8)
pH	*#samples > 8.5*	**2**	**2**	**3**	**3**
	Total samples	3	3	3	3
Turbidity (NTU)	*#samples > 5.0*	0	0	0	0
	Total samples	2	2	2	2
Fecal Coliform (MPN/100 mL)	*#samples > 0*	**3**	**3**	**2**	**2**
	Total samples	3	3	3	3
E. coli (MPN/100 mL)	*#samples > 0*	**3**	**3**	**2**	**2**
	Total samples	3	3	3	3

*Bold numbers show exceedance of drinking water MCLs and SMCLs from WAC 246-290-310: pH > 8.5, SMCL; turbidity > 5.0 NTU, MCL for systems that use filtration other than conventional or direct filtration methods; fecal coliform > 0 MPN/100 mL, MCL for Total Coliform; E. coli > 0 MPN/100 mL, MCL for E. coli following coliform presence.
cfu: colony forming units; mL: milliliter; MPN: most probable number.

7.2.1.4 Arsenic

Arsenic for all samples analyzed in this study, both surface waters and groundwaters was below the instrument detection limit of 0.54 ppb. Therefore, these samples have concentrations well below the primary drinking water MCL of 10 ppb. Because arsenic is carcinogenic, the groundwater quality criteria (GQC) for arsenic is much lower than the drinking water MCL, calculated using the following equation:

$$GQC = \frac{RISK \times BW \times LIFE \times UCF}{CPF \times DWIR \times DUR}$$

Where:

RISK = human cancer risk level = 1 in 1,000,000

BW = body weight = 70 kilograms (kg)

LIFE = lifetime = 70 years

UCF = unit conversion factor = 1,000 micrograms (µg) per mg

CPF = cancer potency factor per mg per kg per day

DWIR = drinking water ingestion rate = 2.0 liters per day

DUR = duration of exposure = 30 years

The cancer potency factor for arsenic, taken from the USEPA Integrated Risk Information System database, is 1.5 mg per kg per day. This value is based on a study of skin cancer for a population in Taiwan that was drinking high levels of arsenic (Tseng et al. 1968; Tseng 1977). The above calculation results in a GQC for arsenic of 0.05 ppb, a value well below the natural amounts in many waters and also below the detection limits of many instruments, including the one used here. Therefore, the results for all waters are inconclusive regarding the groundwater quality criteria for arsenic and a method with a lower detection limit is needed to determine their status.

7.2.2 Suspended Solids

All measurements of total suspended solids (TSS) concentrations, both in this study and in the RSJBOC data (RSBJBOC 2020–2022), are below the drinking water SMCL and GQC of 500 mg/L. However, TSS concentrations are extremely variable for both the Yakima River and Roza Canal, particularly in the late winter to spring when storms and rapid snowmelt periods can lead to episodic floods that wash sediment into the waterways. These one- to two-day episodes are not necessarily captured in the datasets collected or reviewed.

In general, as with major ion chemistry, the Roza Canal water has similar suspended solids concentrations to the Yakima River with no significant trend with distance down the canal (Table 7). Higher values midway along the Roza Canal (e.g., July 7, 2023) suggest there are local sources of sediment that enter the canal, similar to turbidity. In addition, replicate analyses at single sites (Figure 20; May 22, 2023) indicate that sediment load can vary considerably at a single location during a single sampling period.

Table 7: Suspended Solids Concentrations from Samples Collected in 2023 (in mg/L)

Sampling Site	April 6	May 6	May 22	July 7
YR	6	26	6	60
RC1	7	31	14	71
RC2	3	29	29	190
RC3	1	--	--	52
RC4	< 1.0	--	--	92

bdl: below detection limits

The highest value of TSS in the early spring (April and May 2023) is 31 mg/L. A USGS data set of water quality for the Yakima River at Umtanum (USGS NWIS, 2023), 18 kilometers upstream of the Roza Canal Diversion, had 13 measurements of TSS in March, April, and May, of which 4 were above 75 mg/L. In contrast, data collected by the Roza Sunnyside Water Quality program in 2020 to 2022 at milepost 4.95 on the Roza Canal (Figure 21) reveals relatively low TSS (less than 10 mg/L) in all measurements except for a single measurement of 51 mg/L after a runoff event in June. In that all these studies collected samples at intervals of several weeks to months, it is unlikely that they captured the highest TSS conditions, which typically only last a day or two.

In general, high TSS episodes occur during periods of flooding, usually in the spring, which is the target season for MAR injection. This preliminary data indicates that the Roza Canal is likely to experience brief episodes where TSS is greater than 50 to 100 mg/L during this spring shoulder season.

It is useful to also understand the size distribution of suspended fine-grained sediments when considering filtration or treatment requirements for ASR. Figure 22 shows sediment size distributions for the July 6, 2023, surface water samples; these size distributions are representative of all other samples that were measured. The suspended solids range in size from clay to fine sand with a majority of the particles in the silt range (4 to 62 microns). There appears to be slightly more sand in the down-canal samples (RC-3B and RC-4B) further indicating a local source of sediment along the canal.

7.2.3 Herbicides

RID manages aquatic plants, including algae, in the main canal with regular application of three herbicides: acrolein, endothall, and copper (Table 8). The application is publicly posted ahead of time and dyes are released into the water immediately before and after to signal the presence of the herbicides in the water. RSBOJC compiles annual treatment reports, in which treatment events and locations are given along with the herbicide concentration and total amount of product used. In addition, RSBOJC monitors herbicide concentrations, particularly in the outputs from the combined Sunnyside-Roza Irrigation Districts into the Yakima River. Periodic measurements along the Roza Canal are also made. These data are available in monthly discharge monitoring reports (DMRs) prepared by the RID. For this assessment, data were compiled from annual reports for 2020 to 2022 (Roza 2020 to 2022a) and the monthly DMRs for the same years (Roza 2020 to 2022b).

Table 8: Herbicide Chemicals used by Roza Irrigation District

Chemical	Chemical Formula	Water Quality Standard
Endothall	$C_8H_{10}O_5$	Drinking water MCL (federal) 100 μg/L
Acrolein	C_3H_4O	Aquatic Life Quality Criteria: one-hour average does not exceed 3.0 μg/L more than once every three years on average, four-day average does not exceed 3.0 μg/L more than once every three years on average (USEPA 2009)
Copper	Cu	Drinking water action level 1.3 mg/L

μg/L: microliters

Over the past three years, KID has used four herbicide products:

- **Cascade:** Dipotassium salt of Endothall (40.3%), herbicide applied twice at RC 11.0, once in mid-May and once in mid-July. Concentration immediately after application is 2500-3500 □g/L.
- **Teton:** 53.0% Endothall, algicide and herbicide applied May to August at seven locations between RC 59.1 and RC 91.5.

- **Acrolein:** concentrated (about 96%), aquatic herbicide and algicide applied May to September at seven locations between RC 37.2 and RC 91.5.
- **Captain XTR:** Copper ethanolamine complex, 28.2% Cu, aquatic algicide applied June to September at seven locations between RC 59.1 and RC 91.5.

Total application amounts in kg of active ingredient for 2020, 2021, and 2022 are given in Table 9. Herbicides are applied at 12 locations along the main Roza Canal. The application patterns for 2020 to 2022 can be seen in the top three boxes in Figure 22. In the early spring target season for ASR, applications are low compared to later in the irrigation season.

Table 9: Total Herbicide Application Amounts for 2020-2022

Active Ingredient/Herbicide	Target concentration	2020	2021	2022
	ppm	kg*	kg*	kg*
Endothall/Cascade	4	5562	6240	5773
Endothall/Teton	0.05 – 0.2	387	197	79
Acrolein	0.9 – 1.3	2479	2242	2409
Copper/Captain XTR	0.2 – 0.3	481	416	414

*mass of active ingredient applied (m), calculated based on volume (V), density (ρ), and % active ingredient (A): $m = V*\rho*A/100$; data from Roza (2020-2022a).

Monthly monitoring reports (Roza 2020–2022b) track measurements of acrolein, endothall, and copper made throughout the irrigation season at various points in the RID system, including 12 points along the main canal; the bottom three boxes in Figure 23 summarize the herbicide concentration data. Bold numbers show values that exceed the drinking water MCL or aquatic life quality criteria (given in Table 8). The spatial and temporal patterns of exceedances are summarized below:

- Acrolein is applied in June and August to control submersed and floating plants and algae. There is not a drinking water MCL for acrolein, so measurements here were compared to the USEPA's Recommended Water Quality Criteria for Aquatic Life; although this criteria is not applied in the canal or groundwater setting, it does give a basis for comparison. Measured acrolein concentrations were above the 3 µg/L recommended limit in the Aquatic Life Quality Criteria at multiple locations along the canal in June and August 2021. However, because those were single occurrences that may not have lasted for four days, it is not certain that the criteria was exceeded. Furthermore, acrolein is not applied until the late spring, well after the target season for ASR.
- Endothall is a common selective contact herbicide that has been used to manage submerged aquatic vegetation for over 50 years. The USEPA established the MCL for endothall in drinking water at 0.1 ppm. In aquatic environments, endothall acid typically persists in the water less than 10 days (USEPA 2005). There are two applications of endothall each year at RC 11.0: one in mid-May and one in mid-July. Approximately two

hours after this application, concentration measurements are made approximately 10 miles downstream of the application site. The concentration after 2 hours typically exceeds the drinking water MCL, but concentrations also decrease over time. A second measurement made further downstream at RC 94.8 one week after the application in 2019 was well below the MCL and suggests that the concentration declines within a week.

- Captain XTR is a double-chelated copper compound (known ingredients include copper triethanolamine complex and copper monoethanolamine complex) used to control a broad range of algae. There have not been any measurements of copper above the EPA drinking water MCL.

7.3 Analysis of Geochemical Reactions

This section discusses geochemical reactions that may occur as a result of mixing of injected surface water with native groundwater and the basalt rock matrix in which the groundwater resides. Groundwater recharge is typically similar to surface water when it infiltrates the unsaturated zone. But, over time, groundwater becomes geochemically distinct from surface water as a result of interaction with minerals within the aquifer. In general, the artificial recharge of surface water into the basalt aquifers will result in the same overall geochemical evolution that occurs during natural recharge, including the following:

- Alkalinity will increase from that of surface water (<70 mg/L as HCO_3) toward that of groundwater (>150 mg/L as HCO_3).
- As is the general tendency with groundwater, injected water will increase in concentrations of total dissolved solids and shift in types from Ca-Mg-CO_3 toward Na-K-CO_3.
- Silica concentrations will increase because of the presence of volcanic glass in the basalts.

This natural chemical evolution will happen very slowly compared to the timescale of aquifer storage and recovery and does not in itself present water quality concerns. However, specific minerals and glass within the basalt units (including any sedimentary interbeds) can react with the injected water, either dissolving or providing surfaces for cation exchange, sorption, and precipitation of solids. Geochemical modeling was conducted to identify potential mineral precipitation reactions that might cause clogging within an ASR well or dissolution reactions that might increase dissolved chemical concentrations above regulatory MCLs.

7.3.1 Geochemical Modeling

To assess the mixing between source water and groundwater in the presence of the aquifer mineral assemblage, the SpecE8 program within the Geochemist’s Workbench software package was used (Bethke 2022). SpecE8 calculates the equilibrium distribution of chemical species within a water mixture and the saturation state of a large suite of minerals. It also simulates interaction with a solid substrate and sorption of aqueous species onto mineral surfaces. It should be noted that the equilibrium distribution that is calculated is unlikely to be attained because of the slow kinetics at groundwater temperatures, but it serves to identify the direction that reactions will tend. Thus, if the water mixture is supersaturated with respect to a given mineral, that mineral may not precipitate on any relevant timescale.

To simulate the ASR scenario in the Study Area, two end members were mixed: 1) water with an average Roza Canal water chemistry to represent the source water, and 2) groundwater with the chemistry of the Nillson Well groundwater sampled in March 2023 to represent the ambient groundwater. As discussed earlier, we consider the March 2023 water chemistry to be more typical of the Wanapum basalt groundwater.

After injection by ASR, the source water is anticipated to mix gradually with the ambient groundwater and form a "bubble" around the screened section of the well that displaces the native groundwater with the recharge water. Mixing of the native and recharged water occurs initially on the fringes of the bubble or lens, and the injected water continues to interact with the native groundwater and surrounding aquifer material over time. Preferential flow paths and/or differences in permeability facilitate the mixing of these two waters. To represent this range of mixtures, the two end members were mixed in increments of 10%, ranging from 90% groundwater/10% recharge water to 10% groundwater/90% recharge water.

In the SpecE8 software, minerals in the substrate can be added and allowed to react with the fluid mixture. Minerals were chosen based on basalt mineralogy described by Hearn et al. (1990) and from the ASR feasibility study for the Wanapum basalt for the City of Kennewick (Golder Associates Inc. [Golder] 2012). In the Kennewick study, borehole samples were analyzed for mineral composition; this served to identify secondary minerals that are present in the basalt aquifer. Based on these sources, we used the following minerals in the porous substrate of the model: pyroxene, albite, pyrite, magnetite, smectite, hematite.

Initially, Spec8 runs were performed for each of the two end-member waters in the basalt matrix to determine which minerals were saturated. The degree of saturation is expressed by the saturation index (SI):

$$SI = log\left(\frac{Q}{K_{sp}}\right)$$

where:

- Q is the ion product for that mineral
- K_{sp} is the equilibrium solubility product
- If Q is less than K_{sp}, then the mineral is undersaturated and $log(Q/K_{sp})$ will be negative. If Q is greater than K_{sp}, then the mineral is supersaturated and $log(Q/K_{sp})$ will be positive. If the mineral is saturated, $Q = K_{sp}$ and $log(Q/K_{sp}) = 0$.

In the initial runs, two minerals were highly saturated in the end member solutions:

- Antigorite [$(Mg,Fe^{2+})_3Si_2O_5(OH)_4$] in the Roza Canal water with $log(Q/K_{sp}) \approx 30$
- Ca-Nontronite [$(Ca_{0.5},Na)_{0.3}Fe^{3+}{}_2(Si,Al)_4O_{10}(OH)_2 \cdot nH_2O$] in the Wanapum groundwater with $log(Q/K_{sp}) \approx 12$

Antigorite is a high-temperature serpentine mineral with phyllosilicate structure. Because of its high-temperature nature, it is unlikely to precipitate at groundwater temperatures due to kinetic constraints. Furthermore, the saturation state of antigorite is highly dependent on pH. For the same basis (water chemistry), if the pH is set at 7.5, antigorite is no longer supersaturated.

Nontronite is in the smectite group and is a common weathering product of basalt; nontronite is likely present in the basalt aquifer matrix. In subsequent model runs, antigorite and Ca-nontronite were set as free constants, serving to buffer the concentrations of Mg^{2+} and Fe^{2+}, respectively.

Figure 24 shows results of model runs for different mixing ratios of the Roza Canal water and Wanapum basalt. The minerals shown on the figure are common minerals which were supersaturated in one or both end members. Saturation states of most minerals decrease with addition of Roza Canal water, most likely because of the lower activities of Na^+, K^+ and H_2SiO_4, which give rise to lower ion products. The slight increase in the saturation state of calcite is the result of higher Ca^{2+} activities with greater proportions of Roza Canal water. For ASR, this result suggests that many common minerals will be less likely to precipitate with the addition of Roza Canal water into the aquifer.

Redox Reactions

Redox (also termed reduction–oxidation or oxidation–reduction) is a type of chemical reaction in which the oxidation state of a reactant changes. Oxidation is the loss of electrons or an increase in the oxidation state, while reduction is the gain of electrons or a decrease in the oxidation state. In ASR, the recharge water will often introduce dissolved oxygen into low-oxygen or anoxic groundwaters of the basalts. This can cause groundwater in a reduced state to become more oxidized over time as the oxygen reacts with more reduced mineral species, or with any dissolved organic carbon also carried in the source water. Redox reactions can create regulatory concerns when they cause the concentrations of heavy metals in groundwater to increase above drinking water standards as the groundwater becomes more oxidized.

The dissolved groundwater quality that results from these redox reactions depends on the geochemistry of the aquifer matrix, in this case the geochemistry of CRBG units. However, the whole rock geochemistry is only an ideal reference to potential reactions because some elements may be locked into the matrix of the basalt and be inaccessible to recharged water. Conversely, artificially recharged water may flow through pathways that have already caused or initiated mineral dissolution. Minerals in fractured zones are often chemically weathered, and many of the metals of concern may have already been released from the bedrock by natural groundwater flow. Thus, the chemistry of native groundwater, which is in equilibrium with the aquifer matrix, is a better indicator of potential reactions than whole rock geochemistry.

Our results indicate that the concentrations of many of the metals that may be of concern (iron, copper, arsenic, manganese) are relatively low in the March 2023 Nillson Well sample, well below the MCLs for drinking water. The August 2023 Nillson well sample has higher concentrations of iron, manganese, nickel, and copper, which will be discussed below. Both groundwater samples had relatively low sulfate concentrations compared to nearby basalt waters (Figure 16; KID 2023), suggesting that weathering of sulfur-bearing minerals is not as dominant in this area.

In this study, ORP was measured in the field using a Hanna Instruments multimeter (HI98196) and can indicate the oxidation state of the groundwater samples. However, the ORP measurement should be considered a semiquantitative analysis because it is dependent on the concentrations of multiple chemical substances, and redox reactions often do not reach equilibrium in low temperature environmental settings (USEPA 2013). Our field measurements collected in 2023 yielded ORP values ranging from 351 to 425 millivolts (mV) for all surface water samples. The samples collected in July 2023 had the highest ORP values. The Nillson well groundwater had a measured ORP of 274 mV in March 2023 and 195 mV in August 2023. Qualitatively, these results indicate that the groundwaters are more reduced than the surface waters and that the August groundwater sample, which we suspect may represent groundwater from a higher basalt unit (perhaps the Saddle Mountains Aquifer), is more reduced than the March sample. However, both groundwater ORP measurements are well above 0 mV, suggesting that both groundwater and surface water represent oxidizing conditions.

The concentrations of iron, manganese, nickel, and copper in the August 2023 Nillson groundwater samples are two to ten times higher than their concentrations in the March 2023 sample. These higher concentrations could be the result of oxidation-reduction reactions which led to the more reduced state that is observed in the ORP reading and favors the more soluble 2+ valence species. Alternatively, these higher concentrations could be an artifact of interactions with a different suite of minerals in the Saddle Mountains basalts and their interbeds, which might contain higher volumes of soluble metal oxides. The measured values for the August Nillson groundwater are within the range observed in Saddle Mountains basalt groundwaters in the KID area (KID 2023).

To assess the stability of iron species in a potential groundwater-surface water mixture, the Act2 application in Geochemist's Workbench was used to generate stability diagrams for different concentrations of iron (Figure 25). These stability diagrams were generated for a matrix solution with the same major ion activities as a 50:50 mixture of March 2023 Nillson Well groundwater and Roza Canal water. The vertical axis, log a (O_2), represents the oxidation state of the solution with the less negative values representing an oxidizing environment. Figure 25a represents the current concentration of iron (log aFe = -27), Figure 25b and 25c represent higher concentrations, with log aFe = -13 (Figure 25b) and log aFe = -5 (Figure 25c). These diagrams indicate that dissolved species are stable over a range of Eh-pH conditions at low concentrations (activities) of iron. At much higher concentrations of iron, hematite is the stable phase.

Potential Treatment Requirements for Injection

As discussed above, geochemical modeling and analysis of groundwater chemistry suggests that mixing of ASR source water and native groundwater is not likely to cause exceedances of water quality standards. To date, a number of ASR projects involving recharge into the CRBG are underway or completed (e.g., Eaton 2009; Golder 2012) and no major adverse reactions or impacts have occurred in these projects, though treatment of the source water was necessary. The scope of this study does not include a detailed analysis of potential treatment requirements, but the water quality analysis and geochemical modeling have identified several constituents that should be considered for future design of an ASR pilot project.

- **Total Suspended Solids/Turbidity:** Total suspended solids (TSS) in recharge water is an operational consideration and can reduce the efficiency of an injection well or in some cases damage the aquifer itself so that injection becomes difficult. TSS concentrations in the Roza Canal water are variable, but generally below 10 mg/L. However, there are brief episodes of high TSS concentrations, usually in the late winter through spring, which includes the target window for ASR injection. High-flow events can result in TSS concentrations of 100 mg/L or more. Our sediment size distribution data for four sampling dates indicate that the majority of suspended solids are within the silt size range of 4 to 62 microns. Possible treatment methods for TSS include settling ponds, mechanical filtration, and fiber filtration. The highest TSS episodes are relatively short-lived, so it is also possible to halt ASR injection during these events. At full buildout, TSS treatment could be applied at individual ASR wellheads or at a centralized location servicing multiple ASR wells. Well backflush protocols during injection should also be developed to minimize clogging.

- **pH:** There is a steady increase in the pH of surface water as it flows downstream in the Roza Canal and samples downstream of MP 59 consistently have pH values above 8.5, a SMCL for drinking water. The pH of the ambient groundwater is also approximately 8.5. Conditioning for pH may be helpful, but geochemical modeling suggests a low likelihood of a pH-dependent reaction shifting mineral stability for elements like iron and manganese.

- **Bacteriologic Agents:** Both our data and the RSJBOC water quality data (RSJBOC 2020–2022) indicate the presence of E. coli and other bacteria in nearly 100% of Roza Canal water. To meet the GQC in WAC-173-200-040, disinfection will be required. There are a variety of treatment options for disinfection including chemical methods such as chlorination, ultraviolet radiation, and filtration. Chemical methods have the advantage that they are relatively inexpensive and also serve to reduce biofouling from other non-pathogenic organic constituents. However, they can create disinfection by-products which are themselves a water quality concern. The physical and regulatory processes of disinfection by-product formation, attenuation, mitigation and permit variance are well-established and understood.

- **Total Organic Carbon (TOC):** At low levels, TOC is present in Roza Canal water from plant matter and algae. This is a concern for biofouling/clogging of recharge wells. This concern may be addressed by chlorination or other disinfection of recharge water and/or periodic shock chlorination of the well. Filtration for TSS will also reduce the TOC load and disinfection by-product formation potential.

- **Herbicides:** The use of herbicides by RID is a regular part of their operation that will require monitoring and coordination between herbicide applications and diversion of canal water for recharge. Herbicide use during the target recharge period is limited, but there is a large application of endothall in mid-May at MP 4.95. Measurements by RSJBOC Water Quality Lab (RSJBOC 2020–2022) suggest that the herbicide has dissipated within a week. Additional measurements at the withdrawal point for ASR injection should be made to confirm this. Filtration of source water is also anticipated to reduce herbicide concentrations.

- **Clay Mineral Reaction Products:** Our geochemical modelling does not indicate that there is any particular reaction of concern when the Roza Canal water is mixed with the ambient Wanapum basalt groundwater. In fact, increasing proportions of Roza Canal water tends to decrease the solubility of saturated minerals, moving reactions more towards the dissolved species. Among these saturated minerals, smectite minerals are the most likely to precipitate. Smectite and other clays were observed in the production zone of a pilot well in the Kennewick ASR project (Golder 2012) and may reduce aquifer permeability. The solubilities of smectite minerals, particularly nontronite and saponite, should be monitored in any future pilot studies. Well backflush protocols during injection should also be developed to minimize clogging.

- **Trace Metal Reaction Products:** Water quality data have shown that concentrations of trace metals can vary within a single well, likely due to different seasonal inputs from hydraulically separated aquifers. Possible oxidation-reduction reactions depend on these concentrations, which should be well characterized for future target injection wells. The generally low concentrations of trace metals of concern (e.g., iron, manganese, nickel, copper, lead) suggest that the aqueous phases will be stable in groundwater-surface water mixtures except in very reduced environments. Arsenic **may be** present at low concentrations in groundwater and also has a very low regulatory MCL, often below natural concentrations in native groundwater. Arsenic concentrations and speciation should be further characterized for both source water and groundwater.

8. SUMMARY AND CONCLUSIONS

The overall purpose of the project was to evaluate the groundwater storage potential in the Columbia River Basalt formations in the Konnowac Pass area and to identify the best methods of artificial recharge (i.e., via surface infiltration or injection). This report includes an evaluation of the feasibility of implementing an ASR system in the Wanapum Aquifer within the Study Area to inject, store, and recover surface water from the Kachess, Keechelus, and Cle Elum reservoirs. The storage and withdrawal of injected surface water is intended to help stabilize declining groundwater levels in the Wanapum Aquifer and to provide an additional “ASR storage pool” that could provide late-season water supply for agricultural user in the Yakima Basin as an alternative or enhancement to drought management wells. The stabilization of declining groundwater levels is also expected to stabilize and possibly increase groundwater baseflow discharge to the Yakima River downgradient from the injection wells.

Based on the review of available data and technical reports, as well as the field investigation, the conditions of the Wanapum Aquifer appear to be favorable for an ASR system. The Wanapum Basalt is relatively continuous within the Study Area and does not exhibit the structural and erosional complexity of the overlying Saddle Mountains Basalt. The Wanapum is stratigraphically well-defined by the overlying Mabton Interbed, which provides confinement and isolates the Wanapum Aquifer from the overlying Saddle Mountains Aquifer. Furthermore, the primary water use from the Wanapum Aquifer is for agricultural use, and there are several high-capacity wells (1,000 to 3,000 gpm), which is a good indicator of the injection capacity for ASR wells.

We evaluated a general scenario of injecting 20,000 AF per year during the spring months (March, April, and May) using injection wells along the general alignment of the RID main canal south of Rattlesnake Ridge, from Konnowac Pass to near Benton City. Using a range of published hydraulic parameters for the Wanapum Aquifer (i.e., transmissivity and storativity), and assumptions on static groundwater levels, and injection well efficiencies of 50%, the predicted head build-ups from injecting 20,000 AF over 120 days appears to be feasible:

- Using conservative planning-level hydraulic properties, a 20-well ASR system with wells spacings of 10,000 feet apart, would produce 20,000 AF per year of injection capacity, but predicted build-up of head would likely approach ground surface. Less head build-up (which would be more favorable) would occur with higher well efficiency, larger well spacings, or lower injection rates.
- Using “best case” planning-level hydraulic properties, a 20-well ASR system with wells spacings of 10,000 feet apart, would produce 20,000 AF per year of injection capacity with significantly less build-up of head, even at a well efficiency of 50%. Under best case hydraulic properties, a 20,000 AF injection capacity could be achieved with fewer wells; or a higher annual injection capacity could be considered.

We prepared an example operational water balance time-series model of how an ASR system might operate year-after-year to provide a first approximation of potential total volumes of water that could be managed via ASR over a long period of time. The time-series model combined the injection and withdrawal capacity of a theoretical ASR wellfield with potential constraints on the availability of surface water and demand for ASR recovery during dry years. Actual reservoir volumes over the period 1981 to 2023 were used to generate operating triggers for delivery of surface water to ASR wells and for recovery of ASR storage. The triggers were essentially a set of simplified conjunctive use rules that prioritize the surface water supply over artificially storage groundwater and ties the delivery of surface to ASR wells and the recovery of the ASR storage pool to the amount of reservoir storage available in any given month. The model example showed the following results, over 42 years of operation using simplified operating rules:

- A total of approximately 800,000 AF of water could have been delivered and injected into the Wanapum Aquifer. The cumulative volume is equivalent to 18,800 AF per year, which is approximately equal to the estimated historical groundwater pumping rate from the Wanapum Aquifer.
- A total of 440,000 AF of water could have been delivered for consumptive use from the ASR storage pool during specific years when summer reservoir levels were low.
- A total of 360,00 AF would remain in the ASR storage pool volume of at the end of the simulation. This remaining storage pool would essentially represent recovery of water levels in the Wanapum Aquifer.

Surface water quality samples were collected from the five locations: one from the Yakima River above the diversion to the Roza Canal, and four along the Roza Canal. The samples were collected in April, July, and October 2023 to evaluate for general chemistry and trace metals. The results from the Roza Canal showed that the water quality is essentially the same as the Yakima River, with the exception of pH, which tends to increase along the length of the main canal and has been measured as high as 9.8. All other constituents met drinking water standards per WAC 246-290-310 except for bacteria (presence of E. coli and total coliform), and episodic spikes in TSS and turbidity (typically in response to storm events or snowmelt in the spring).

Herbicide concentrations were also evaluated in the Roza Canal based on monthly and annual monitoring reports prepared by the RID and other neighboring irrigation districts. The primary herbicides used in the canal are endothall, acrolein, and a copper compound, which are typically applied in the late spring to summer months to control plant and algae growth. Concentrations of these herbicides typically dissipate within one week of their usage.

Two groundwater samples were collected from a Wanapum Basalt well, the Nillson Well, in March and August 2023. The March sample showed a more "evolved" chemical signature (i.e., Na-K-HCO3) that was representative of Wanapum groundwater in the region, compared to the August sample which was less evolved (Ca-Mg-HCO3), suggesting that the latter was a potential mixture of Saddle Mountains and Wanapum groundwaters.

Geochemical modeling results indicate no adverse reactions are predicted when mixing Roza Canal water with the native (ambient) groundwater in the Wanapum Aquifer. As the proportion of Roza Water increases within the groundwater storage zone of the Wanapum Aquifer, the solubility of saturated minerals is predicted to decrease, thereby resulting in chemical reactions trending toward dissolved species. Among the saturated minerals, smectite is the most likely to precipitate and should be monitored (particularly nontronite and saponite).

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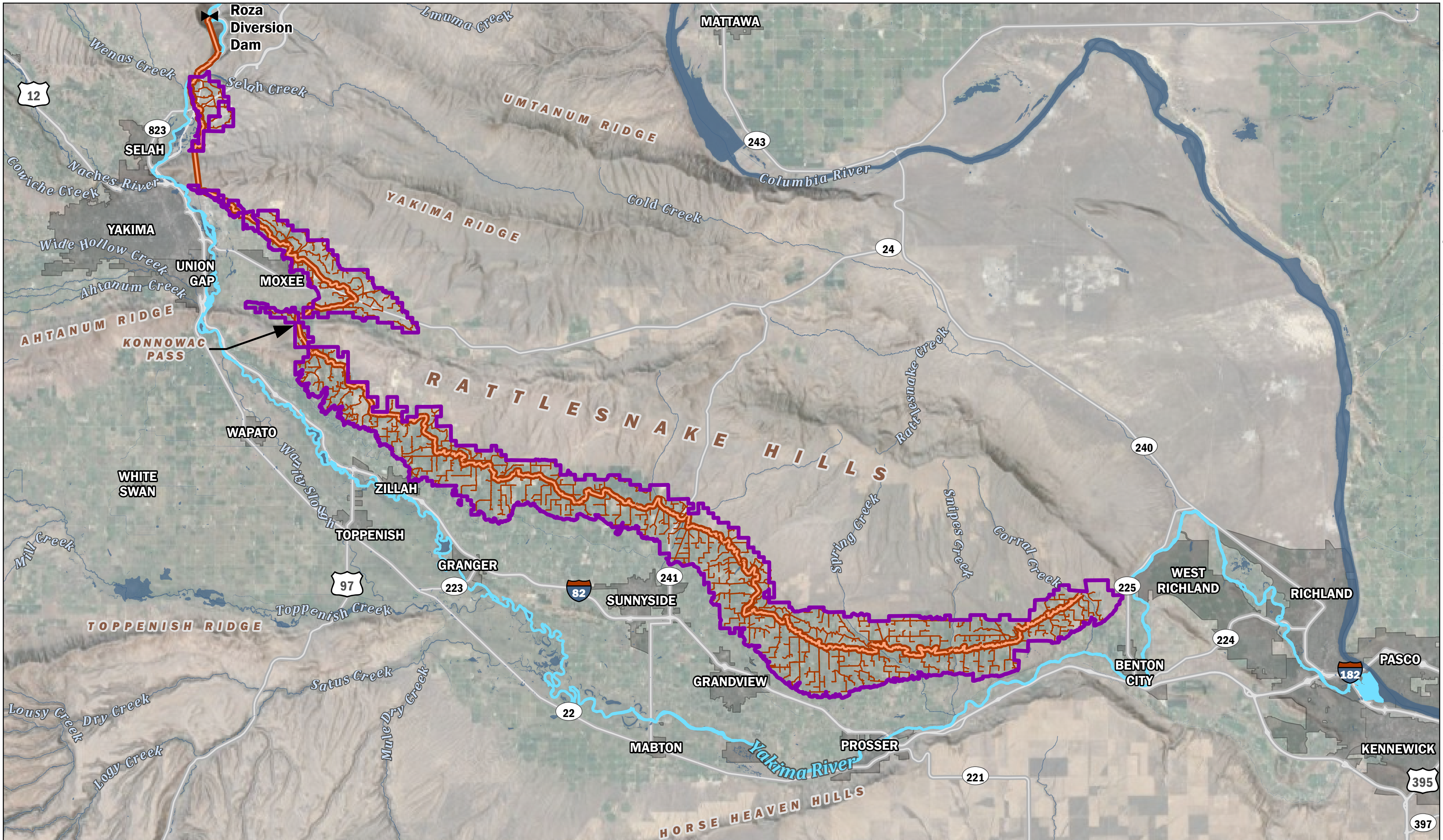
FIGURES



Roza Diversion Dam
Roza Irrigation District
Main Canal
Lateral

N
0 3.5 7 Miles

Study Area

Evaluation of Aquifer Storage and Recovery Feasibility
YRBWEP Groundwater Committee
Konnowac Pass ASR
Yakima County, Washington

Geosyntec consultants

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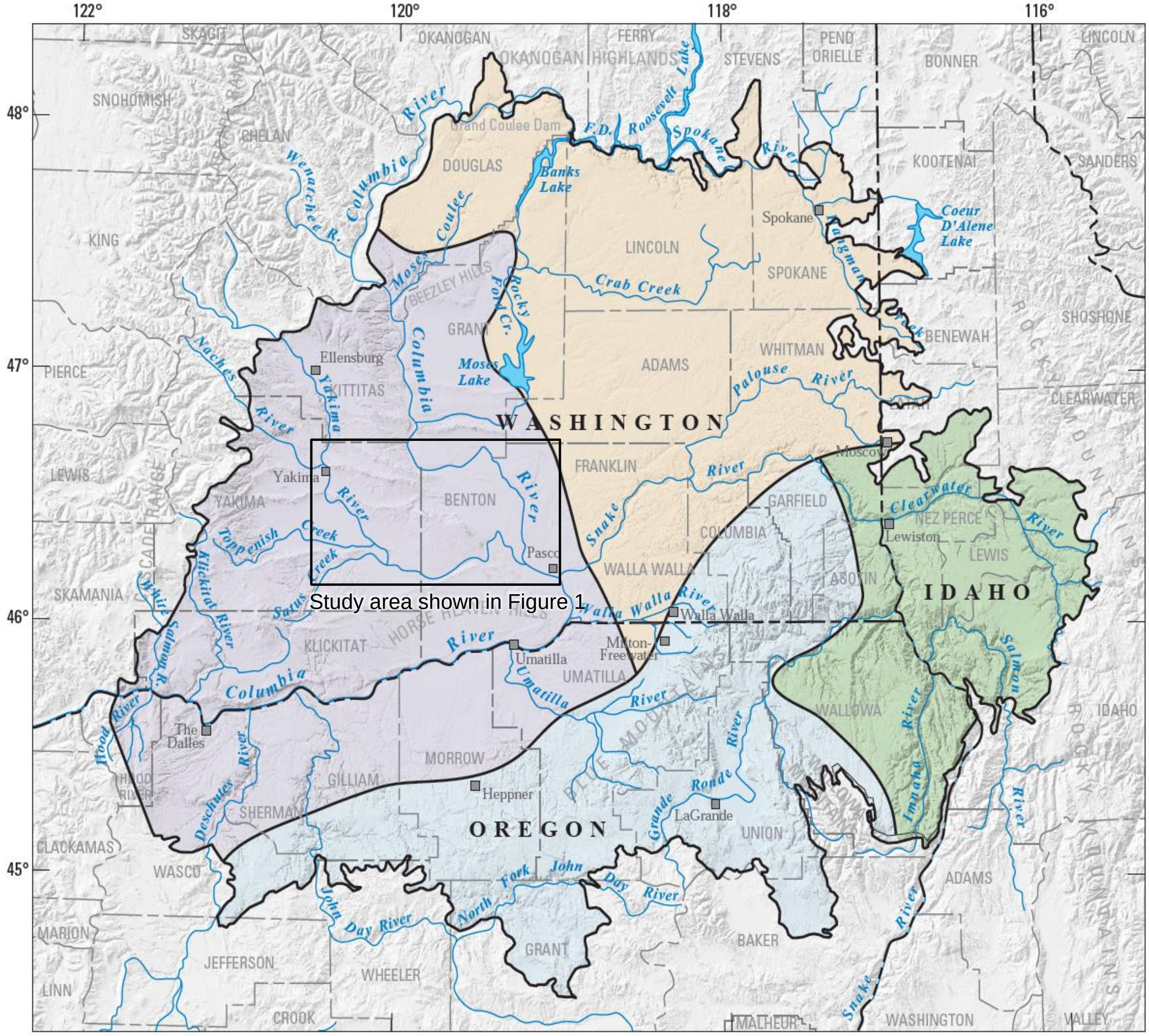


Figure modified from Kahle and others, 2011

- Yakima Fold Belt
- Palouse Slope
- Blue Mountains
- Clearwater Embayment

State boundary

County boundary

City

Columbia Plateau Regional Aquifer System
Geologic Structural Regions

Yakima Basin

Geosyntec consultants

CWU

Figure **2**

Seattle, WA | 25-Mar-2024

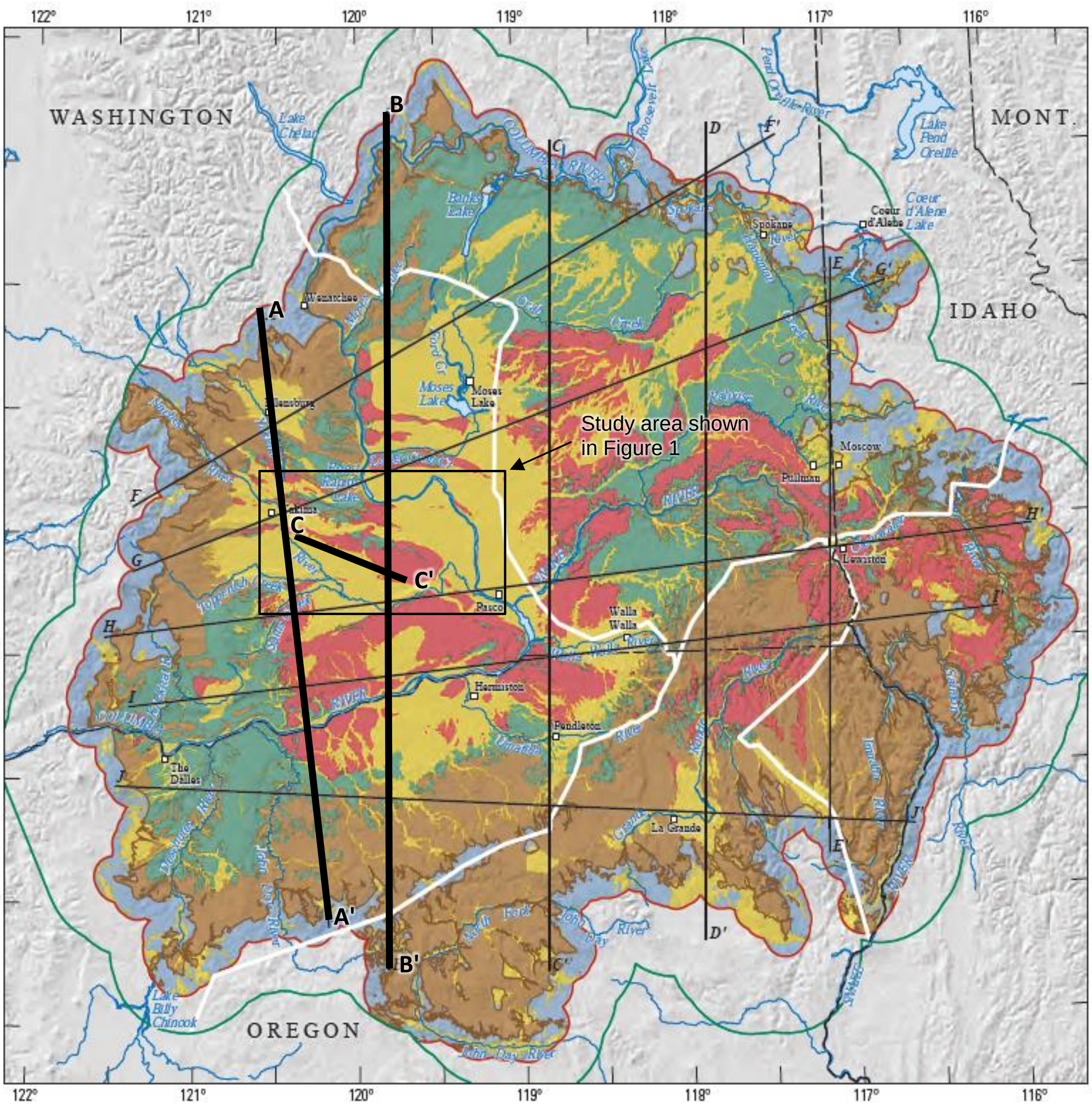
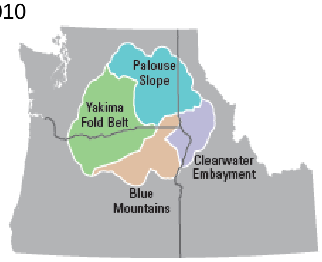


Figure modified from Burns and others, 2010



0 20 40 60 80 100 Miles
0 20 40 60 80 100 Kilometers

Geologic units

- Overburden (sedimentary)
- Saddle Mountains Basalt
- Wanapum Basalt
- Grande Ronde Basalt
- Older Bedrock

A — A′ Trace of cross-section

Modeled extent of Columbia River Basalt Group

Data extent

Geologic model extent

Structural regions of the Columbia Plateau Regional Aquifer System—Names shown on map at right

Columbia Plateau Regional Aquifer System
Surficial Geology
Yakima Basin

Geosyntec consultants	CWU	Figure 3
Seattle, WA	25-Mar-2024	

	Formation	Member	Flow / Unit	Age (Ma)
Quaternary to Pliocene	Overburden	Alluvium and mass wasting		Present to 6
		Touchet, loess, Thorp gravels, and Missoula flood deposits		
Columbia River Basalt Group (Miocene)	Upper Ellensburg	Snipes Mtn. Conglomerate		6 to 15
	Saddle Mountains Basalt	Elephant Mountain		
	Lower Ellensburg	Rattlesnake Ridge		
	Saddle Mountains Basalt	Pomona		
	Lower Ellensburg	Selah		
	Saddle Mountains Basalt	Umatilla	Slliusi	
			Umatilla	
	Lower Ellensburg	Mabton		14.5
	Wanapum Basalt	Priest Rapids	Lolo	15 to 15.6
			Rosalia	
		Roza		
	Lower Ellensburg	Squaw Creek		
	Wanapum Basalt	Frenchman Springs	Sentinel Gap	
			Sand Hollow	
			Silver Falls	
			Ginko	
	Lower Ellensburg	Vantage		15.4
	Grande Ronde Basalt	Sentinel Bluffs		15.6 to 16
		Winter Water		
		Field Spring		
		Indian Ridge		
		Buttermilk Canyon		
		Armstrong Canyon		
		Ortley		
		Grouse Creek		
		Wapshilla Ridge		
		Mt. Horrible		
		Cold Spring Ridge		
		Hoskins Gulch		
		China Creek		
		Frye Point		
		Downey Gulch		
		Brady Gulch		
		Kendrick Grade		
		Center Creek		
		Skeleton Creek		
		Rogersburg		
		Teepee Buttee		
		Buckhorn Springs		

Based on Reidel (2013)

Major Geologic Units Present in the Study Area

Yakima Basin

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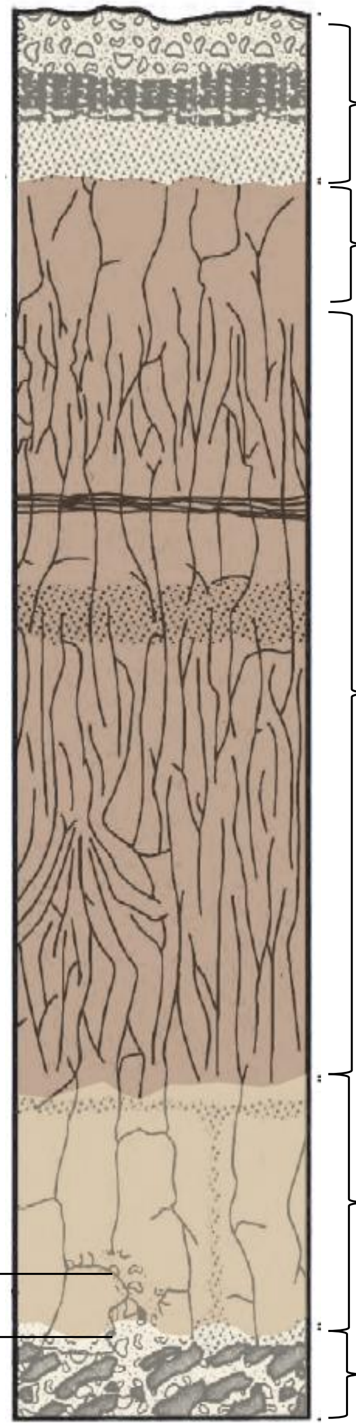

Figure modified from Kahle and others (2011) and Reidel and others (2013)

Diagram of Typical Columbia River Basalt Group Flow Features

Yakima Basin

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Figure 5

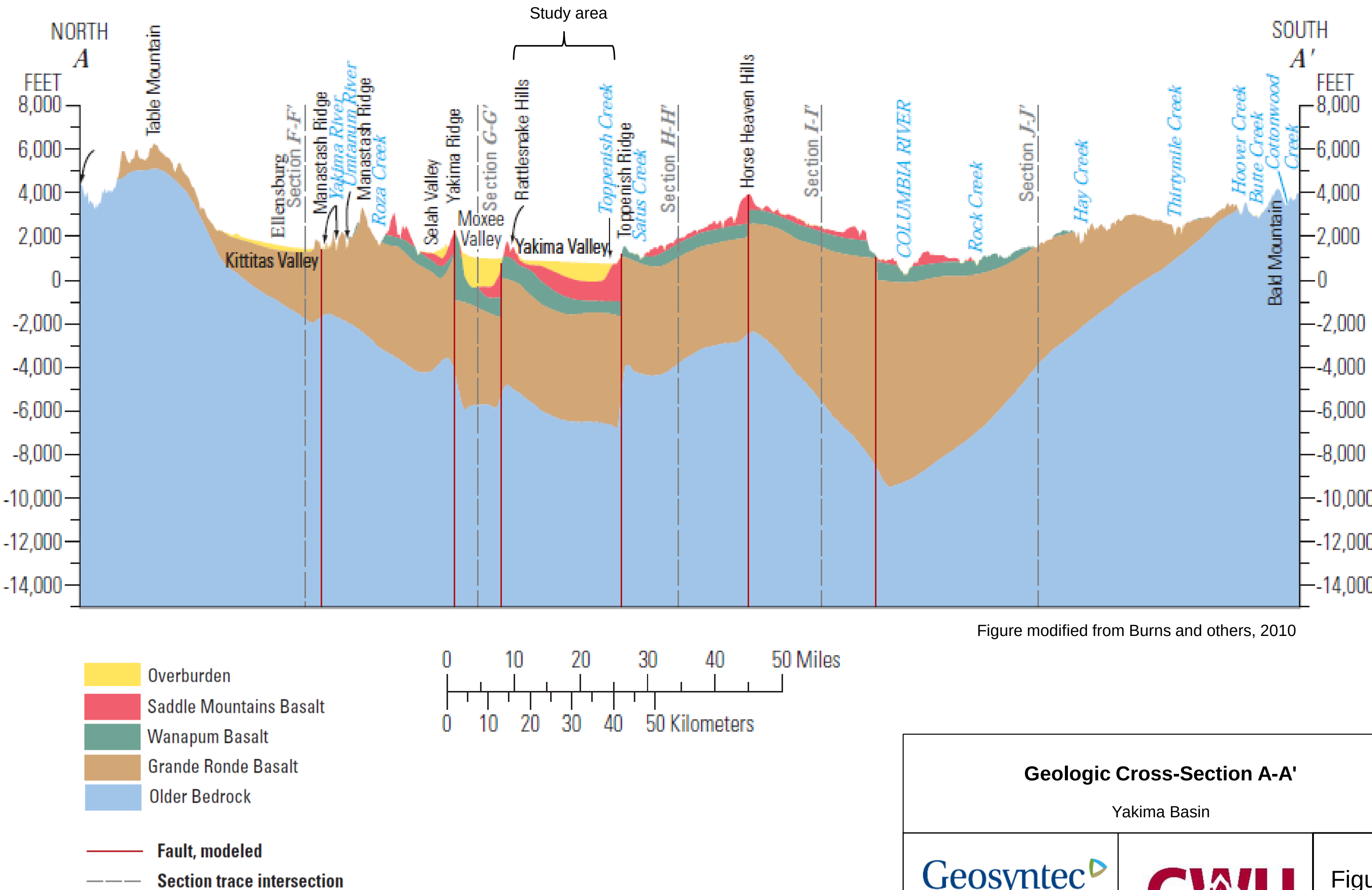

Figure modified from Burns and others, 2010

Geologic Cross-Section A-A'

Yakima Basin

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Seattle, WA | 25-Mar-2024

Study area

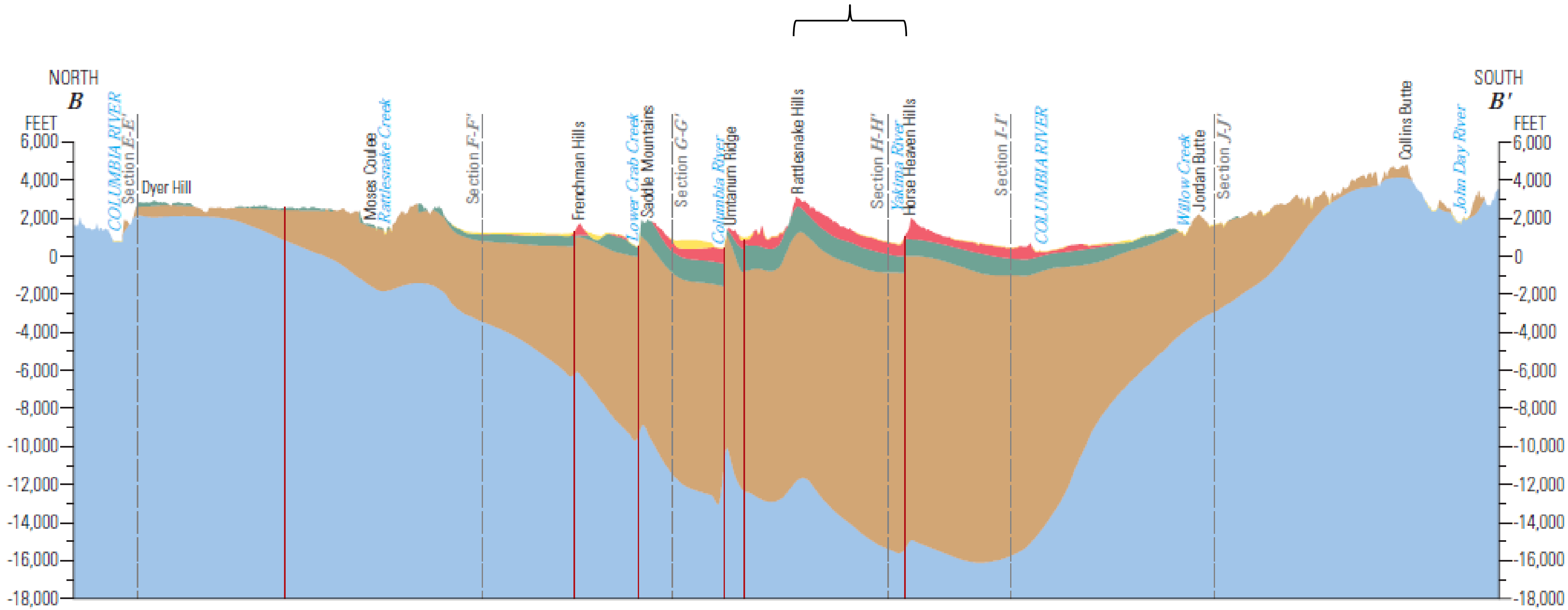

Figure modified from Burns and others, 2010

0 10 20 30 40 50 Miles

0 10 20 30 40 50 Kilometers

- Overburden
- Saddle Mountains Basalt
- Wanapum Basalt
- Grande Ronde Basalt
- Older Bedrock

Fault, modeled

Section trace intersection

Geologic Cross-Section B-B'

Yakima Basin

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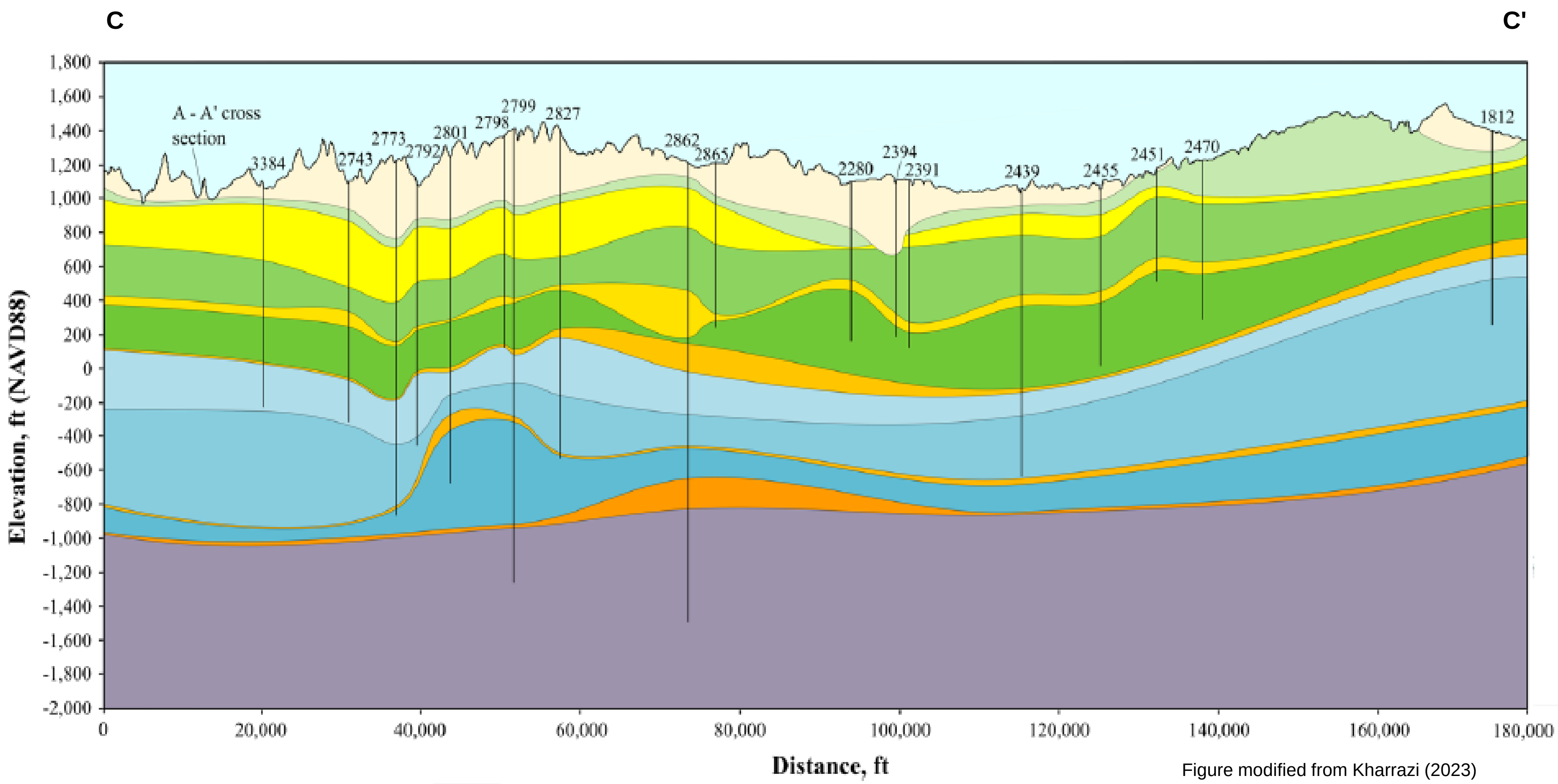
Seattle, WA

25-Mar-2024

Figure 7



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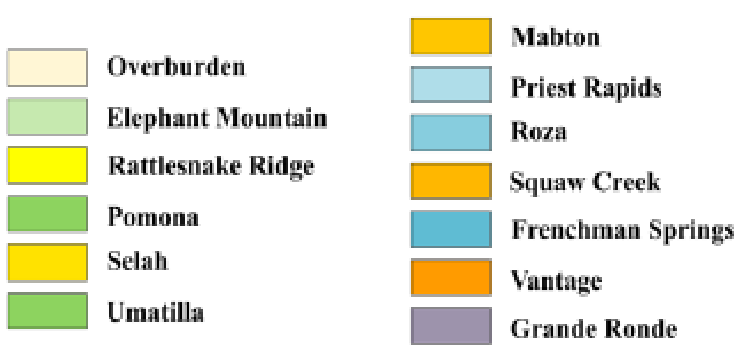

Geologic Cross-Section C-C'

Yakima Basin

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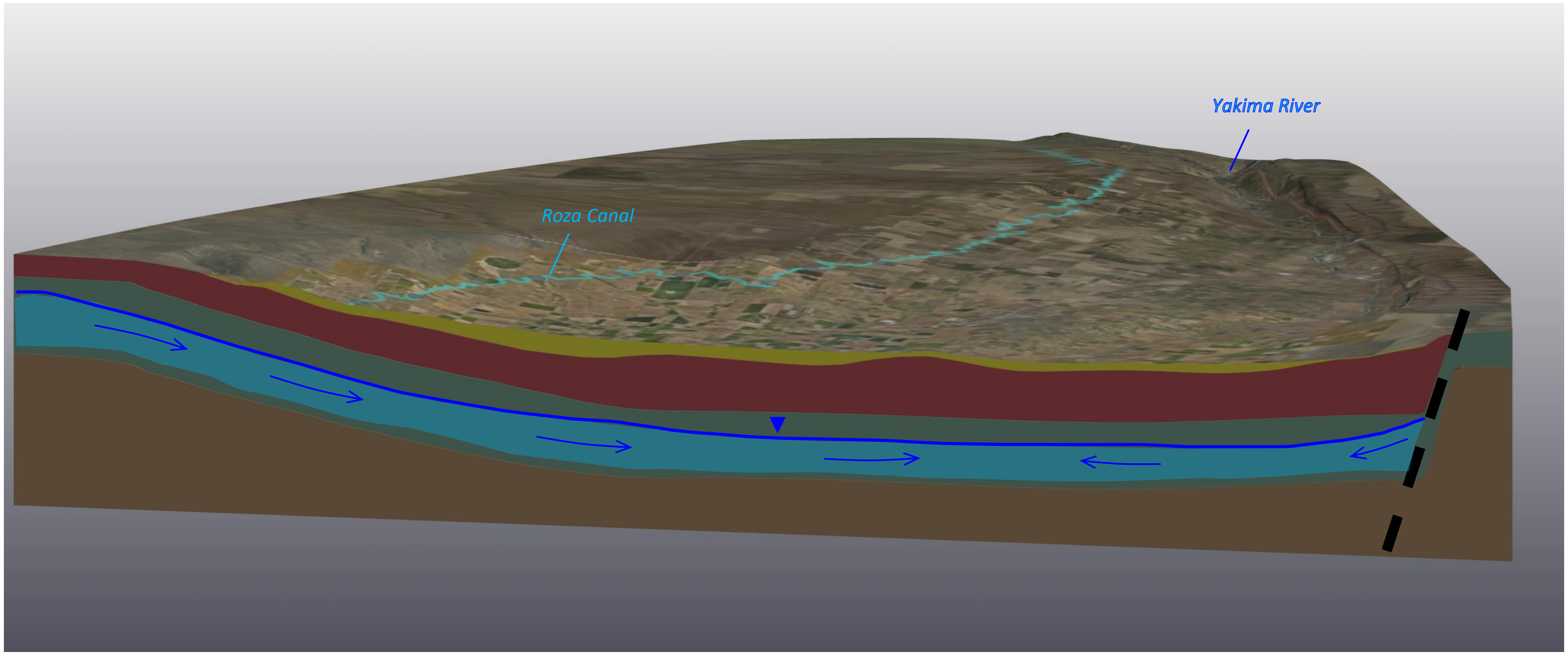

Geology

- Overburden
- Saddle Mountains Basalt
- Wanapum Basalt
- Grande Ronde Basalt

Potentiometric/Phreatic Surface in the Wanapum Aquifer

Generalized groundwater flow direction

Regional fault

Conceptual Groundwater Compartment in the Wanapum Aquifer

Yakima Basin

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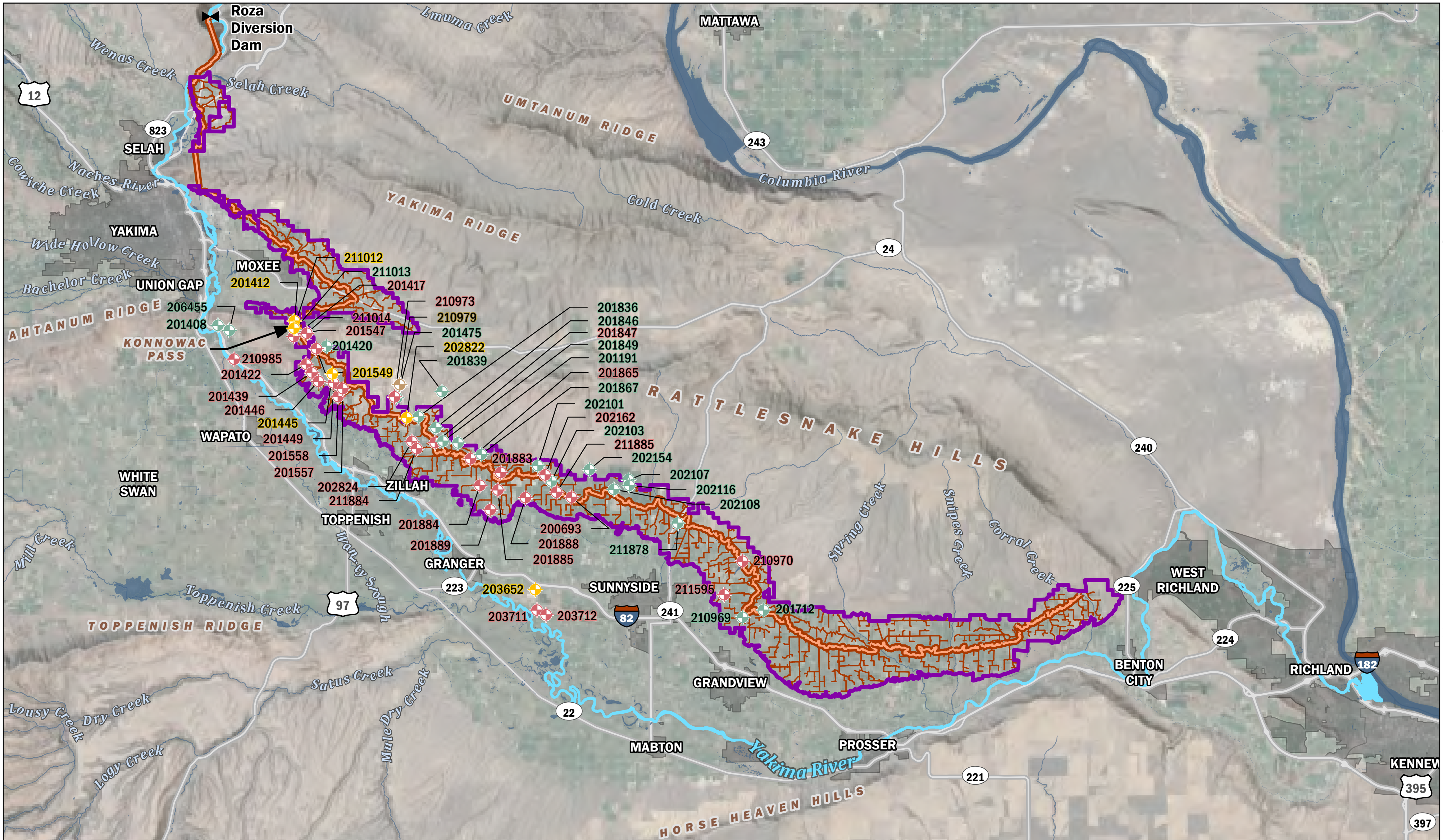
Seattle, WA

25-Mar-2024

Figure 9



Well Location (By Aquifer)

- Saddle Mountains Basalt
- Wanapum Basalt
- Ellensburg Formation
- Grande Ronde Basalt
- Roza Diversion Dam
- Roza Irrigation District
- Main Canal
- Lateral

Note:
Well IDs based on Ecology's Central Regional Office Groundwater Database "CRGWDB" obtained from the Environmental Information Management system

N

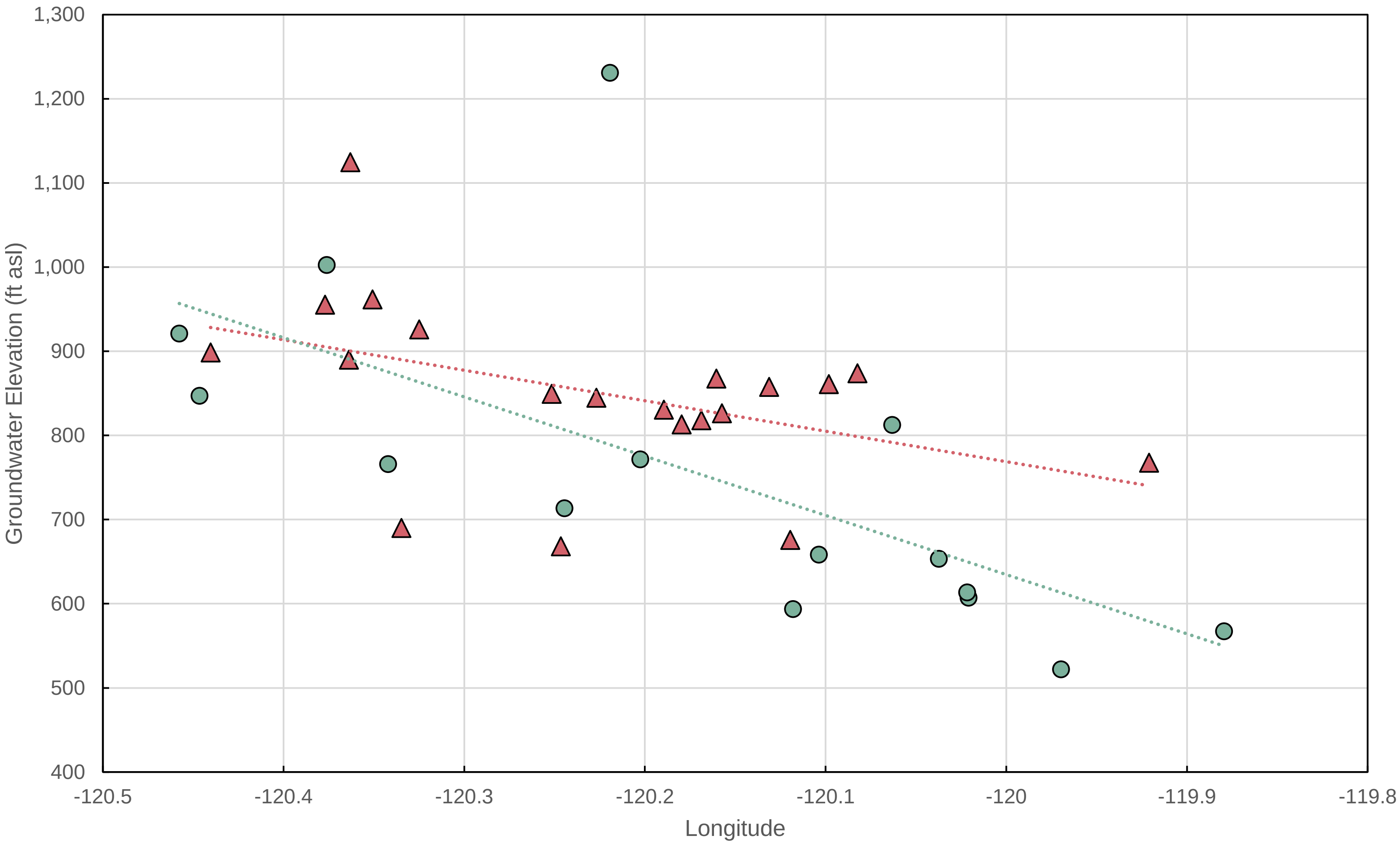
0 18,500 37,000 Feet

Groundwater Wells on South Flank of Rattlesnake Hills

Evaluation of Aquifer Storage and Recovery Feasibility
YRBWEP Groundwater Committee
Konnowac Pass ASR
Yakima County, Washington

Geosyntec consultants

FEB-2024	BY: DH / NLK	FIGURE NO. 10
PROJECT NO. PNG0983	REVISED BY: HMD	



Groundwater Elevations in Saddle Mountains and Wanapum Aquifers

Yakima Basin

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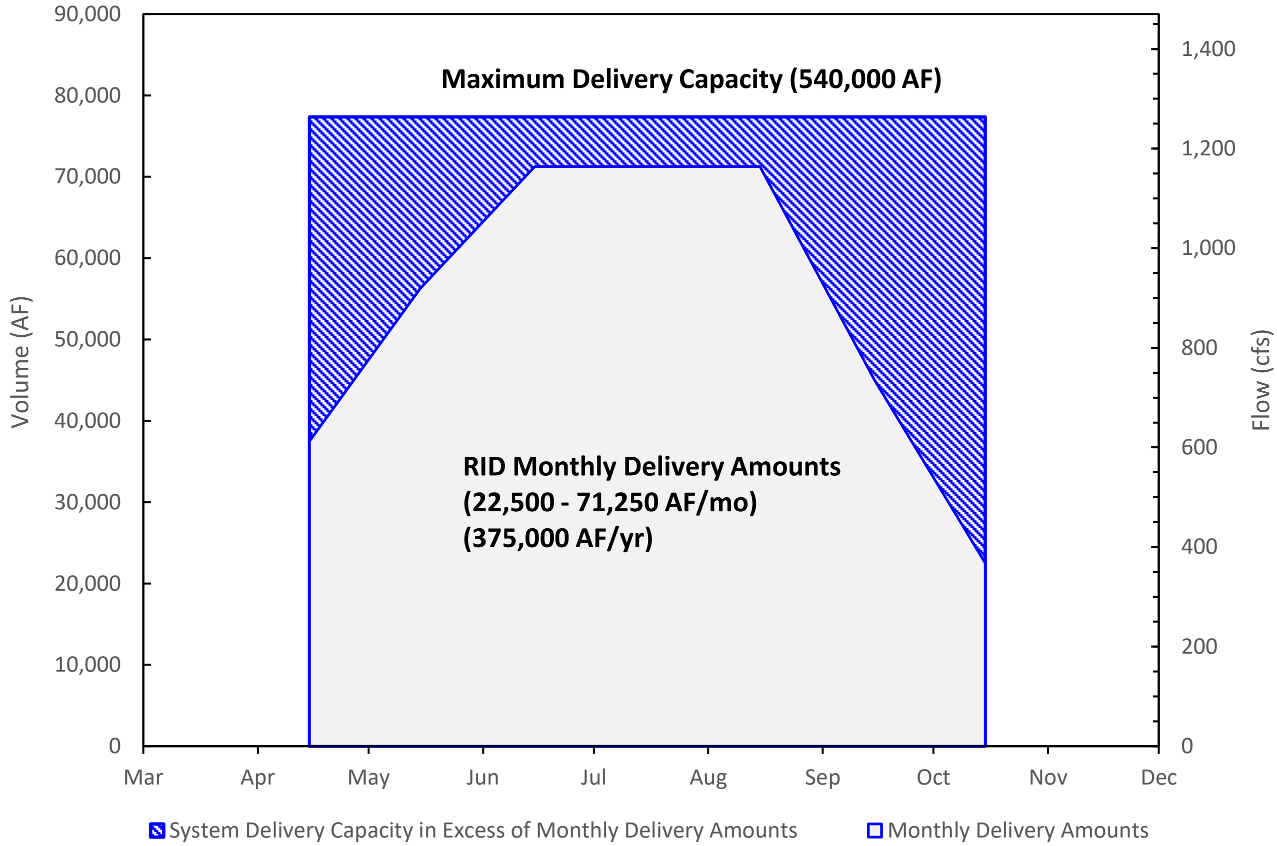
Figure **11**

Seattle, WA

25-Mar-2024



Delivery amounts based on RID watermaster's report (April 2022).
Maximum system capacity assumed to 1,300 cfs.

Month	Delivery Amount (AF/mo)	Allowable flow (cfs)
April	37,500	625
May	56,250	937
June	71,250	1187
July	71,250	1187
August	71,250	1187
September	45,000	750
October	22,500	750

Roza Irrigation District System Demand

Yakima Basin

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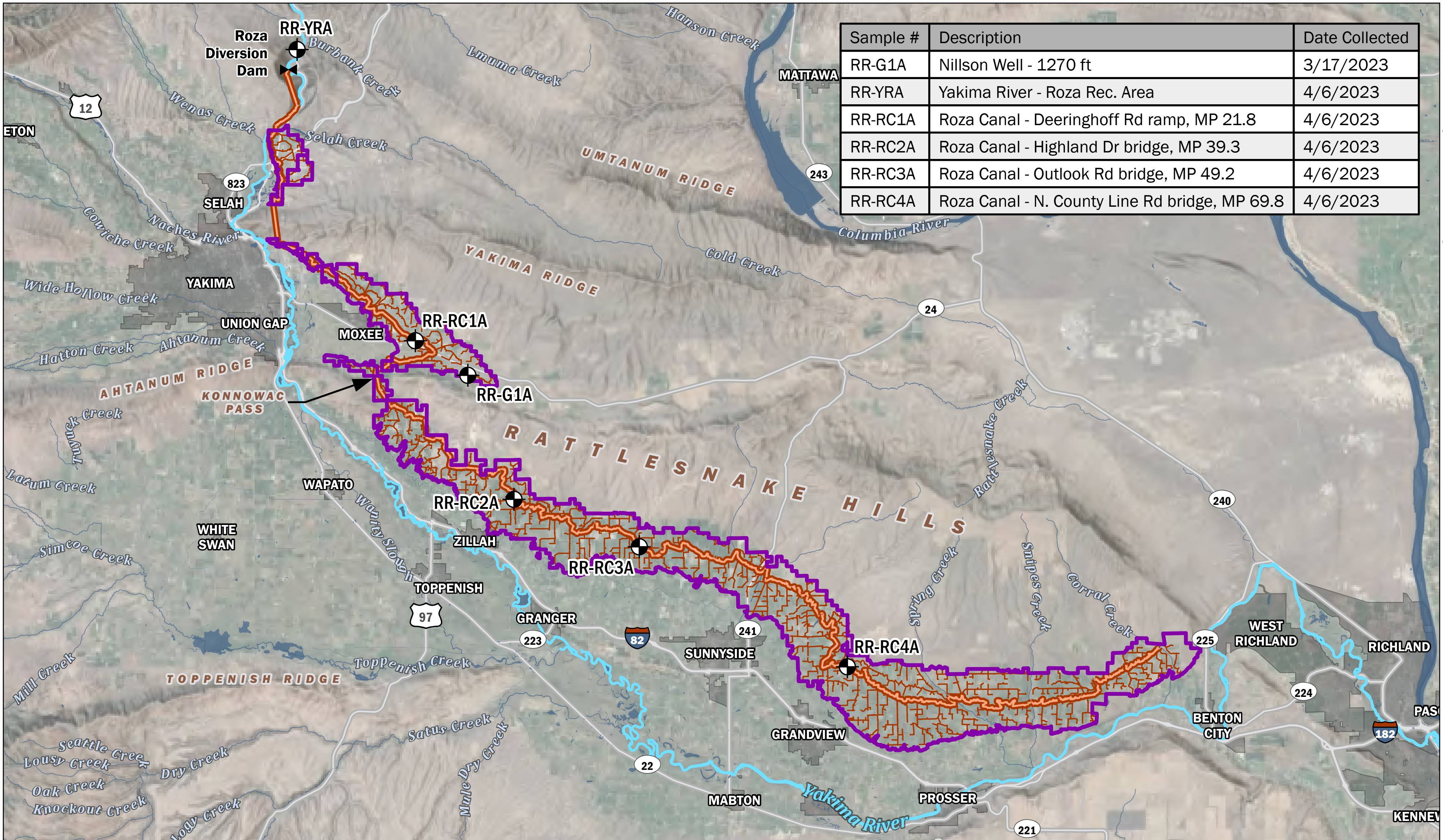
Figure **12**

Seattle, WA | 25-Mar-2024



Sample #	Description	Date Collected
RR-G1A	Nillson Well - 1270 ft	3/17/2023
RR-YRA	Yakima River - Roza Rec. Area	4/6/2023
RR-RC1A	Roza Canal - Deeringhoff Rd ramp, MP 21.8	4/6/2023
RR-RC2A	Roza Canal - Highland Dr bridge, MP 39.3	4/6/2023
RR-RC3A	Roza Canal - Outlook Rd bridge, MP 49.2	4/6/2023
RR-RC4A	Roza Canal - N. County Line Rd bridge, MP 69.8	4/6/2023

Sample Location
Roza Diversion Dam
Roza Irrigation District
Main Canal
Lateral

N

0 18,500 37,000 Feet

Water Sample Locations

Evaluation of Aquifer Storage and Recovery Feasibility
YRBWEP Groundwater Committee
Konnowac Pass ASR
Yakima County, Washington

Geosyntec consultants	FEB-2024	BY: DH / NLK	FIGURE NO. 13
	PROJECT NO. PNG0983	REVISED BY: HMD	

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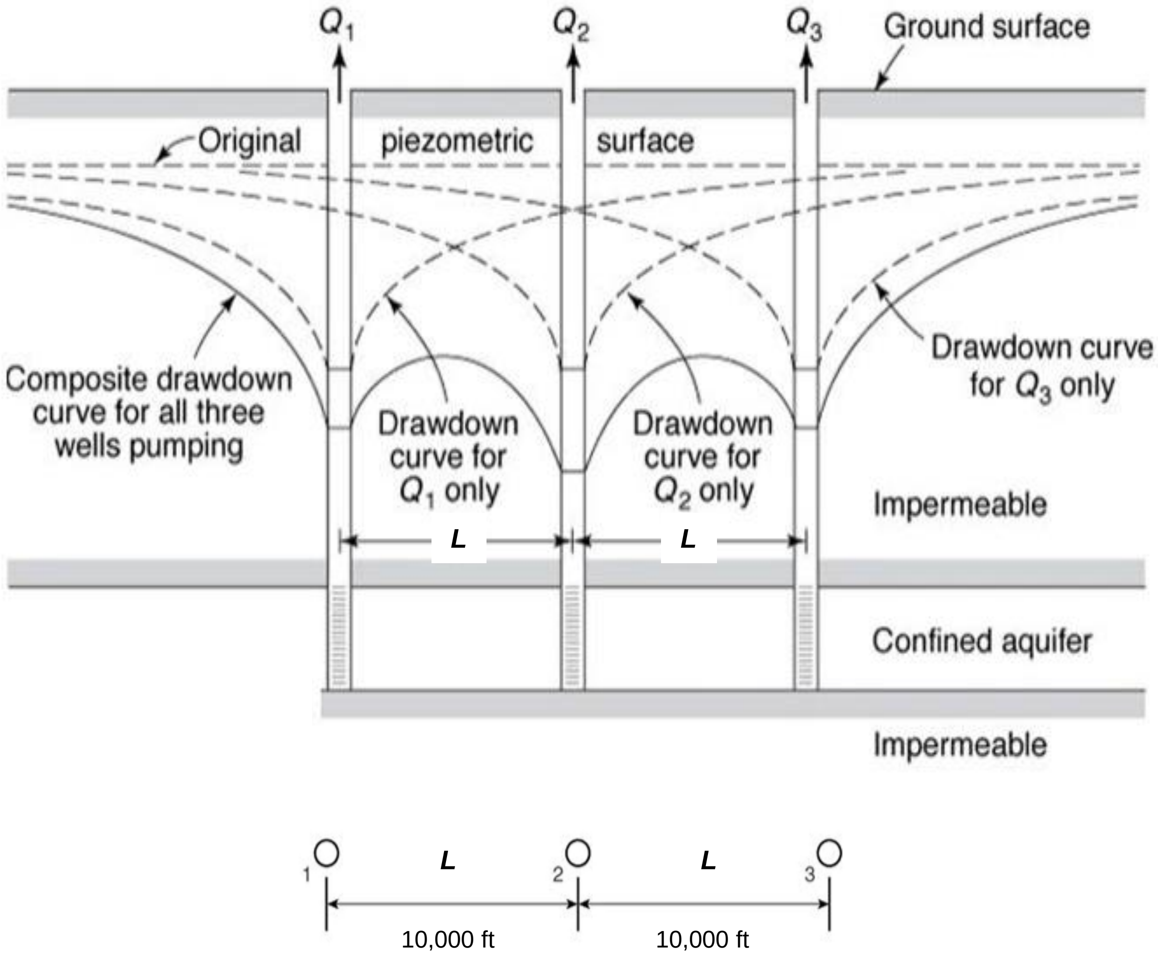
GIS Path: G:\projects\RattlesnakeRidgeASR_PNG0983\RattlesnakeRidgeASR_PNG0983.aprx; 13 - Water Sample Locations || User: haley.duran || Print Date: 2/8/2024

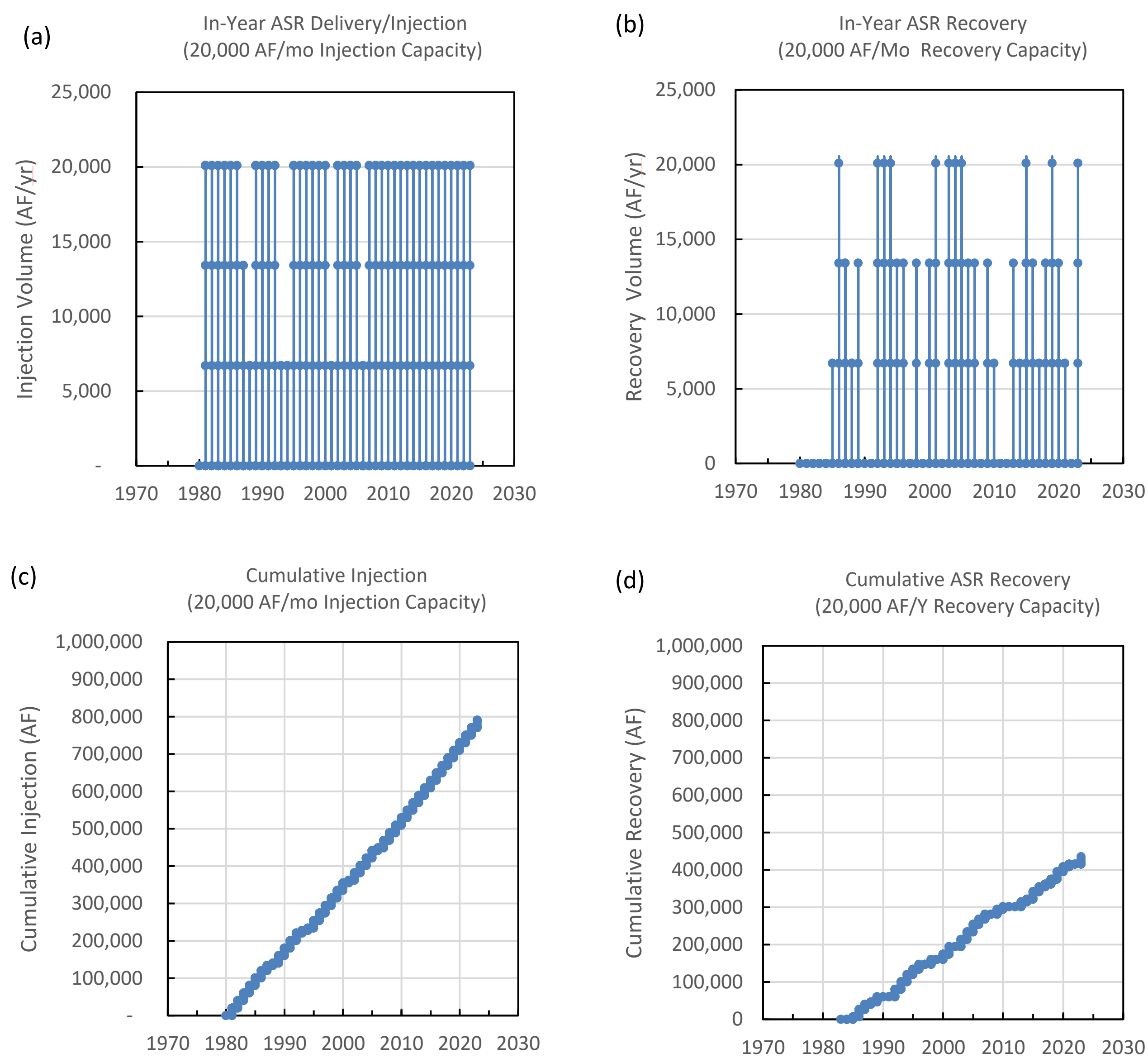


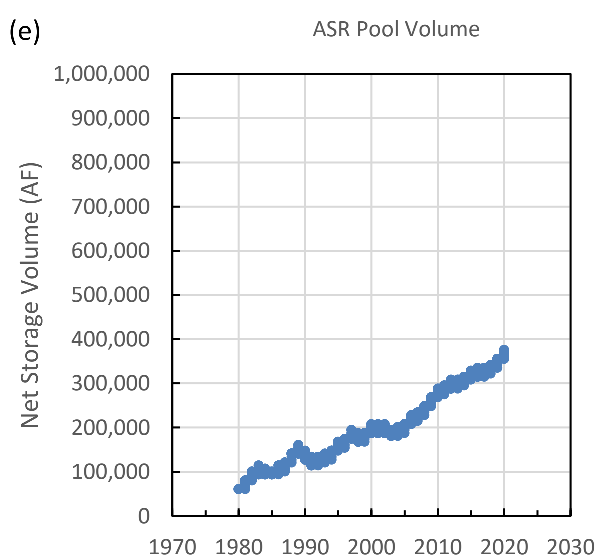
ASR Conceptual Wellfield Model using Theis Superposition Method

Yakima Basin

Geosyntec consultants | CWU | Figure 14

Seattle, WA | 25-Mar-2024

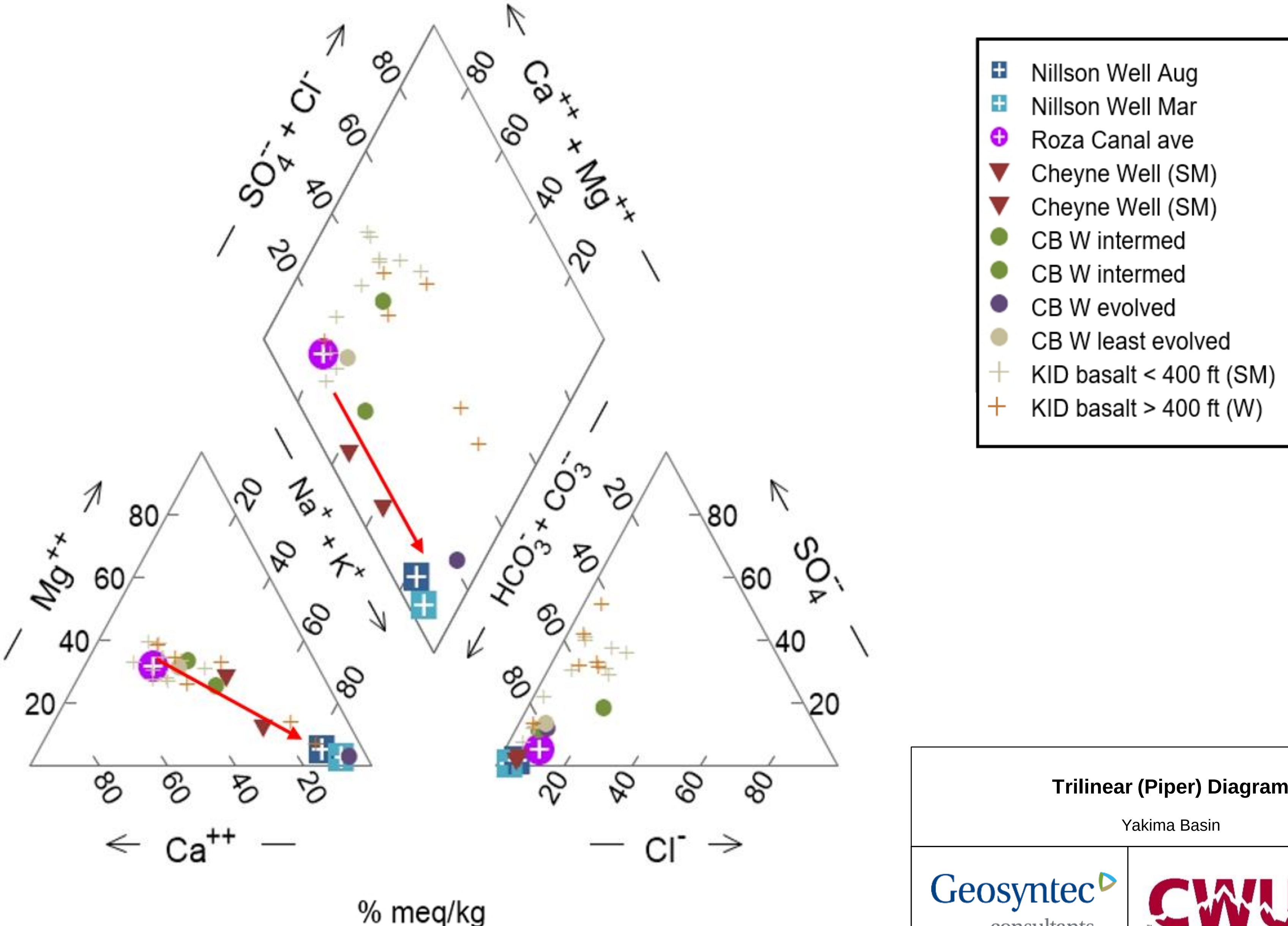




Hypothetical ASR Operation (1981 to 2023)

Yakima Basin

Geosyntec consultants	CWU	Figure **15**
Seattle, WA	25-Mar-2024	

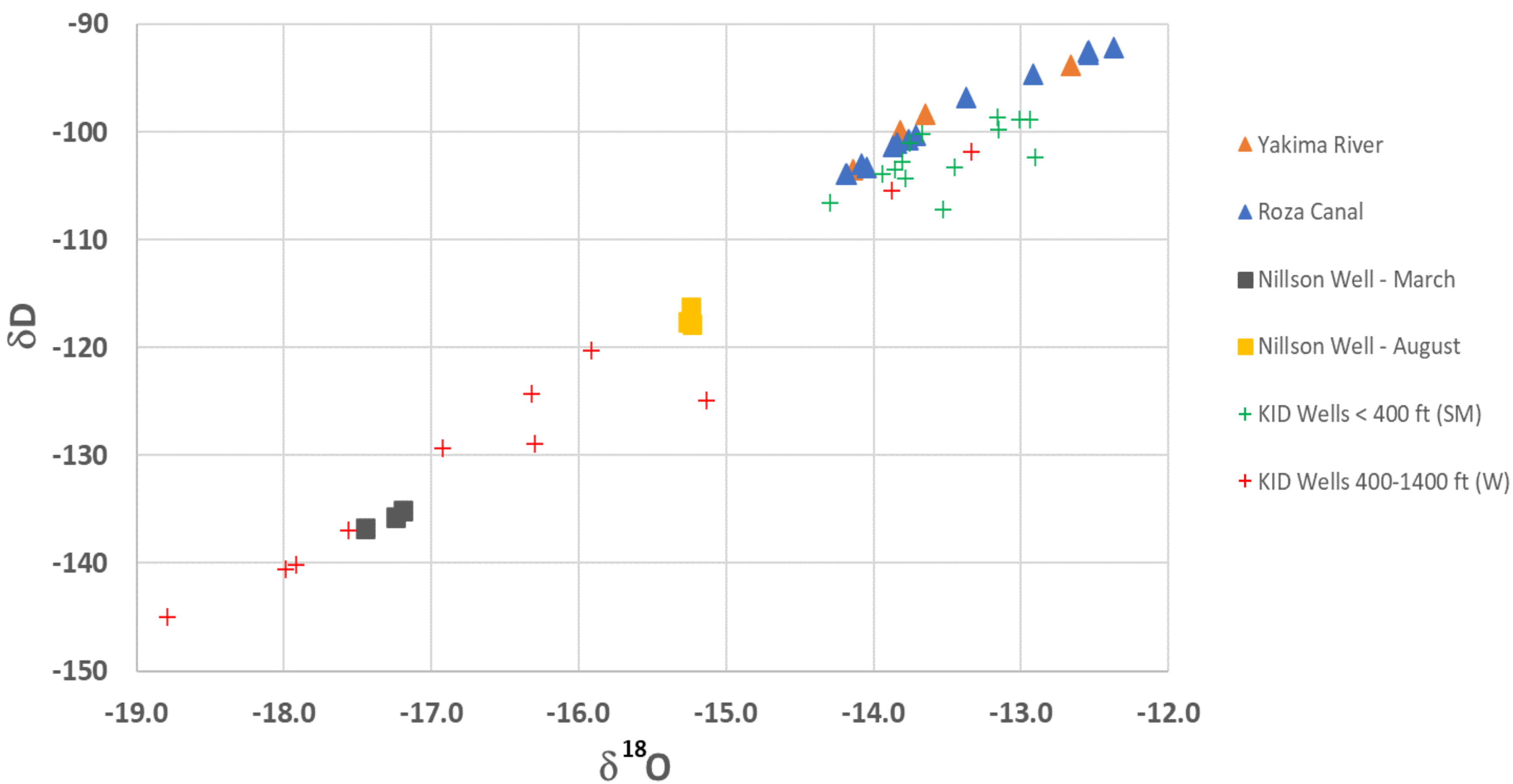


Trilinear (Piper) Diagram

Yakima Basin

Geosyntec consultants | CWU | Figure **16**

Seattle, WA | 25-Mar-2024

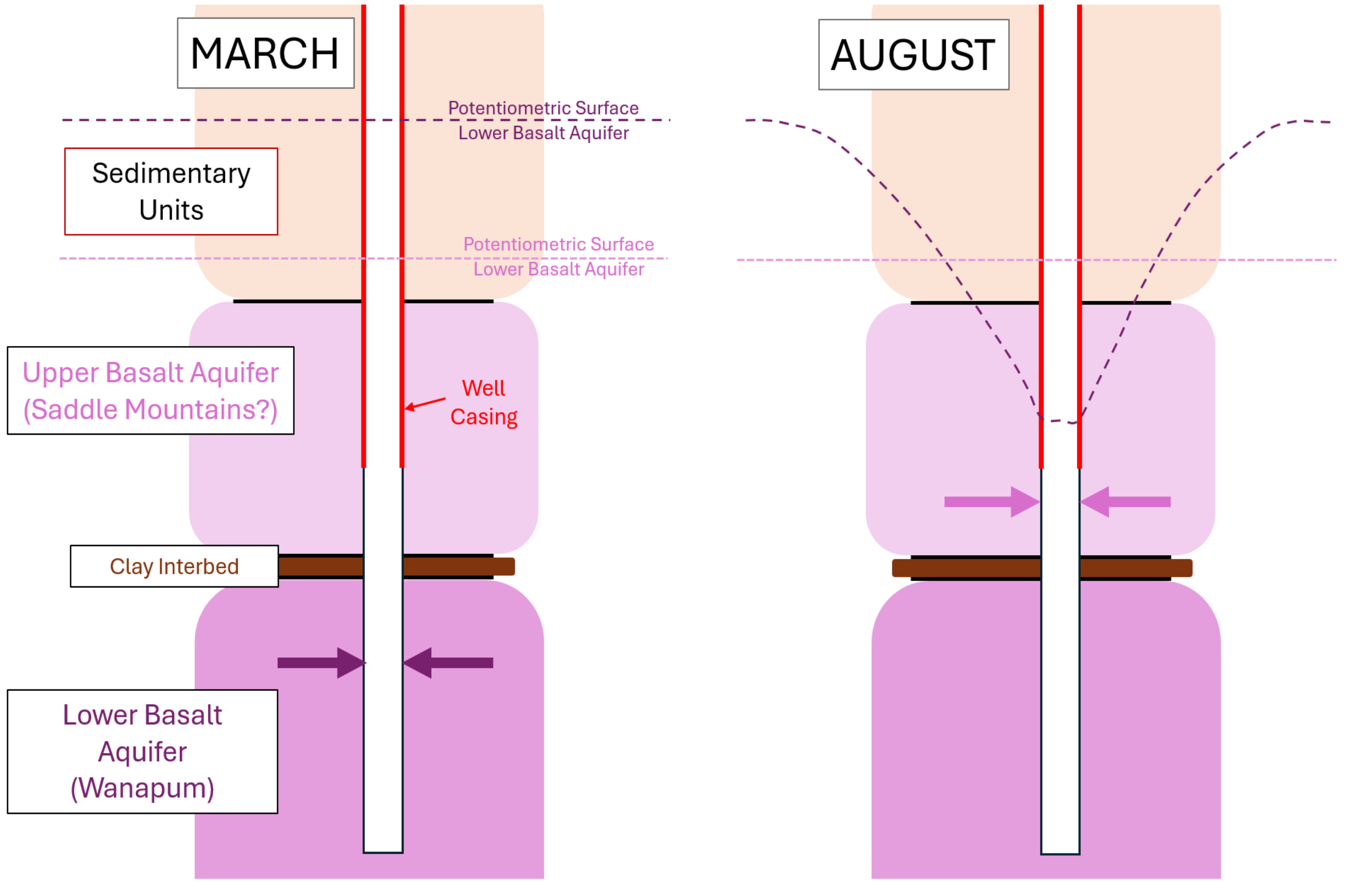


Stable Isotope Ratios

Yakima Basin

Geosyntec consultants | CWU | Figure 17

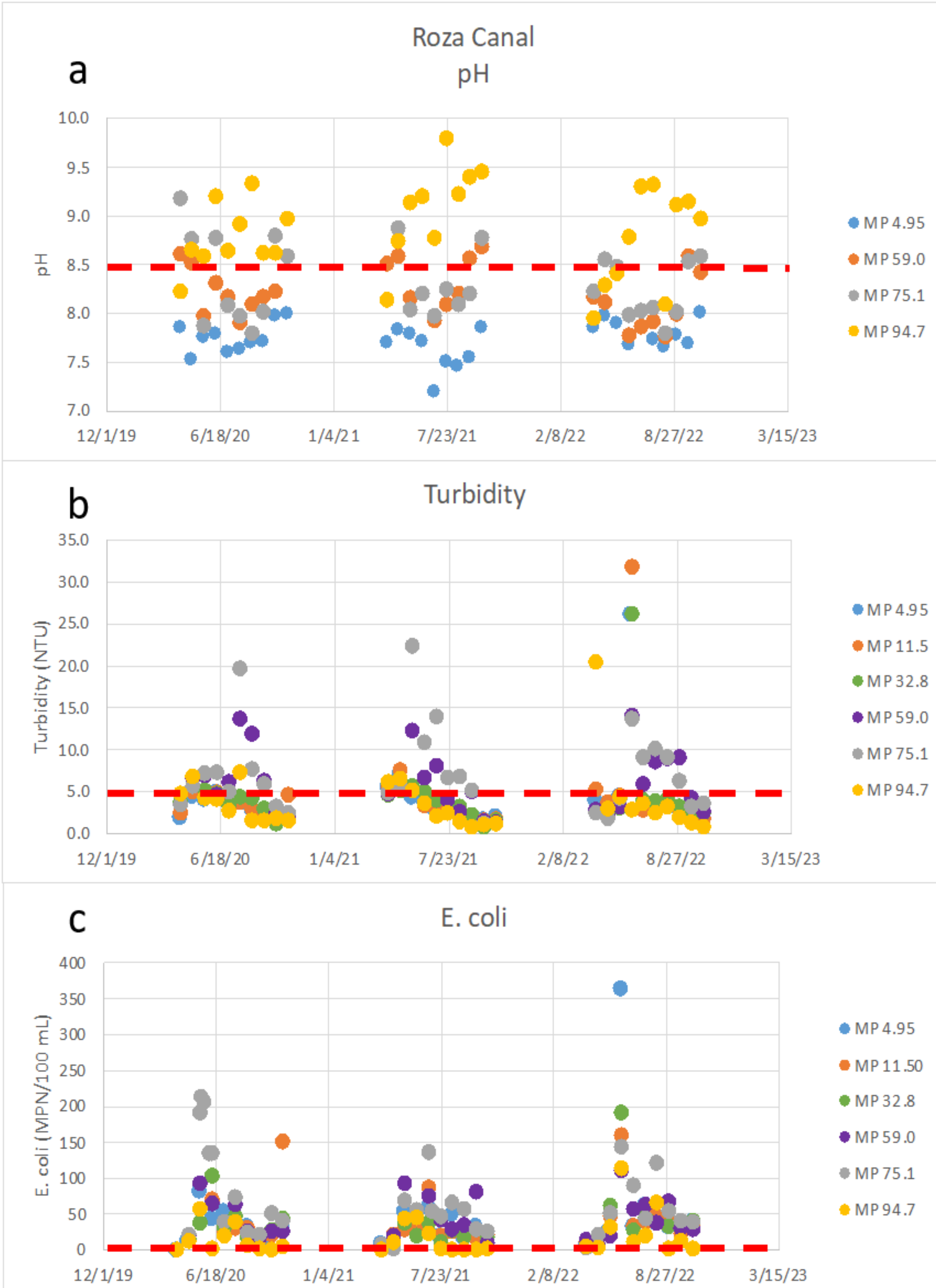
Seattle, WA | 25-Mar-2024



Conceptual Understanding of the Isotopic Shift in the Nillson Well

Yakima Basin

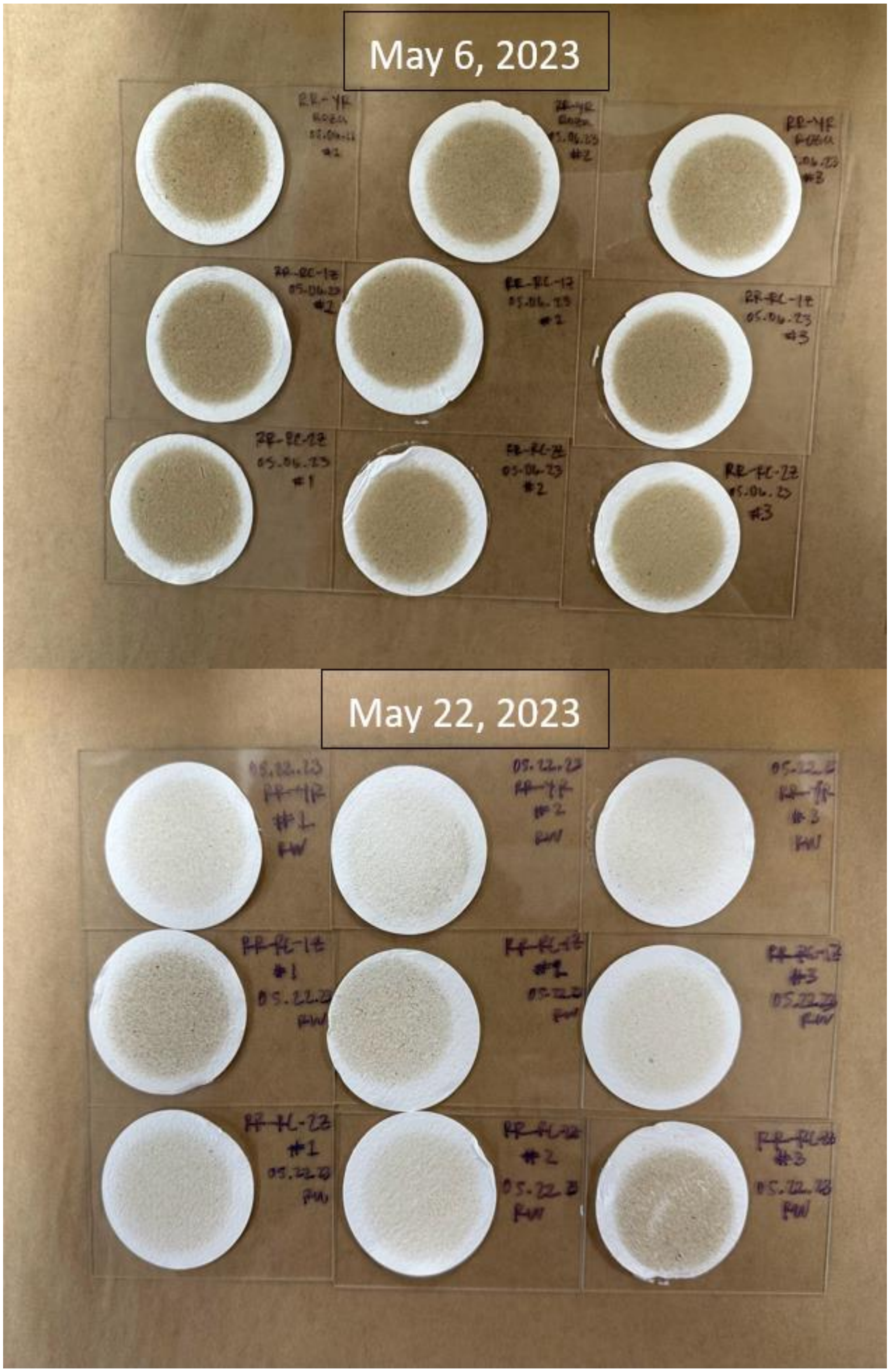
Seattle, WA	25-Mar-2024	Figure 18



Dashed red lines represent the primary drinking water MCLs for pH and E. coli and SMCL for turbidity (WAC 246-290-310).

pH, Turbidity, and E. coli Measurements in Roza Canal during Irrigation Season (2020-2022)
Yakima Basin

Geosyntec consultants	CWU	Figure **19**
Seattle, WA	25-Mar-2024	

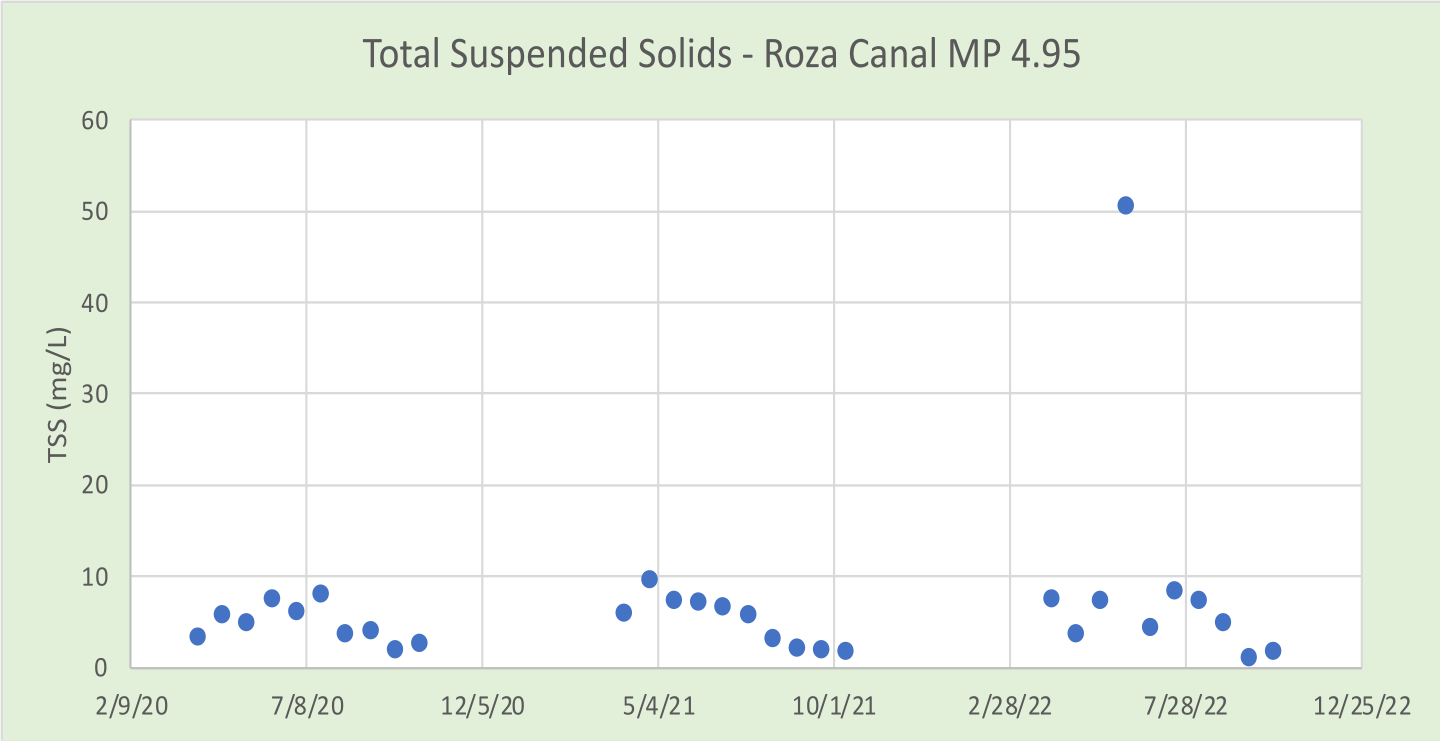


Note: filters contain sediment from 300 mL of water sample. Each row consists of three samples collected from a single site (top to bottom: YR, RC1, and RC2).

Suspended Solids from Yakima River and Roza Canal (May 2023)

Yakima Basin

Geosyntec consultants	CWU	Figure 20
Seattle, WA	25-Mar-2024	



Data from RSJBOC (2020-2022)

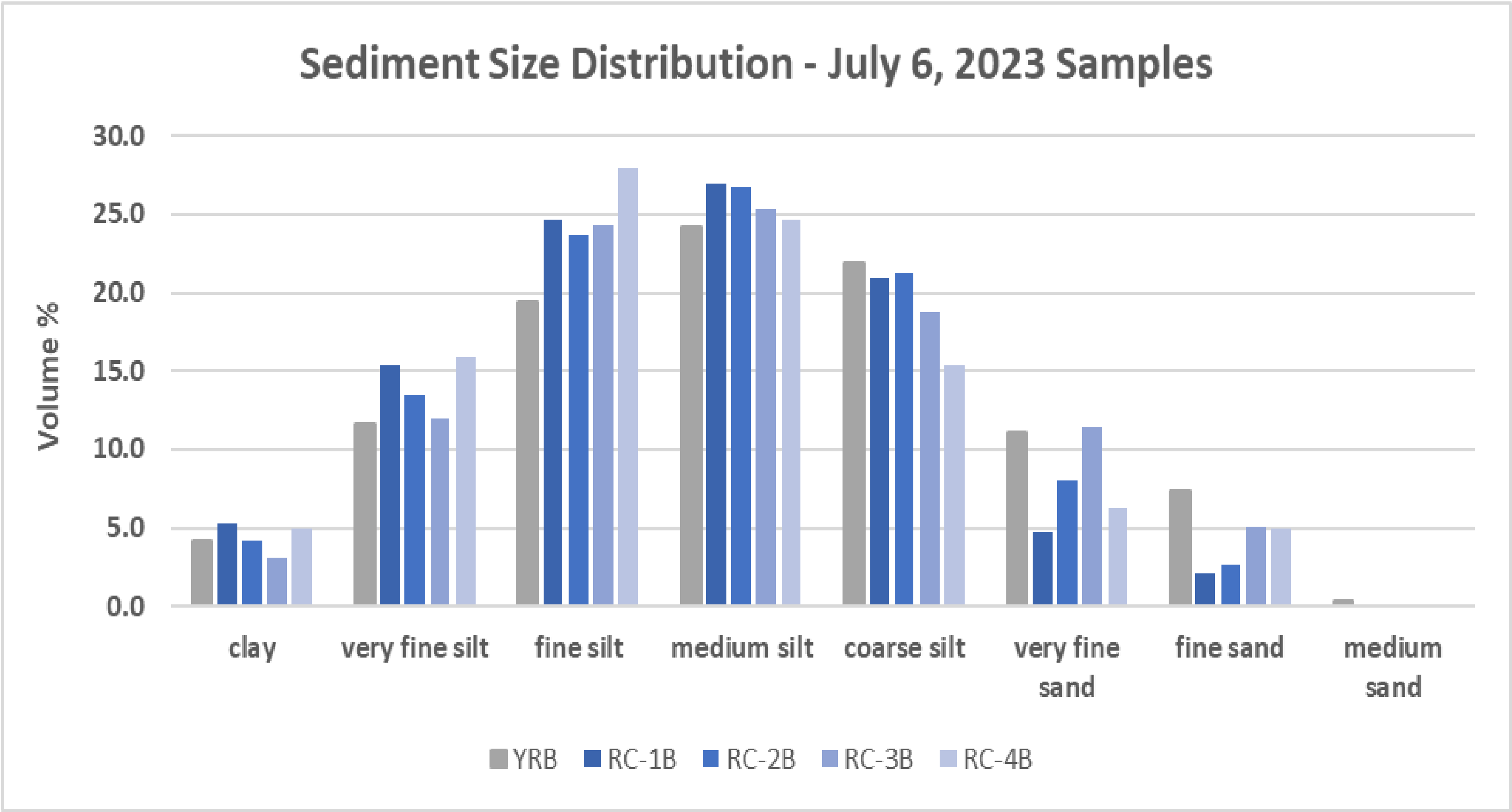
Total Suspended Solids Measurements in Roza Canal at MP4.95 during Irrigation Seasons (2020-2022)
Yakima Basin

Geosyntec consultants

Seattle, WA

25-Mar-2024

Figure **21**



Sediment size distribution of five surface water samples collected on July 6, 2023. Sizes were determined using the Malvern Mastersizer 3000 and are divided based on the Wentworth grade scale (Wentworth, 1922)

Sediment Size Distribution from Yakima River and Roza Canal

Yakima Basin

Geosyntec consultants | CWU | Figure 22
Seattle, WA | 25-Mar-2024

2020 Herbicide Applications

RC Mile	May	June	July	Aug	Sep
11.0	1960		3602		
37.2		457		496	
51.5		311		316	
59.1		106			99
62.2		240		274	
67.3		77			76
74.7		117		145	
75.1		48		51	71
82.0			61	25	37.7
84.6		27	33.8	50.2	
		60			
88.5	11		21.9	11	6
					48
91.5	8	19	18	8.1	4
					34

2021 Herbicide Applications

RC Mile	May	June	July	Aug	Sep
11.0	2616		3624		
37.2		384		453	
51.5		311		320	
59.1					
62.2		179		274	
67.3				59	
74.7		108		132	
75.1	17			37	
	75		73		34
82.0	9			44	
	39		39		19
84.7		61	40	34	
88.5	4			19	
	15		14		7
91.5	3	19	13	6	11.3

2022 Herbicide Applications

RC Mile	May	June	July	Aug	Sep
11.0	2242		3531		
37.2		384		412	
51.5		311		367	
59.1	67	91			
62.2		192		274	
67.3	46	71			
74.7		93		155	
75.1	31		52		49
82.0	17		27		
84.7		48	68	35	48
88.5	7				
91.5		16	22		19

2020 Measured Concentrations

RC Mile	May	June	July	Aug	Sep
11	**2420**, 4.56*		**2510**		
37.2					
51.5					
59.1		0.0047			134
62.2					
67.3		0.0047			127
74.7					
75.1				98	111
82			0.0257	105	123
84.6					
88.5				93, 7	
91.5				86, 13	

* second measurement one week after treatment

2021 Measured Concentrations

RC Mile	May	June	July	Aug	Sep
11	**3410**		**3180**		
37.2		**83**, ND		**1320**	
51.5		**50**		**976**	
59.1					
62.2				**1420**	
67.3				**141, 2**	
74.7				**808**	
75.1	48, 47		0.069		
82	51, 40		0.0564	140	
84.6			0.0482	129	
				0.0796	
88.5	56		0.0783	179	
91.5	50		0.079	164	0.0982, 0.0127

2022 Measured Concentrations

RC Mile	May	June	July	Aug	Sep
11	**2640**		**2920**		
37.2					
51.5					
59.1		0.0095			
62.2		ND			
67.3		0.0132			
74.7					
75.1			128		
82			119		
84.6		ND			
88.5					
91.5					

Cascade - Endothall	Teton - Endothall	Acrolein	Captain XTR - Copper

Amounts are total loads of active ingredient in kg

Measured concentration in ug/L for Cascade, Teton, and Acrolein; in mg/L for copper

Bold represents values above drinking water standard (Cascade) or EPA target (Acrolein)

Data from RID (2020-2022a, 2020-2022b)

Herbicide Application and Measured Concentrations for 2020-2022

Yakima Basin

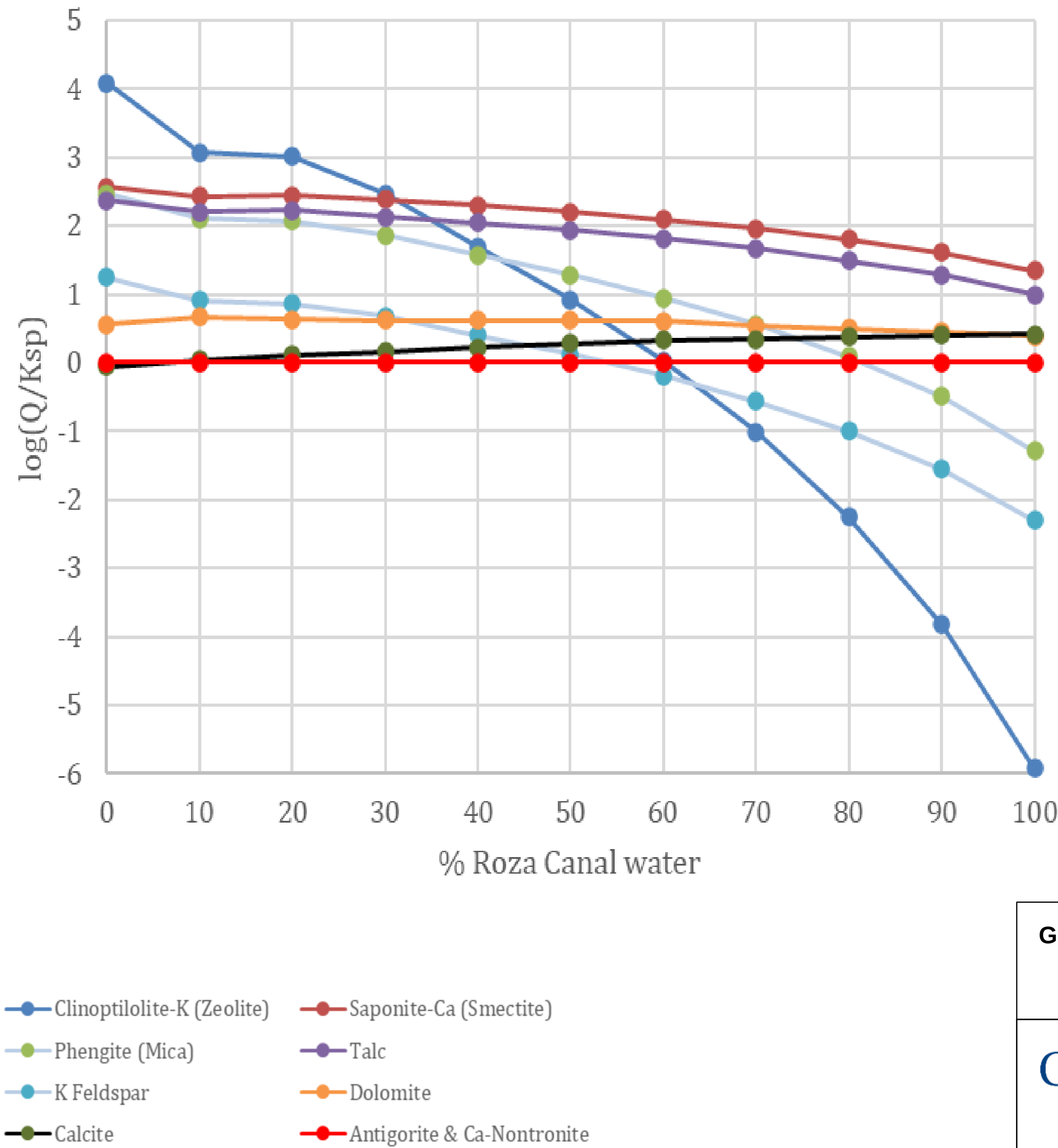
Geosyntec consultants

CWU

Seattle, WA

25-Mar-2024

Figure 23



Solubilities of minerals in different percent mixtures of Wanapum groundwater and Roza Canal water. Results from Geochemist's Workbench modelling described in text.
Q = ion product for mineral,
Ksp = equilibrium solubility product.

Antigorite and Ca-Nontronite (red line and dots) were set as buffers for Mg2+ and Fe2+, respectively, and are in equilibrium with the water mixtures (Q = Ksp).

Geochemical Model Results of Source Water with Ambient Groundwater

Yakima Basin

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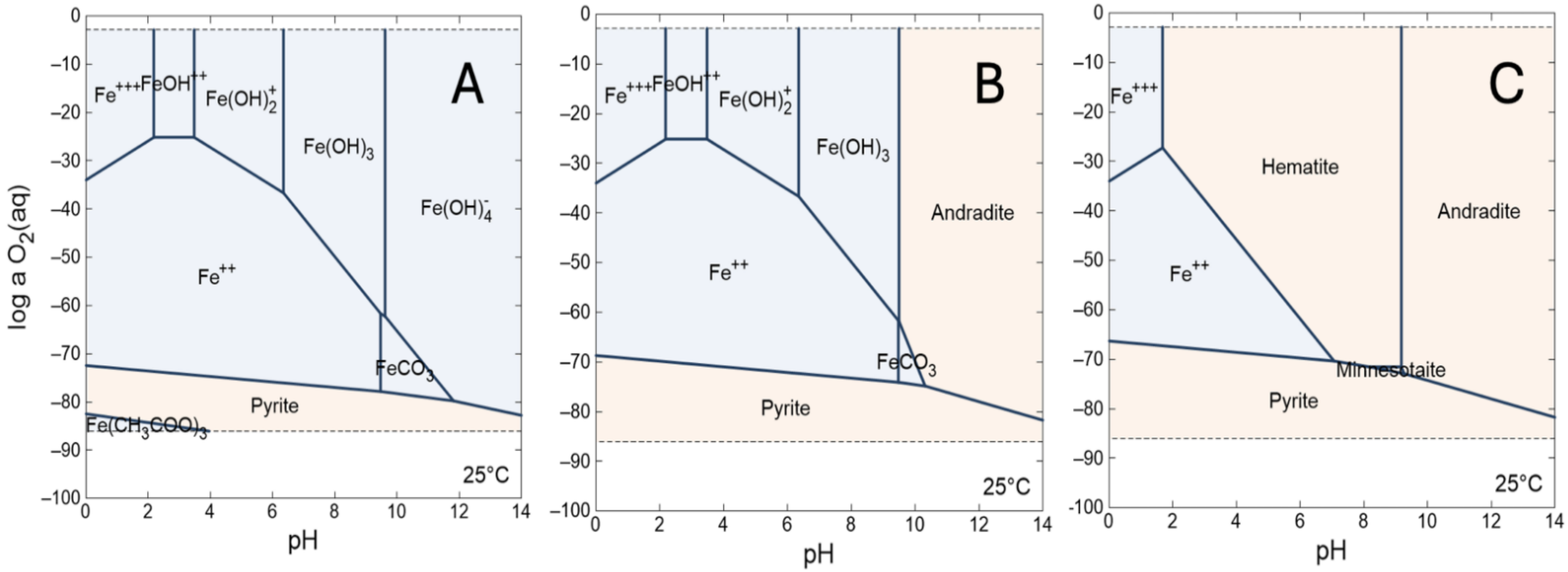
Figure **24**



Fe Stability diagrams for increasing activities of Fe.
A a(Fe) = 10-26 (measured activity);
B a(Fe) = 10-13;
C a(Fe) = 10-5. Blue shaded zones are aqueous species, tan zones are solids. Diagrams were generated using the Act2 app in Geochemist's workbench with major ion activities for a 50:50 mixture of Roza Canal water and Nillson well groundwater.

Fe Stability Diagrams

Yakima Basin

Geosyntec consultants

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Figure **25**

Seattle, WA

25-Mar-2024

APPENDIX A
CRBG Geochemistry and Groundwater Quality (Previous Studies)

Table A-1

Parameter	SiO_2	CaO	MgO	Na_2O	K_2O	Al_2O_3	FeO*	MnO	TiO_2	P_2O_5
Unit	wt%	wt%	wt%	wt%	wt%	wt%	wt%	wt%	wt%	wt%
Grande Ronde Basalt, n = 231										
Median	54.2	9.0	5.1	3.0	1.1	14.5	11.1	0.2	1.7	0.3
Minimum	51.7	6.4	2.9	1.7	0.4	13.6	8.8	0.1	1.1	0.2
Maximum	57.5	10.6	6.6	3.5	2.2	15.7	13.8	0.3	2.6	0.5
Average	54.3	8.8	4.9	3.0	1.2	14.5	11.1	0.2	1.8	0.3
Wanapum Basalt, n = 312										
Median	51.8	8.5	4.1	3.0	1.3	13.4	13.6	0.2	3.1	0.7
Minimum	49.8	5.9	2.2	2.4	0.9	12.7	10.7	0.2	2.4	0.5
Maximum	56.5	10.5	5.8	3.9	2.2	14.8	15.2	0.6	3.7	1.1
Average	52.3	8.3	4.0	3.0	1.4	13.5	13.5	0.2	3.0	0.7
Saddle Mountains Basalt, n = 273										
Median	53.4	8.5	4.2	2.8	1.4	13.8	12.3	0.2	2.8	0.8
Minimum	47.6	4.0	0.3	2.1	0.2	11.5	6.1	0.1	1.3	0.2
Maximum	58.4	12.4	8.4	4.2	3.2	17.0	17.7	0.3	3.9	1.9
Average	52.7	8.4	4.4	3.0	1.7	14.1	12.2	0.2	2.7	0.7
All Columbia River Basalts, n = 1,015**										
Median	52.4	8.7	4.5	3.0	1.2	14.0	12.5	0.2	2.6	0.5
Minimum	47.6	4.0	0.3	1.7	0.2	11.5	6.1	0.1	0.9	0.2
Maximum	58.4	13.7	8.6	4.9	3.2	17.9	17.7	0.6	4.5	1.9
Average	52.6	8.7	4.6	3.0	1.3	14.2	12.4	0.2	2.5	0.6

Summary of data from Hooper (2020). Analyses were by XRF in the GeoAnalytical Laboratory, Geology Department, Washington State University. Analyses are reported as a weight percent, normalized on a volatile-free basis, with total iron reported as FeO (Johnson et al.,1999).

**All Columbia River Basalts also include the Imnaha Basalts and Eckler Mountain Basalt.

Geosystems. 1 (1) 1-14.
doi:10.1029/2000GC000040

Table A-2

Element	Grande Ronde Basalt n = 231				Wanapum Basalt n = 312				Saddle Mountains Basalt n = 273				All Columbia River Basalts** n = 1015			
ppm	med	min	max	ave	med	min	max	ave	med	min	max	ave	med	min	max	ave
Sc	40	31	51	40	40	26	50	40	33	17	46	34	38	17	51	37
V	318	247	422	319	415	136	500	362	253	128	434	262	322	128	500	317
Cr	92	3	152	82	29	2	123	40	33	0	307	76	53	0.0	488	73
Ni	22	1	210	25	5	0	56	11	11	0	139	26	19	0.0	417	29
Cu	47	7	116	47	17	0	49	19	19	0	150	29	34	0.0	297	50
Zn	106	81	163	107	145	124	189	147	129	74	278	130	128	74	278	127
Ga	20	15	25	20	23	16	28	23	22	14	28	22	22	14	28	22
Rb	25	7	58	27	32	10	54	33	36	2.0	60	32	28	1.0	71	29
Sr	317	259	412	328	319	278	384	318	266	210	355	266	312	210	1410	313
Y	33	24	45	33	45	40	70	48	48	21	110	47	42	20	110	42
Zr	144	111	202	148	191	161	262	199	253	104	533	300	185	69	533	209
Nb	12	7	18	12	17	14	24	18	24	8.0	57	24	17	4	57	18
Ba	461	339	999	491	575	426	1580	671	714	147	4330	1640	515	116	4330	821
La	17	0	37	16	24	1	49	24	37	0	84	37	24	0	84	25
Ce	40	16	69	39	59	29	99	60	78	14	180	77	56	3	180	59
Pb	6	0	13	6	6	0	14	6	9	0	17	8	7	0	17	7
Th	3	0	7	3	4	1	10	4	6	0	12	6	4	0	12	4

Summary of data from Hooper (2020). Analyses are by XRF in the GeoAnalytical Laboratory, Geology Department, Washington State University. Analyses are reported as a parts per million (ppm), normalized on a volatile-free basis (Johnson et al.,1999).

**All Columbia River Basalts also include the Imnaha Basalts and Eckler Mountain Basalt.

Source: Hooper P., 2000, Chemical discrimination of Columbia River basalt flows. Geochemistry, Geophysics, Geosystems. 1 (1) 1-14. doi:10.1029/2000GC000040

Table A-3. Summary of USGS Regional Columbia River Basalt Groundwater Quality (Steinkampf, 1989)

Parameter	Units	Criteria (WAC 173-200)	Saddle Mountains*			Wanapum**		
			Maximum	Minimum	Mean	Maximum	Minimum	Mean
Specific conductance	uS/cm		1,460	175	498.2	1,970	102	402.5
Dissolved solids (calculated)	mg/L	500	890	140	340.2	1,100	69	269.5
Sodium	mg/L		100	7.3	34.5	130	2.4	28
Chloride	mg/L	*250*	130	1.3	24.3	300	7	17.2
Nitrate + nitrite (as N)	mg/L	10	54	0.1	4.8	35	0.1	3.7
Silica	mg/L		72	36	55.6	100	10	48.3
Sulfate	mg/L	*250*	490	0.2	53	290	0.2	29.3
Temperature	°C		25.5	8.6	18.36	43.4	6.2	15.5
Dissolved oxygen	mg/L		10.1	0.1	4.5	10.6	0.1	5.2
Calcium	mg/L		98	1.9	38.28	180	0.5	32.8
Magnesium	mg/L		62	0.28	19.4	75	0.1	14.8
Fluoride	mg/L	4	2.9	0.2	0.58	3.4	0.1	0.5
Bicarbonate	mg/L		392	108	195.4	406	53	178.1
Iron	mg/L	*0.3*	0.79	0.003	0.03	1.1	0.003	0.03
Potassium	mg/L		13	1.5	6.9	22	0.9	4.9
pH	s.u.	*6.5-8.5*	**8.7**	7	7.7	**9.4**	**6.1**	7.4

Notes:

* Saddle Mountains Basalt - 131 samples

** Wanapum Basalt - 410 samples

°C - degrees Celsius

mg/L - milligrams per liter

uS/cm - microSiemens per centimeter

s.u. - standard units of pH

N - nitrogen

Red bold values indicate exceedances of Groundwater Criterion listed in WAC 173-200

Italicized values represent secondary contaminant limits

Table A-4. Kennewick ASR-1 Groundwater Quality Summary (GSI 2020)

Analyte Group / Analyte	Units	Groundwater (WAC 173-200)	Wanapum Native Groundwater ASR-1 (Initial Testing) Result	ASR-1 (pre-ASR) Result	ASR-MW-1 (pre-ASR) Result
FIELD PARAMETERS					
pH (field)	s.u.	6.5 to 8.5	8	8	7.9
Specific Conductance	µS/cm		424	376	421
Temperature	°C		27.2	27.3	11.1
Turbidity	NTU		ND	ND	---
Dissolved Oxygen	mg/L		0.32	0.17	3.7
Oxidation-Reduction Potential	mV		---	-37	---
INORGANICS					
Alkalinity	mg/L as $CaCO_3$		212	208	207
Ammonia-Nitrogen	mg/L as N		ND	0.08	0.06
Bicarbonate	mg/L as $CaCO_3$		210	208	207
Carbonate	mg/L as $CaCO_3$		ND	ND	ND
Chloride	mg/L	250	11.7	12.5	11.7
Cyanide	mg/L		ND	ND	---
Fluoride	mg/L	4	0.87	0.92	0.83
Hardness	mg/L as $CaCO_3$		70	64	---
Nitrate+Nitrite (total N)	mg/L as N		ND	ND	ND
Nitrate-N	mg/L as N	10	ND	ND	ND
Nitrite-N	mg/L as N		ND	ND	ND
Orthophosphate as P	mg/L		0.018	ND	ND
Silica (as SiO_2)	mg/L		---	66.6	80.3
Sulfate	mg/L	250	0.5	0.2	ND
Sulfide	mg/L		ND	ND	ND
TOTAL METALS / METALLOIDS					
Aluminum	mg/L		ND	ND	ND
Antimony	mg/L		0.00002	ND	ND
Arsenic	mg/L	0.00005	0.0004	ND	ND
Barium	mg/L	1	0.054	0.0514	0.0795
Beryllium	mg/L		ND	ND	ND
Cadmium	mg/L	0.01	0.000006	ND	ND
Calcium	mg/L		15	13.9	14
Chromium	mg/L	0.05	0.0001	ND	ND
Cobalt	mg/L		0.000054	ND	ND
Copper	mg/L	1	0.00016	0.044	ND
Iron	mg/L	0.3	0.044	0.018	0.03
Lead	mg/L	0.05	0.000084	ND	ND
Magnesium	mg/L		7.66	7.1	6.9
Manganese	mg/L	0.05	0.03	0.027	0.017
Mercury	mg/L	0.002	---	---	---
Molybdenum	mg/L		0.011	0.002	
Nickel	mg/L		0.0005	ND	ND
Potassium	mg/L		12.9	11	13.9
Selenium	mg/L	0.01	0.0006	ND	ND
Silver	mg/L	0.05	ND	ND	ND
Sodium	mg/L		62	55	70
Thallium	mg/L		ND	ND	ND
Uranium	mg/L		0.000007	ND	ND
Vanadium	mg/L		0.00039	ND	ND
Zinc	mg/L	5	0.0005	0.0067	0.00624
DISINFECTION BY-PRODUCTS (DBPs) & RESIDUAL DISINFECTANTS					
Bromate	mg/L		ND	ND	ND
Chlorite	mg/L		ND	ND	ND
Total Residual Chlorine	mg/L		ND	ND	---
Bromochloroacetic Acid	µg/L		---	ND	ND
Dibromoacetic Acid, DBAA	µg/L		ND	ND	ND
Dichloroacetic Acid, DCAA	µg/L		ND	ND	ND
Monobromoacetic Acid, MBAA	µg/L		ND	ND	ND
Monochloroacetic Acid, MCAA	µg/L		ND	ND	ND
Trichloroacetic Acid, TCAA	µg/L		ND	ND	ND
Total Haloacetic Acids (Total HAA's)	µg/L		ND	ND	ND
Bromodichloromethane	µg/L	0.3	ND	ND	ND
Bromoform	µg/L	5	ND	ND	ND
Chloroform	µg/L	7	ND	ND	ND
Dibromochloromethane	µg/L	0.5	ND	ND	ND
Total Trihalomethane (TTHM)	µg/L				

Table A-4. Kennewick ASR-1 Groundwater Quality Summary (GSI 2020)

Analyte Group / Analyte	Units	Groundwater (WAC 173-200)	Wanapum Native Groundwater		
			ASR-1 (Initial Testing)	ASR-1 (pre-ASR)	ASR-MW-1 (pre-ASR)
			Result	Result	Result
MISCELLANEOUS					
Chemical Oxygen Demand	mg/L		ND	ND	ND
Color	Color units	15	ND	ND	---
Corrosivity†	Standard units	noncorrosive	---	-0.28	---
Dissolved Organic Carbon	mg/L		0.83	0.7	0.52
MBAS (foaming agents)	mg/L	0.5	ND	ND	---
Methane	mg/L		---	0.65	---
Odor	T.O.N	3 Threshold Nos.	---	ND	---
Oxidation-Reduction Potential	mV		---	-37	---
pH (Laboratory)	s.u.	6.5 to 8.5	8.02	7.81	---
Conductivity	µmhos/cm			492	445
Total Dissolved Solids	mg/L	500	324	308	280
Total Organic Carbon	mg/L		0.42	0.72	0.67
Total Suspended Solids	mg/L		ND	ND	---
Turbidity	NTU		ND	ND	---
RADIOLOGICALS					
Gross Alpha	pCi/L	15	ND	---	---
Gross Beta	pCi/L	50	---	---	---
Radium 226	pCi/L	3	---	ND	---
Radium 228	pCi/L	5 (as combined Radium)	ND	---	---
Radon 222	pCi/L		---	---	---
Strontium 90	pCi/L	8	ND	---	---
Uranium Activity	pCi/L		ND	ND	ND

Notes:

Data from GSI (2020) City of Kennewick ASR Year 6 Pilot Testing Summary Report

Volatile organic compounds (VOCs), synthetic organic compounds (SOCs), and herbicides / pesticides were non-detect and not shown in this summary table

--- indicates not analyzed, measured, or defined

Shaded cells identify exceedances of applicable MCL, SMCL, or advisory level (sodium)

°C - degree Celcius

$CaCO_3$ - calcium carbonate

mg/L - milligrams per liter

µg/L - micrograms per liter

µS/cm - microSiemens per centimeter

µmhos/cm - micromhos per centimeter

MCL - maximum contaminant level

MCLG - maximum contaminant level goal

mV - millivolts

N - nitrogen

ND - non detect

NTU - Nepthelometric turbidity units

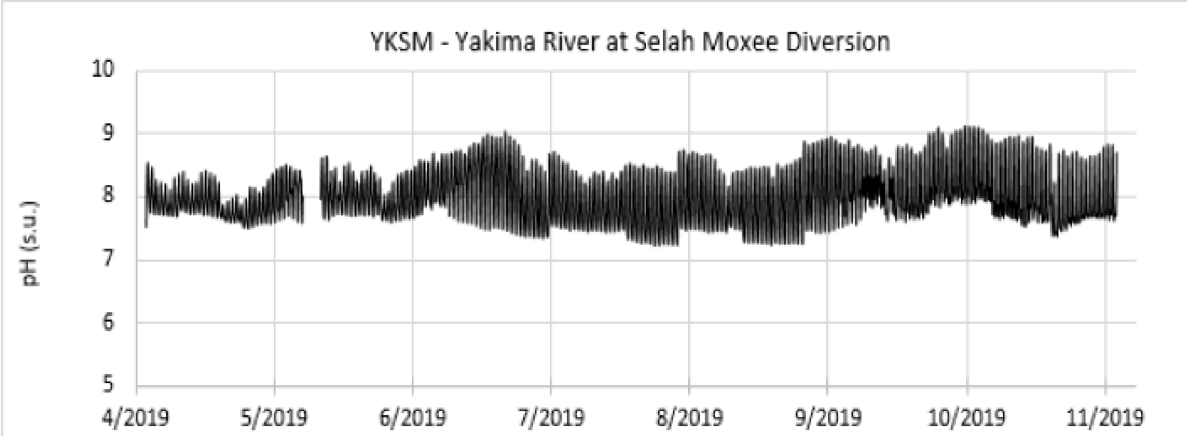
pCi/L - picocuries per liter

SMCL - secondary maximum contaminant level

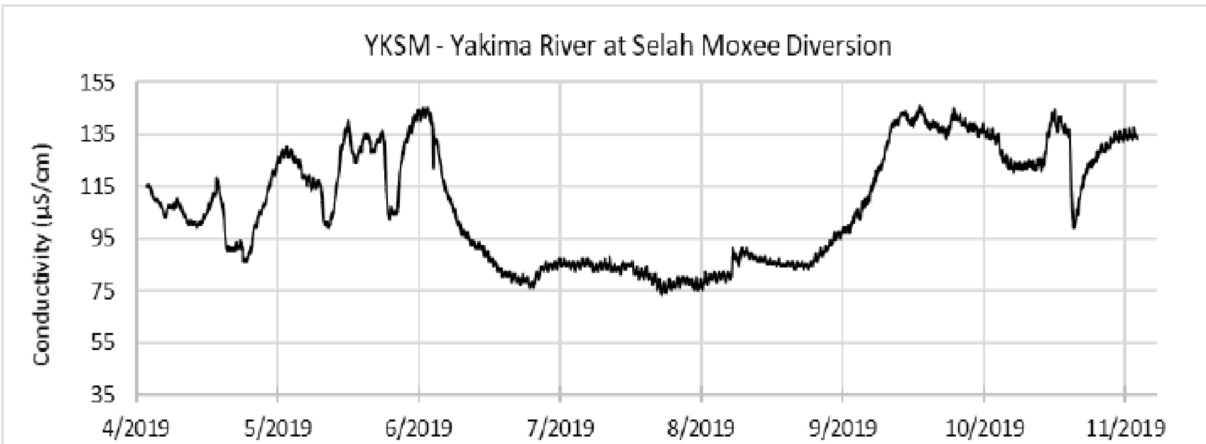
s.u. - standard units of pH

T.O.N. - threshold odor number

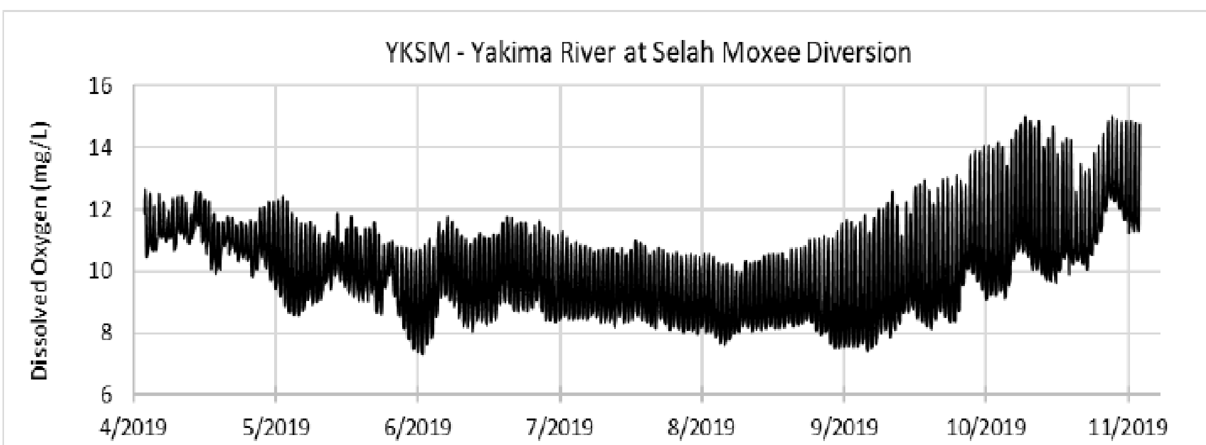
APPENDIX B
Water Chemistry Plots
(Ecology, 2021)



Continuous pH data for location YKSM from 4/3/2019 to 11/6/2019.



Continuous conductivity data for location YKSM from 4/3/2019 to 11/6/2019



Continuous DO data for location YKSM from 4/3/2019 to 11/6/2019.

Yakima River Water Quality at Selah-Moxee Diversion (from Ecology 2021)

Yakima Basin, Washington

Geosyntec consultants

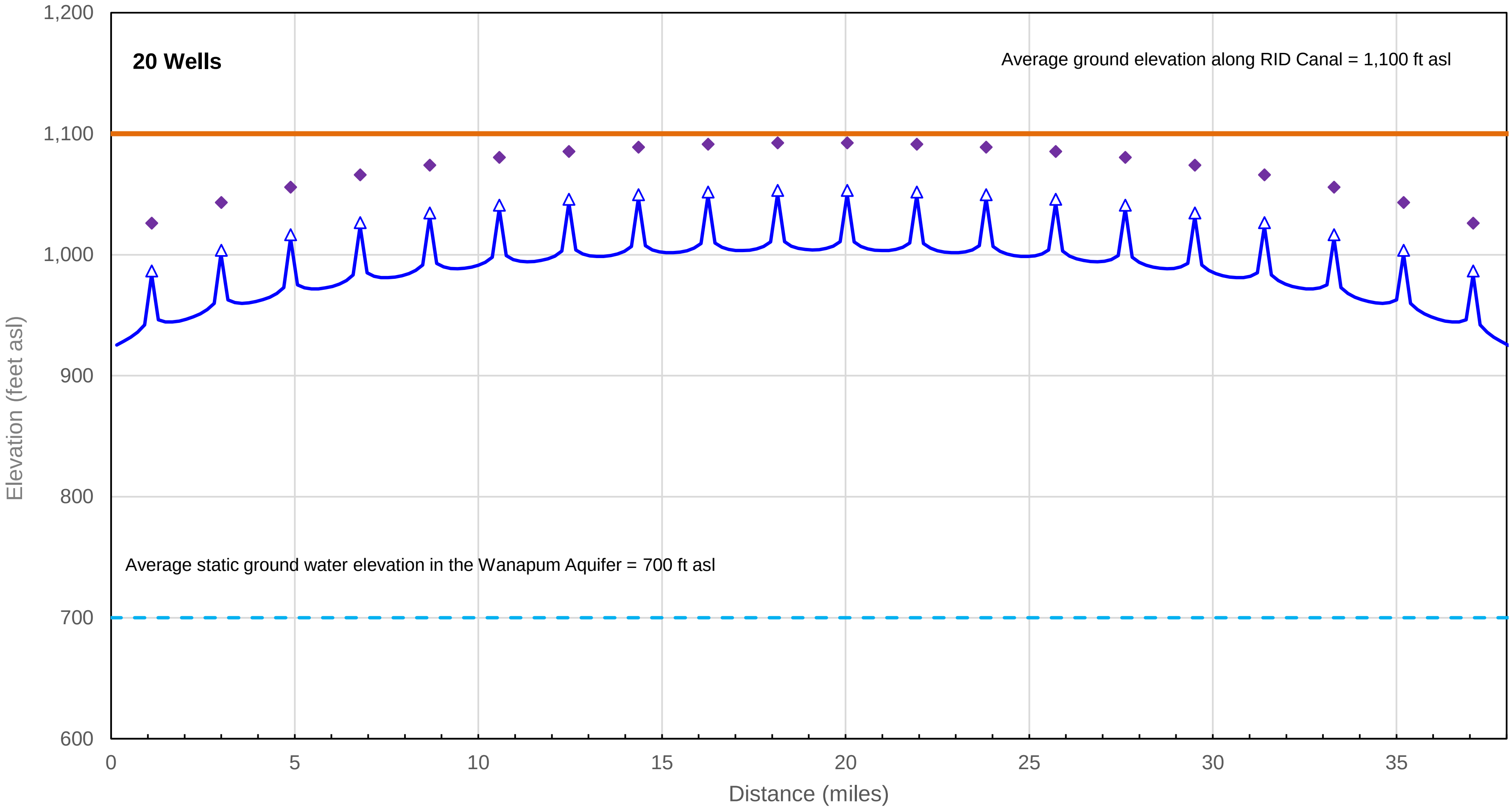
CWU

Figure **B-1**

Seattle, Washington

30-Jan-2024

APPENDIX C
ASR Wellfield Hydraulic Analysis Results



Predicted Head Build-Up

Static Groundwater Elevation

Ground Elevation (average)

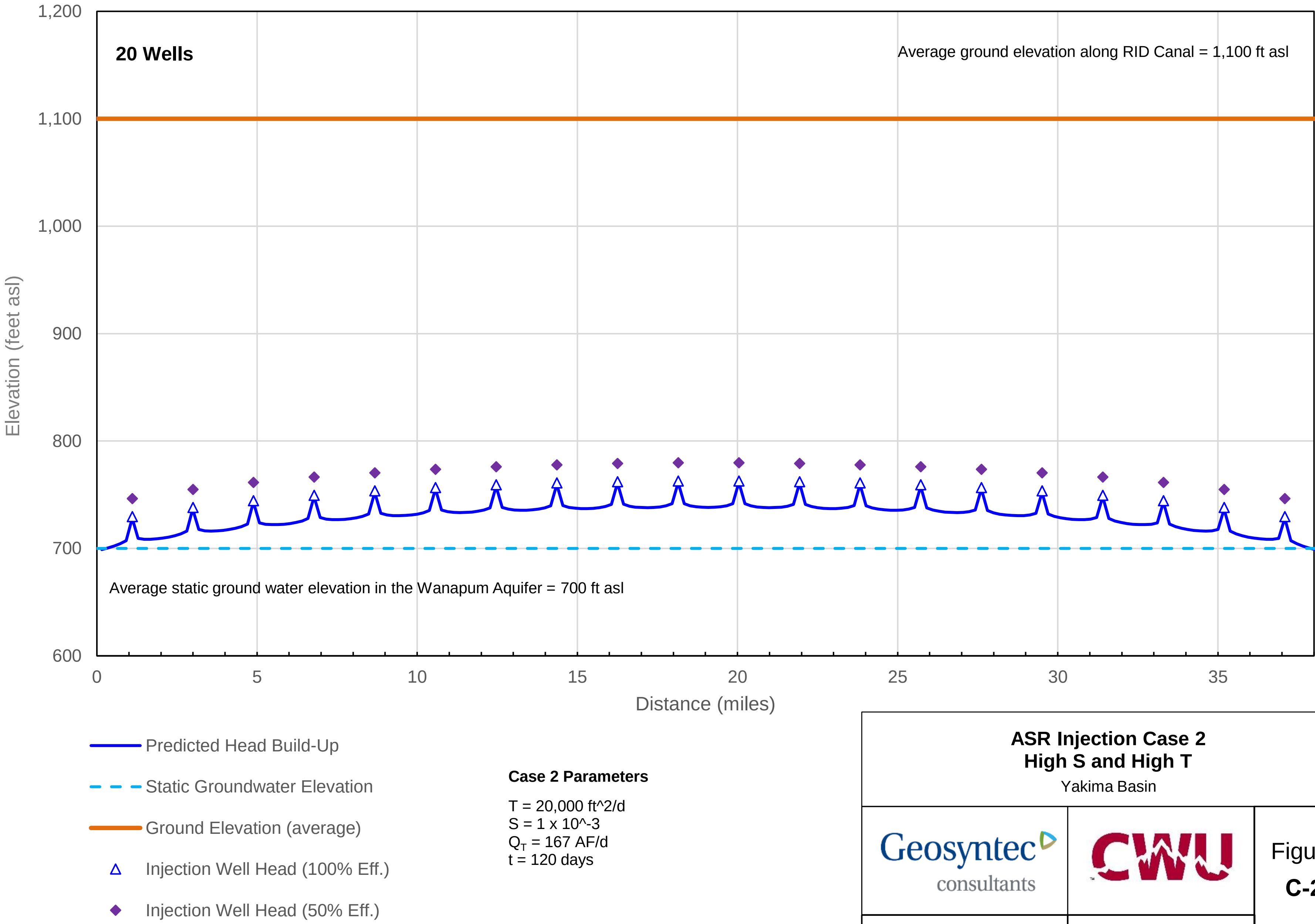
△ Injection Well Head (100% Eff.)

◆ Injection Well Head (50% Eff.)

Case 1 Parameters

T = 10,000 ft^2/d
S = 1 x 10^-5
Q_T = 167 AF/d
t = 120 days

ASR Injection Case 1 **Low S and Low T** Yakima Basin		
Geosyntec consultants	CWU	Figure **C-1**
Seattle, WA	9-Feb-2024	



Case 2 Parameters

T = 20,000 ft^2/d
S = 1 x 10^-3
Q_T = 167 AF/d
t = 120 days

ASR Injection Case 2
High S and High T
Yakima Basin

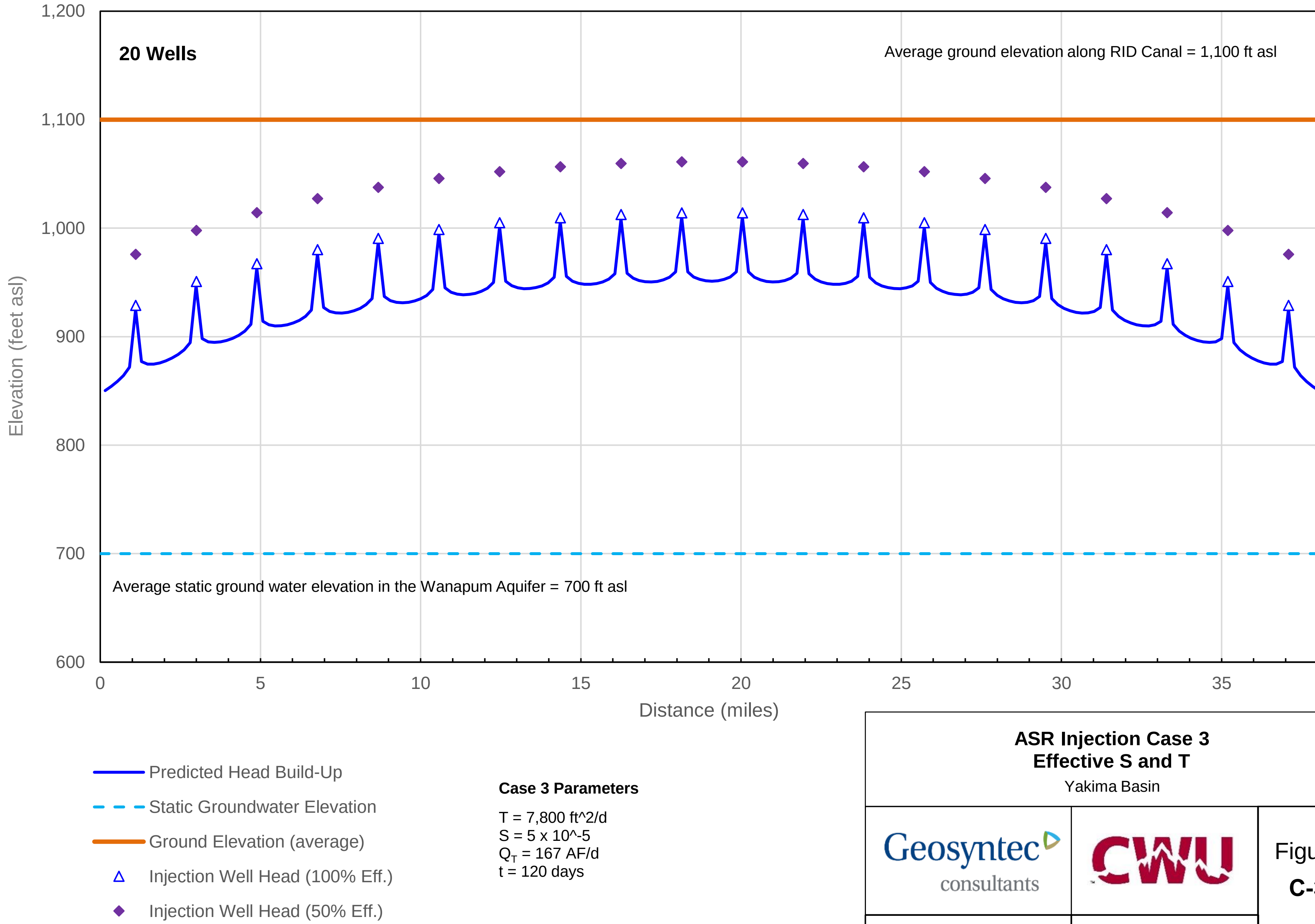
Geosyntec consultants

CWU

Figure **C-2**

Seattle, WA

9-Feb-2024



Case 3 Parameters

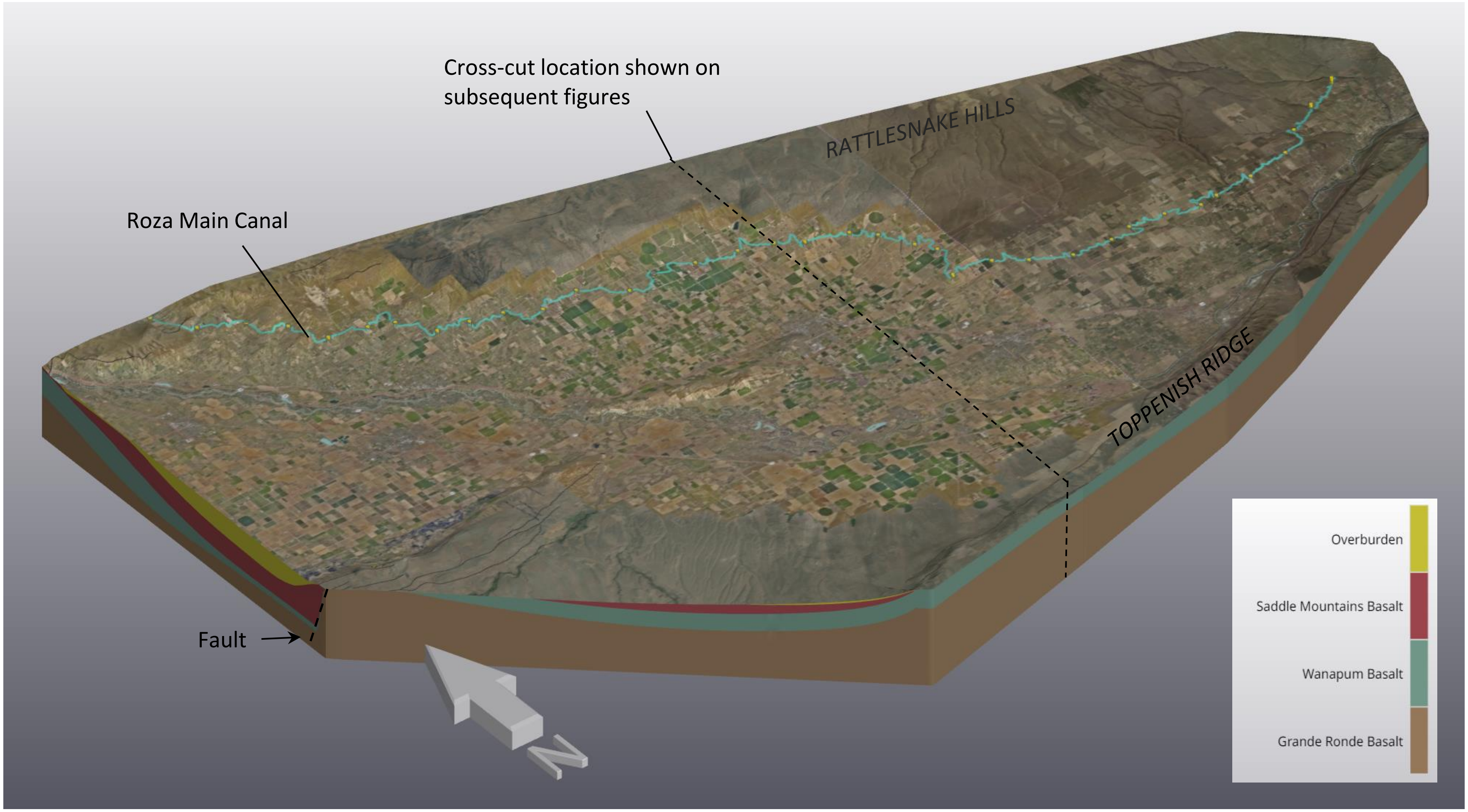
T = 7,800 ft^2/d
S = 5 x 10^-5
Q_T = 167 AF/d
t = 120 days

ASR Injection Case 3
Effective S and T
Yakima Basin

Geosyntec consultants | CWU | Figure **C-3**

Seattle, WA | 9-Feb-2024

APPENDIX D
3D Conceptual Hydrogeologic Model of the ASR Wellfield

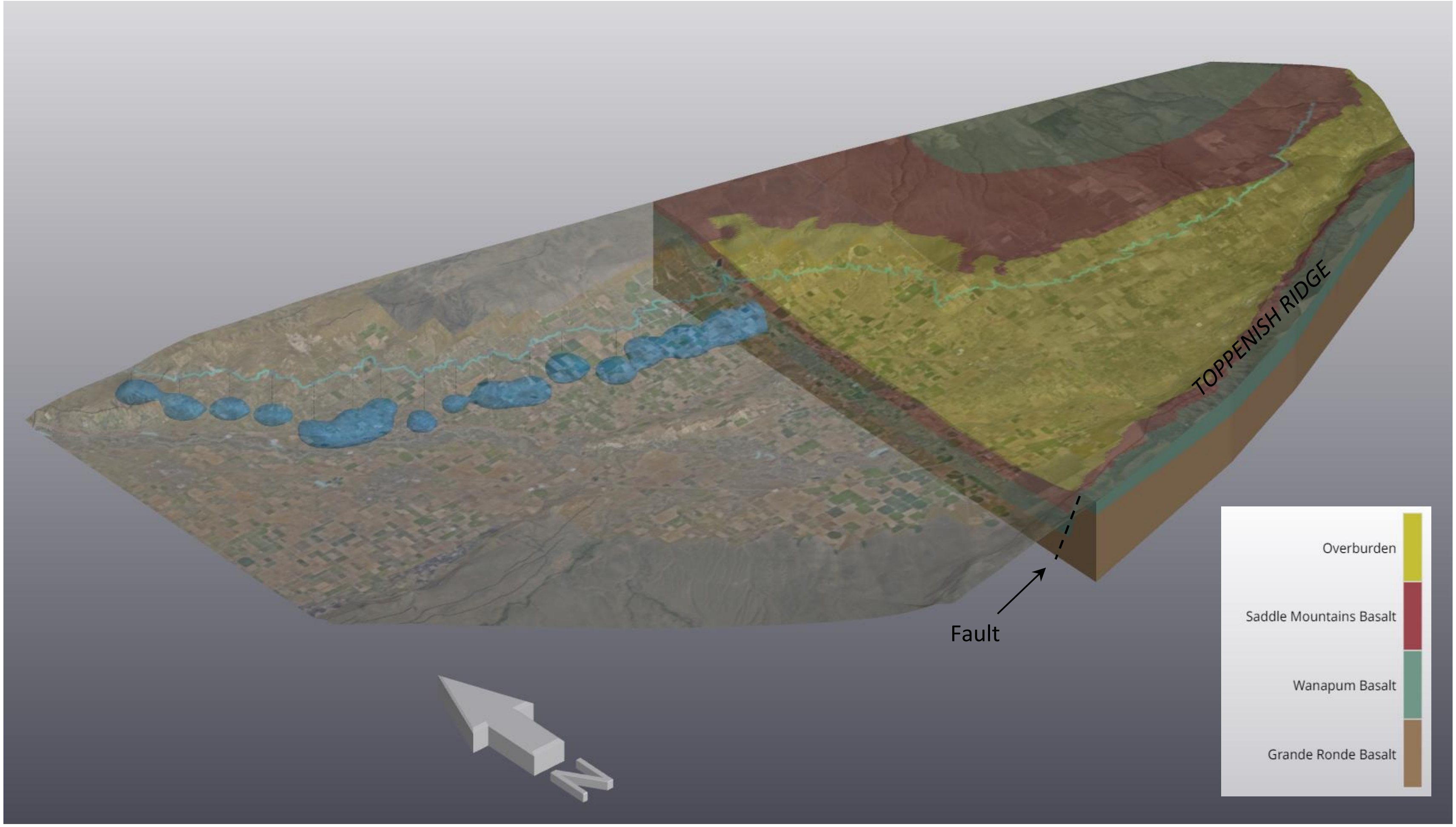


Yellow dots along Roza Main Canal represent hypothetical ASR well locations

3D Conceptual ASR Wellfield Model

Yakima Basin

Geosyntec consultants | CWU | Figure **D-1**
Seattle, WA | 30-Jan-2024

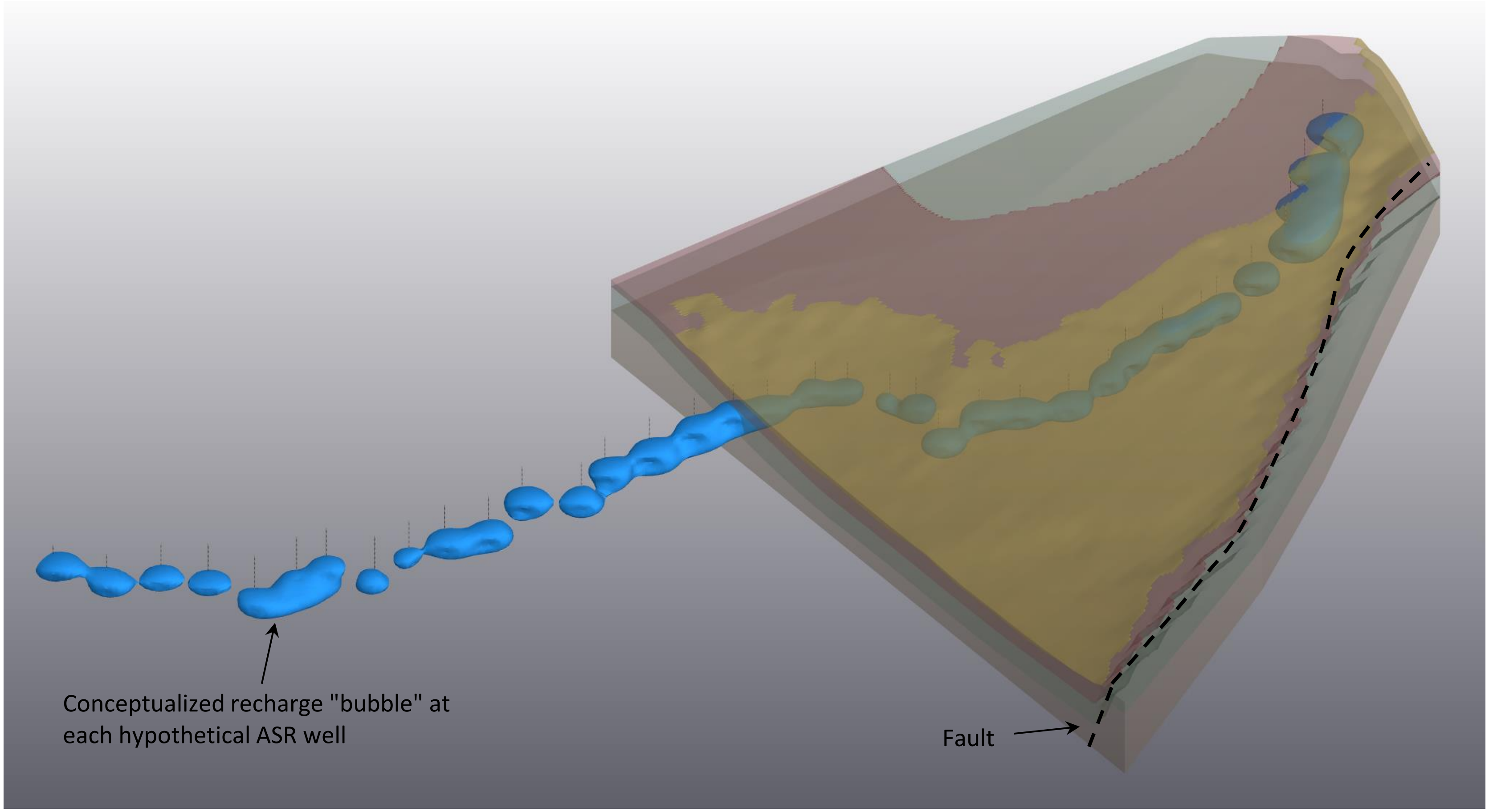


3D Conceptual ASR Wellfield Model with Transparent Aerial Overlay and Geology Cutaway

Yakima Basin

Geosyntec consultants	CWU	Figure **D-2**
Seattle, WA	30-Jan-2024	

PATH: C:\Users\Derek.Holom\OneDrive - Geosyntec\Documents\Projects\CWU\Konnowac Pass ASR\Appendices | FILE NAME: Appendix D - 3D Screenshots.xlsx



3D Conceptual ASR Wellfield Model with Geology Cutaway and No Aerial Overlay

Yakima Basin

Geosyntec consultants

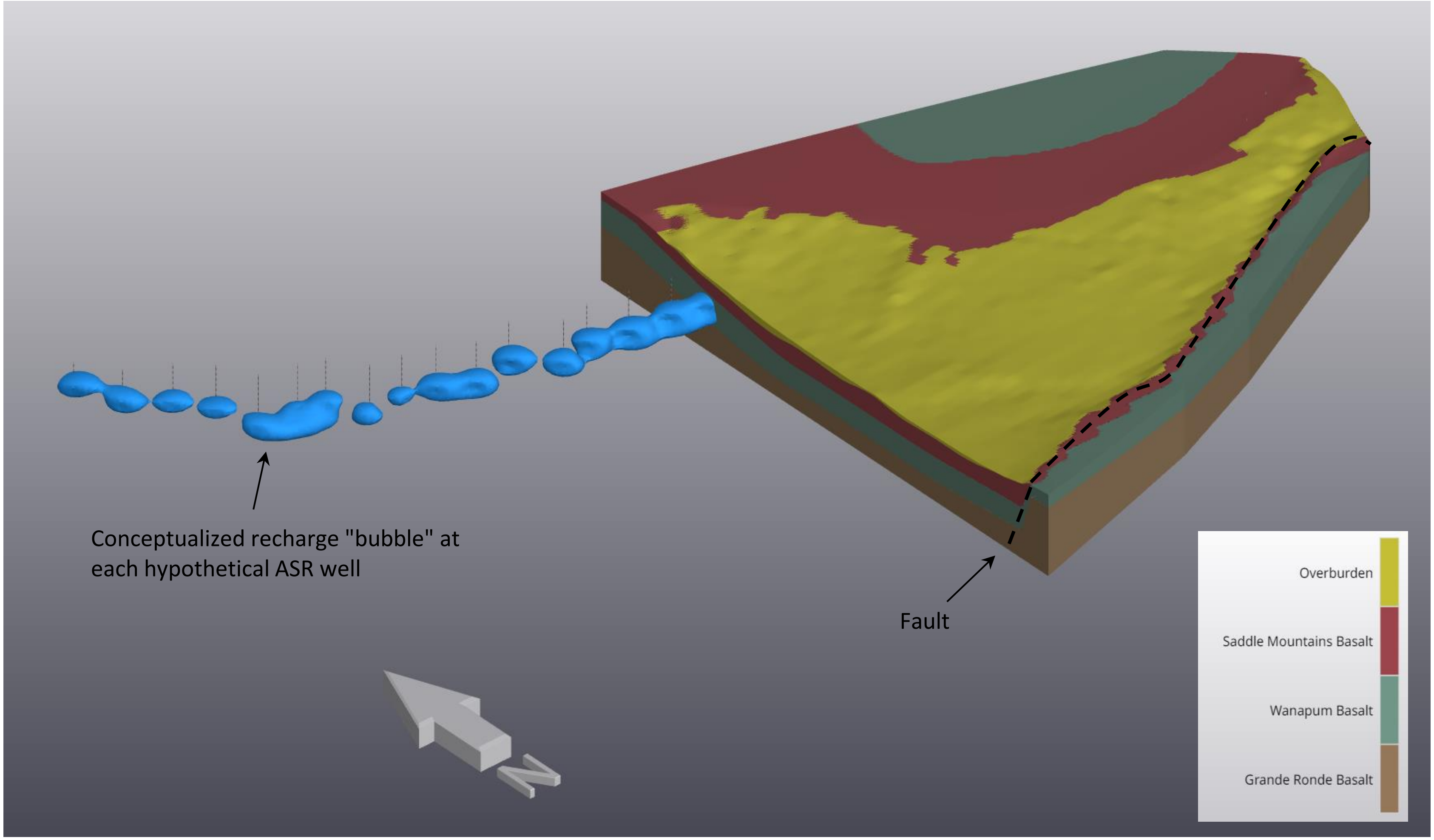
CWU

Figure **D-3**

Seattle, WA

30-Jan-2024

PATH: C:\Users\Derek.Holom\OneDrive - Geosyntec\Documents\Projects\CWU\Konnowac Pass ASR\Appendices | FILE NAME: Appendix D - 3D Screenshots.xlsx



3D Conceptual ASR Wellfield Model with No Aerial Overlay

Yakima Basin

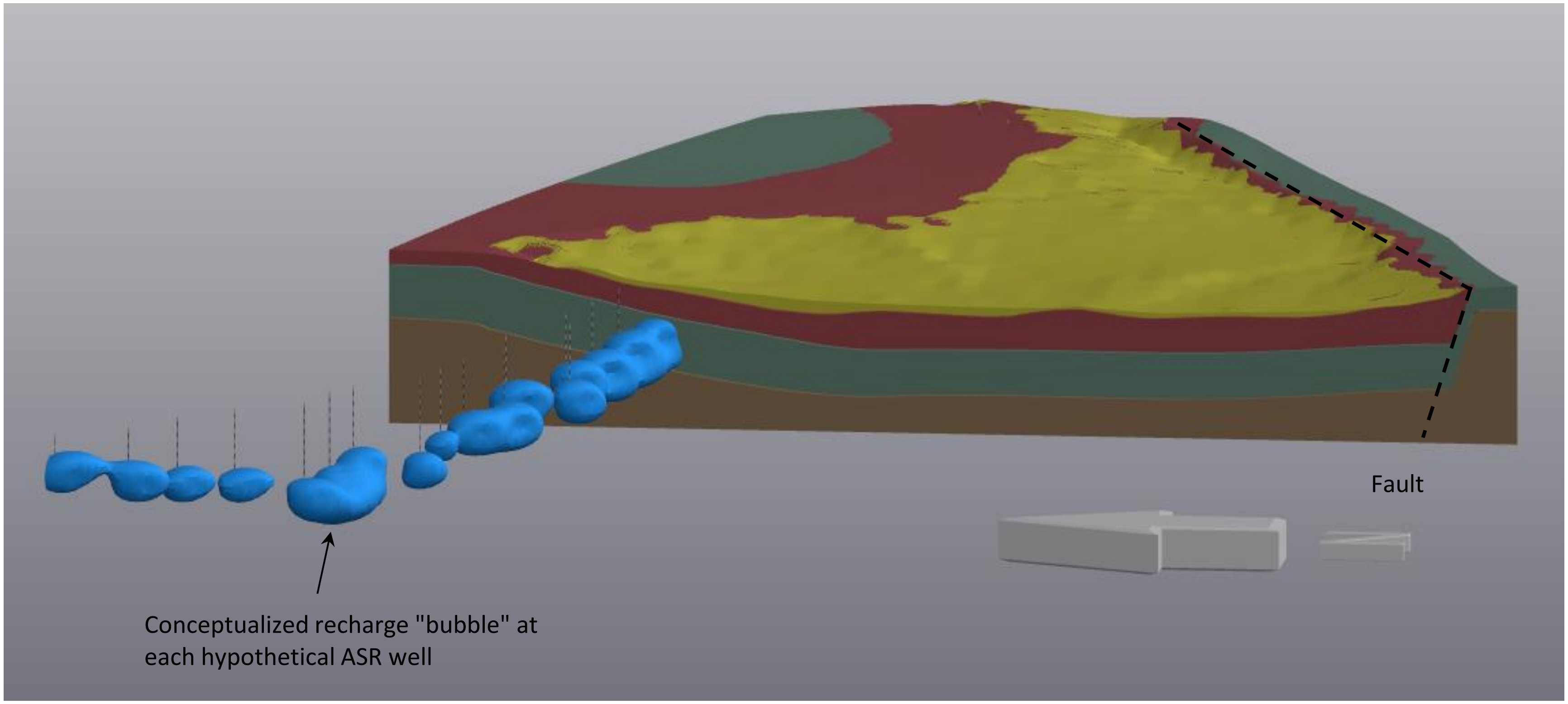
Geosyntec consultants

CWU

Figure **D-4**

Seattle, WA

30-Jan-2024



3D Conceptual ASR Wellfield Model with Geology Cutaway (View to the East)

Yakima Basin

Geosyntec consultants

CWU

Figure **D-5**

Seattle, WA

30-Jan-2024

PATH: C:\Users\Derek.Holom\OneDrive - Geosyntec\Documents\Projects\CWU\Konnowac Pass ASR\Appendices | FILE NAME: Appendix D - 3D Screenshots.xlsx

APPENDIX E
Surface Water and Groundwater Quality Data

Table E-1. Water Quality Field Measurements

Sample	pH	ORP	Temp.	Cond.	SC*	DO		Alkalinity	
		mV	°C	µS/cm	µS/cm	ppm	%	meq/L	ppm HCO_3
Surface Water									
Sampling A - 4/6/23									
RR-YRA	7.3	342	7.1	100	136	11.6	97.0	1.20	73.4
RR-RC-1A	9.3	398	8.1	96	130	11.5	96.0	1.16	70.7
RR-RC-2A	8.6	377	8.6	102	134	11.9	101.0	1.17	71.2
RR-RC-3A	9.5	351	9.7	102	133	11.2	98.4	1.05	64.1
RR-RC-4A	9.6	388	10.8	102	131	11.1	100.0	1.08	66.2
Sampling B - 7/7/23									
RR-YRB	8.4	425	6.7	85	121	11.9	96.8	1.11	67.7
RR-RC-1B	8.4	413	9.2	96	128	11.1	97.9	1.09	66.6
RR-RC-2B	8.4	415	8.7	92	125	11.3	97.6	1.11	67.7
RR-RC-3B	9.1	414	9.5	98	129	11.0	98.2	1.13	69.0
RR-RC-4B	9.3	405	10.0	94	124	11.0	97.9	1.08	65.7
Sampling C - 10/5/23									
RR-YRC	8.3	368	15.5	130	149	9.8	102.7	1.27	77.2
RR-RC-1C	8.8	370	16.7	133	150	9.9	103.4	1.21	74.0
RR-RC-2C	8.8	377	16.9	135	151	9.8	102.7	1.15	70.3
RR-RC-3C	8.9	384	17.2	136	152	9.8	103.5	1.16	70.6
RR-RC-4C	9.0	391	17.7	135	149	9.7	103.2	1.13	68.7
Groundwater – Nillson Well									
RR-G1A Mar	8.4	274	26.3	315	312	5.8	76.2	2.95	180.2
RR-G1B Aug	8.6	195	28.0	223	217	7.2	90.7	1.75	106.5

*Specific conductance, referenced to 25°C, correction of 2 µS/cm/°C

Table E-2. Major Element, Trace Element and Stable Isotope Data

Sample	RR-YRA	RR-RC-1A	RR-RC-2A	RR-RC-3A	RR-RC-4A	RR-YRB	RR-RC-1B	RR-RC-2B	RR-RC-3B	Detection Limit	Drinking Water MCL, SMCL*	Groundwater Criteria*
Element or Isotope											*WAC 246-290-310*	*WAC 173-200-040*
Na (ppm)	5.41	5.42	5.52	5.50	5.50	4.77	4.90	4.80	4.83	0.4	20	
Mg (ppm)	4.79	4.71	4.82	4.71	4.57	4.36	4.38	4.36	4.40	0.02		
K (ppm)	0.78	0.75	0.77	0.80	0.78	0.80	0.84	0.77	0.79	0.036		
Ca (ppm)	12.2	11.8	12.3	12.1	11.9	11.5	11.8	11.6	11.6	0.046		
Si (ppm)	4.65	4.55	4.22	4.18	4.04	6.22	6.12	5.97	5.57	0.01		
$\delta^{18}O$ (‰)	-13.82	-13.71	-13.87	-13.84	-13.76	-14.14	-14.05	-14.08	-14.19			
δD (‰)	-99.9	-100.3	-101.3	-101.0	-100.7	-103.5	-103.3	-103.0	-103.9			
Al (ppb)	bdl	bdl	bdl	bdl	1.90	bdl	bdl	bdl	bdl	1.39	50 to 200 (SMCL)	
V (ppb)	1.72	1.27	1.46	1.50	2.49	1.58	1.94	1.88	1.90	0.22		
Cr (ppb)	0.20	0.20	0.19	0.18	0.19	0.18	0.17	0.18	0.18	0.15	100	50
Mn (ppb)	1.62	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	0.83	50 (SMCL)	50
Fe (ppb)	0.91	0.87	bdl	0.98	2.50	0.98	0.96	0.97	1.01	0.61	300 (SMCL)	300
Co (ppb)	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	0.07		
Ni (ppb)	0.53	bdl	bdl	bdl	0.55	bdl	bdl	0.50	bdl	0.48		
Cu (ppb)	0.44	0.41	bdl	0.40	0.47	bdl	0.47	bdl	bdl	0.35	1300	1000
Zn (ppb)	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	1.08	5000	5000
As (ppb)	**bdl**	**bdl**	**bdl**	**bdl**	**bdl**	**bdl**	**bdl**	**bdl**	**bdl**	**0.54**	10	**0.05**
Se (ppb)	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	0.079	50	10
Mo (ppb)	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	0.54		
Cd (ppb)	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	0.22	5	10
Ba (ppb)	9.50	4.88	9.08	5.63	7.17	7.77	8.07	8.57	7.55	0.073	2000	1000
Pb (ppb)	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	0.05	15	50
U (ppb)	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	0.44	30	

*bold values show measurements which exceed MCL, SMCL, or groundwater standard
bdl = below detection limit

Table E-2. Major Element, Trace Element and Stable Isotope Data (continued)

Sample	RR-RC-4B	RR-YRC	RR-RC-1C	RR-RC-2C	RR-RC-3C	RR-RC-4C	RR-G1A	RR-G1B	Detection Limit	Drinking Water MCL, SMCL*	Groundwater Criteria*
Element or Isotope										*WAC 246-290-310*	*WAC 173-200-040*
Na (ppm)	4.81	5.51	5.61	5.82	5.93	5.89	**52.5**	**32.9**	0.4	**20**	
Mg (ppm)	4.39	5.23	5.22	5.38	5.27	5.19	0.69	1.05	0.02		
K (ppm)	0.80	1.30	1.25	1.29	1.62	1.17	6.72	5.67	0.036		
Ca (ppm)	11.7	12.6	12.5	12.6	12.5	12.4	4.31	4.56	0.046		
Si (ppm)	4.76	6.89	6.91	6.64	6.57	6.36	26.8	22.0	0.01		
$\delta^{18}O$ (‰)	-14.18	-12.66	-12.37	-12.55	-12.54	-12.54	-17.30	-15.25			
δD (‰)	-103.9	-93.8	-92.2	-92.6	-92.5	-92.8	-135.9	-117.2			
Al (ppb)	1.57	bdl	bdl	bdl	bdl	bdl	3.34	7.69	1.39	50 to 200 (SMCL)	
V (ppb)	2.47	3.70	4.41	3.93	4.13	3.43	bdl	0.24	0.22		
Cr (ppb)	0.17	bdl	bdl	bdl	bdl	bdl	bdl	bdl	0.15	100	50
Mn (ppb)	bdl	bdl	bdl	bdl	bdl	bdl	6.95	14.60	0.83	50 (SMCL)	50
Fe (ppb)	1.34	1.51	2.25	1.98	1.98	1.48	8.96	71.3	0.61	300 (SMCL)	300
Co (ppb)	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	0.07		
Ni (ppb)	0.51	0.72	0.65	0.62	0.89	bdl	bdl	2.30	0.48		
Cu (ppb)	0.37	1.41	0.94	1.03	2.30	0.65	6.04	181.1	0.35	1300	1000
Zn (ppb)	bdl	1.49	1.20	2.54	4.89	2.21	19.37	21.4	1.08	5000	5000
As (ppb)	**bdl**	**bdl**	**bdl**	**bdl**	**bdl**	**bdl**	**bdl**	**bdl**	**0.54**	10	**0.05**
Se (ppb)	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	0.079	50	10
Mo (ppb)	bdl	bdl	bdl	bdl	bdl	bdl	0.78	bdl	0.54		
Cd (ppb)	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	0.22	5	10
Ba (ppb)	8.34	11.8	10.9	11.7	10.9	10.0	6.28	5.60	0.073	2000	1000
Pb (ppb)	bdl	bdl	bdl	bdl	bdl	bdl	4.01	4.83	0.05	15	50
U (ppb)	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	0.44	30	

*bold values show measurements which exceed MCL, SMCL, or groundwater standard
bld = below detection limit

Table E-3. Major Ion Chemistry and Charge Balance

Sample	Na^+	Mg^{2+}	K^+	Ca^{2+}	Cation Total	Alkalinity	NO_3^-	Cl^-	SO_4^{2-}	F^-	Anion Total	CBE*
	meq/L	meq/L	meq/L	meq/L	meq/L	meq/L	meq/L	meq/L	meq/L	meq/L	meq/L	%
Surface Water												
Sampling A - 4/6/23												
RR-YRA	0.24	0.39	0.02	0.61	1.26	1.20	0.01	0.18	0.06	0.00	1.45	-6.9
RR-RC-1A	0.24	0.39	0.02	0.59	1.23	1.16	0.00	0.14	0.05	0.00	1.36	-4.9
RR-RC-2A	0.24	0.40	0.02	0.62	1.27	1.17	0.00	0.18	0.06	0.00	1.41	-5.0
RR-RC-3A	0.24	0.39	0.02	0.60	1.25	1.05	0.00	0.17	0.06	0.00	1.29	-1.5
RR-RC-4A	0.24	0.38	0.02	0.59	1.23	1.08	0.00	0.17	0.06	0.00	1.32	-3.6
Sampling B - 7/7/23												
RR-YRB	0.21	0.36	0.02	0.58	1.16	1.11	0.00	0.14	0.05	0.00	1.31	-5.9
RR-RC-1B	0.21	0.36	0.02	0.59	1.18	1.09	0.00	0.14	0.05	0.00	1.28	-4.1
RR-RC-2B	0.21	0.36	0.02	0.58	1.17	1.11	0.00	0.14	0.05	0.00	1.30	-5.4
RR-RC-3B	0.21	0.36	0.02	0.58	1.17	1.13	0.00	0.13	0.05	0.00	1.32	-6.1
RR-RC-4B	0.21	0.36	0.02	0.58	1.17	1.08	0.00	0.13	0.05	0.00	1.27	-3.8
Sampling C - 10/5/23												
RR-YRC	0.24	0.43	0.03	0.63	1.33	1.27	0.02	0.12	0.07	0.01	1.48	-5.2
RR-RC-1C	0.24	0.43	0.03	0.62	1.33	1.21	0.02	0.11	0.08	0.01	1.43	-3.4
RR-RC-2C	0.25	0.44	0.03	0.63	1.36	1.15	0.02	0.11	0.08	0.01	1.37	-0.4
RR-RC-3C	0.26	0.43	0.04	0.62	1.36	1.16	0.06	0.13	0.08	0.01	1.43	-2.7
RR-RC-4C	0.26	0.43	0.03	0.62	1.33	1.13	0.02	0.12	0.08	0.01	1.35	-0.7
Groundwater – Nillson Well												
RR-G1A Mar	2.28	0.06	0.17	0.21	2.73	2.95	0.00	0.14	0.00	0.09	3.19	-7.8
RR-G1B Aug	1.43	0.09	0.14	0.23	1.89	1.75	0.00	0.11	0.02	0.07	1.95	-1.6

*Charge balance error: CBE = (cation total – anion total)*100/(cation total + anion total), all measured in meq/L

Table E-4. Other Water Quality Parameters – Suspended Solids, Nutrients, Microbials, Herbicides

Sample	TSS	Turbidity	TOC	DOC	Ammonia N	TKN	Total Nitrate + Nitrite	Total P	Fecal Coliform	E.coli	Acrolein	Endothall
	mg/l	*NTU*	*mg/l*	*mg/l*	*mg/l*	*mg/l*	*mg/l*	*mg/l*	*cfu/100 mL*	*cfu/100 mL*	*µg/l*	*µg/l*
Surface Water												
Sampling A - 4/6/23												
RR-YRA	6	0.55	2	0.56	bdl	0.413	0.08	0.012	**6**	6		
RR-RC-1A	7	0.54	2.2	1.9	bdl	0.334	bdl	0.008	**1**	1		
RR-RC-2A	3	0.5	2.6	1.9	bdl	0.359	bdl	0.008	**1**	1		
RR-RC-3A	1	0.57	2.2	2	bdl	0.363	bdl	0.021	bdl	bdl		
RR-RC-4A	bdl	0.64	2.1	2.3	bdl	0.439	bdl	0.02	bdl	bdl		
Sampling B - 7/7/23												
RR-YRB	60	0.57	1.9	1.7	0.06	0.449	0.2	0.022	**4**	3		
RR-RC-1B	71	0.63	1.7	2	0.188	0.697	0.145	0.024	**22**	16		
RR-RC-2B	190	0.63	1.7	1.8	0.215	0.668	0.145	0.018	**3**	3		
RR-RC-3B	52	0.55	2	1.7	0.153	0.569	0.056	0.021	**2**	1		
RR-RC-4B	92	0.7	2.2	2	0.356	0.893	bdl	0.013	**8**	8		
Sampling C - 10/5/23												
RR-YRC			1.9	1.9	0.58	0.409	0.388		**present**	present		
RR-RC-1C			2	1.5	0.026	0.439	0.337		**present**	present	bdl	bdl
RR-RC-2C			2.1	1.5	bdl	0.322	0.292		**present**	present		
RR-RC-3C			2.2	1.4	0.184	0.784	0.346		**present**	present	bdl	bdl
RR-RC-4C			1.9	1.5	0.031	0.427	0.28		**present**	present		
Groundwater – Nillson Well												
RR-G1A Mar			1.3		bdl	bdl	bdl	bdl				
Detection Limit	1	0.05	0.5	0.5	0.02	0.3	0.02	0.005	1	1	1.5	9
Drinking Water Standards*		1 or 5					10		**0**			
Groundwater Criteria*									**1**			

*Drinking Water Standards from WAC-246-290-310; Groundwater Criteria from WAC-173-200-040; Turbidity criteria depends on filtration method; Criteria under Fecal Coliform are for Total Coliform.
bdl = below detection limit

Table E-5. Roza Canal Water Quality Measurements for 2020-2022

Water Quality Measure	n*	Summary Statistics	Mile Point along Roza Canal						Drinking Water Standard WAC-246-290-310	Groundwater Criteria WAC-173-200-040
			MP 4.95	MP 11.5	MP 32.8	MP 59.0	MP 75.1	MP 94.7		
Total Suspended Solids (mg/L)	30	*median*	5.4						500 (SMCL)	500
		max	50.7							
		min	1.1							
Turbidity (NTU)	30	*median*	3.4		3.9	**5.4**	**5.9**	2.8	1 or **5****	
		max	**31.8**		**26.2**	**14.1**	**22.4**	**20.5**		
		min	1.4		0.9	1.4	1.2	0.9		
Specific Conductance (mS/cm)	30	*median*	106.9			102.1	101.6	103.2	700 (SMCL)	
		max	207.6			140.0	152.2	141.0		
		min	71.2			67.1	68.2	74.1		
pH	30	*median*	7.7			8.2	8.2	**8.9**	6.5 to **8.5** (SMCL)	6.5 to **8.5**
		max	8.0			**8.7**	**9.2**	**9.8**		
		min	7.2			7.8	7.8	8.0		
Dissolved Oxygen (mg/L)	30	*median*	9.7							
		max	11.5							
		min	7.9							
E. coli (MPN/100 mL)	29 to 34	*median*	34.1	29.2	28.9	30.5	51.6	6.4		
		max	365.4	160.7	191.8	111.2	214.3	114.5		
		min	1.0	1.0	1.0	1.0	1.0	1.0		
Nitrate + Nitrite as N (mg/L)	10 to 30	*median*	0.15	0.14	0.11	0.10	0.10	0.02	10	
		max	0.31	0.29	0.28	0.24	0.24	0.07		
		min	0.05	0.10	0.05	0.05	0.04	0.01		
Total Kjeldahl Nitrogen (mg/L)	10 to 30	*median*	0.20	0.19	0.17	0.27	0.28	0.26		
		max	0.43	0.25	0.25	0.54	0.88	0.37		
		min	0.07	0.09	0.12	0.18	0.20	0.16		
Total Phosphorous (mg/L)	10 to 30	*median*	0.042	0.045	0.033	0.047	0.054	0.029		
		max	0.121	0.061	0.063	0.075	0.116	0.049		
		min	0.018	0.025	0.027	0.027	0.026	0.011		

Data source: RSBOJC (2020-2022)

*number of samples for E. coli – 30 (MP 4.95, MP 32.8, MP 59.0, MP 94.7), 29 (MP 11.5), 34 (MP 75.1); number of samples for nutrients – 30 (MP 4.95), 10 (MP 11.5), 11 (MP 32.8, MP 59.0, MP 75.1, MP 94.7)

**Turbidity criteria depends on filtration method.

APPENDIX F
Study Area Well Logs

RESOURCE PROTECTION WELL REPORT

Notice of Intent No. R-78001

(SUBMIT ONE WELL REPORT PER WELL INSTALLED)

RECEIVED
SEP 08 2010
DEPARTMENT OF ECOLOGY, CENTRAL REGIONAL OFFICE

Construction/Decommission *("x" in circle)*

- ◉ Construction 385706
- ○ Decommission *Original Construction Notice of Intent Number* ______

Type of Well *("x" in circle)*

- ◉ Resource Protection
- ○ Geotech Soil Boring

Property Owner: Yakima County

Unique Ecology Well ID Tag No. ALC040

Consulting Firm: Pacific Groundwater

Driller or Trainee Name: Justin Egeland

Driller or Trainee Signature: [signature]

Driller or Trainee License No. 2974 (2843)

If trainee, licensed driller's Signature and License no. ______

Site Address: Cheyne Landfill 4790 Cheyne rd

City: Zillah County: Yakima

Location: SW 1/4-1/4 SW 1/4 Sec 36 Twn 12N R 20 EWM (circle one) or WWM

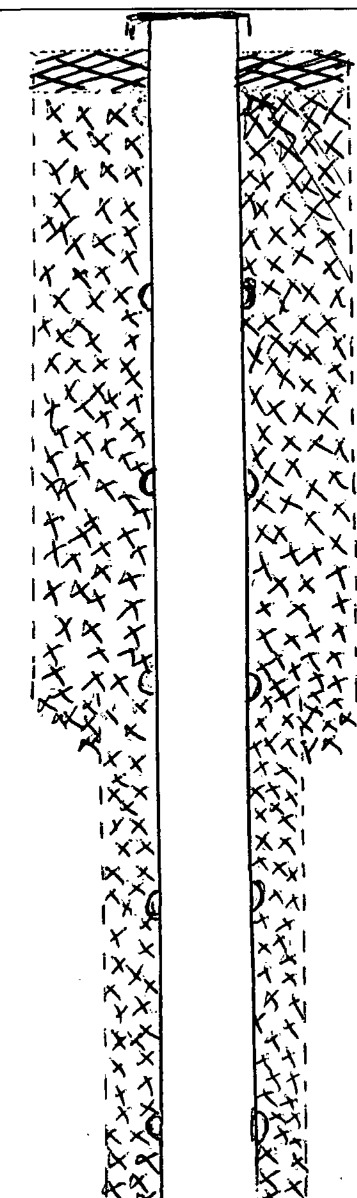
Lat/Long (s, t, r still REQUIRED) Lat Deg ______ Lat Min/Sec ______ Long Deg ______ Long Min/Sec ______

Tax Parcel No. 201236 33001

Cased or Uncased Diameter 4" Static Level 494 bgs

Work/Decommission Start Date 6-1-10

Work/Decommission Completed Date 7-26-10

Construction/Design	Well Data	Formation Description
4" carbon steel 0' – 336.38' bgs		All below ground surface
Portland type II neat cement 0'–5' bgs		0-15' fill
Bentonite #8 crumbles 5' bgs – 250' bgs		15-29' silty sand (MS)
Dielectric sacrificial coupling 336.38' – 337.78' bgs		29'-38' Sand (S)
Bentonite slurry 250' – 497' bgs		38'-68 Pink silt (M) + small pea gravels
11 3/4" carbon steel temp. casing 0' – 150' bgs		68'-75' Brown silt (M) small pea gravels
8" carbon steel temp casing 0' – 538.80 bgs		75'-110' Silty clay (CM)
All temp casing has been removed		110'-150' Green, blue clay
centralizers emplaced every 40'		150'-190' Black Basalt
		190'-204' light brown + pink sandy clay
		204'-209' light grey clay
		209'-222' Rusty brown beach sand
		222'-245' Greenish blue clay
		245'-252' Rusty brown beach sand
		252'-265' Brown silty clay
		265'-268' Brown silt
		268-270' Rusty brown silt
		270'-277' Dark brown sand
		277'-319' light brown sand

Scale 1"= ______

RESOURCE PROTECTION WELL REPORT

Notice of Intent No. R 78001

(SUBMIT ONE WELL REPORT PER WELL INSTALLED)

RECEIVED
SEP 0 8 2010
DEPARTMENT OF ECOLOGY - CENTRAL REGIONAL OFFICE

Construction/Decommission *("x" in circle)*
- ● Construction 385706
- ○ Decommission *Original Construction Notice of Intent Number* ______

Type of Well *("x" in circle)*
- ● Resource Protection
- ○ Geotech Soil Boring

Property Owner: Yakima County

Unique Ecology Well ID Tag No.: ALC 040

Consulting Firm: Pacific Groundwater

Driller or Trainee Name: Justin Egeland

Driller or Trainee Signature: [signature]

Driller or Trainee License No.: 2974 (2843)

If trainee, licensed driller's Signature and License no. ______

Site Address: Cheyne landfill 4790 Cheyne Rd

City: Zillah County: Yakima

Location: SW 1/4- 1/4 SW 1/4 Sec 36 Twn 12N R 20 (EWM circle one) or WWM

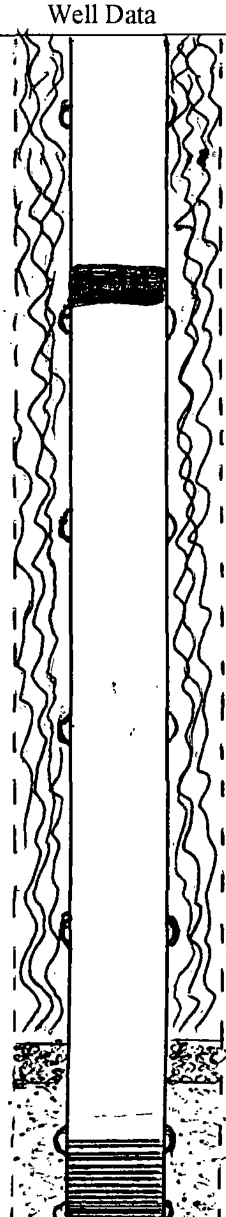
Lat/Long (s, t, r still REQUIRED) Lat Deg ____ Lat Min/Sec ____ Long Deg ____ Long Min/Sec ____

Tax Parcel No.: 201236-33001

Cased or Uncased Diameter: 4" Static Level: 494 bgs

Work/Decommission Start Date: 6-1-10

Work/Decommission Completed Date: 7-26-10

Construction/Design	Well Data	Formation Description
4" sch 10 304L stainless riser pipe 337.76 – 515.86 bgs		All below ground surface
4" sch 10 304L cont. wire wrap screen .020" 515.86 – 537.40 bgs with end cap		319'–331' Dark brown silt
bentonite pellets 3/8" emplaced 497'– 512' bgs		331'–337' fine sandy gravels
Colorado silica sand 10/20 mesh 512'–550' bgs		337'–362' blue/green clay
		362'–367' grey beach sand
		367'–379' blue/green clay
		379'–385' blue/green sand
		385'–404' Grey sand
		404'–436' grey sandy wood chips with pyrite
		436'–456' Grey sand
		456'–458' very hard blue clay
		458'–485' soft blue clay
		485'–489' hard blue/green clay
		489'–494' grey clay
		494'–507' blue/green clay
		507'–509' Sandy blue/green clay
		509'–512' hard blue clay
		512'–546' black weathered basalt mixed w/ Redish/blue clay
		546'–550' very hard black basalt
		550' TD

Scale 1"= ______ Page 2 of 2 ECY 050-12 (Rev 2/01)

Please print, sign and return to the Department of Ecology

Nillson Well

The Department of Ecology does NOT Warranty the Data and/or the Information on this Well Report.

Water Well Report

Original – Ecology 1st copy – owner 2nd copy – driller

ECOLOGY

Construction/Decommission

☐ Construction

☐ Decommission ORIGINAL INSTALLATION Notice of Intent Number ____

153566

Current Notice of Intent No W15074 1

Unique Ecology Well ID Tag No AHP784

Water Right Permit No G4 29667P

Property Owner Name Roy Farms Inc JR

Well Street Address 401 Walters Rd

City Moxee County Yakima

Location E ½ 1/4 SE 1/4 Sec 14 Twn 12 R 20 EWM ☑ or WWM ☐ circle one

Lat/Long (s t r still REQUIRED) Lat Deg ____ Lat Min/Sec ____ Long Deg ____ Long Min/Sec ____

Tax Parcel No ____

Received AUG 1 8 2004 DEPT OF ECOLOGY CENTRAL REGION

PROPOSED USE ☐ Domestic ☐ Industrial ☐ Municipal ☐ DeWater ☑ Irrigation ☐ Test Well ☐ Other ____

TYPE OF WORK Owner's number of well (if more than one) ____

☐ New well ☑ Reconditioned *Method* ☐ Dug ☐ Bored ☐ Driven

☐ Deepened ☐ Cable ☑ Rotary ☐ Jetted

DIMENSIONS Diameter of well 12 inches drilled 12 & 9 7/8"

Depth of completed well 1270 ft

CONSTRUCTION DETAILS

Casing Installed ☑ Welded 12 Diam from +1 ft to 942 ft

☐ Liner installed ____ Diam from ____ ft to ____ ft

☐ Threaded ____ Diam from ____ ft to ____ ft

Perforations ☐ Yes ☑ No

Type of perforator used ____

SIZE of perfs ____ in by ____ in and no of perfs ____ from ____ ft to ____ ft

Screens ☐ Yes ☑ No ☐ K Pac Location ____

Manufacturer's Name ____

Type ____ Model No ____

Diam ____ Slot size ____ from ____ ft to ____ ft

Diam ____ Slot size ____ from ____ ft to ____ ft

Gravel/Filter packed ☐ Yes ☑ No ☐ Size of gravel/sand ____

Materials placed from ____ ft to ____ ft

Surface Seal ☑ Yes ☐ No To what depth? 942 ft

Material used in seal cement

Did any strata contain unusable water? ☐ Yes ☐ No

Type of water? ____ Depth of strata ____

Method of sealing strata off ____

PUMP Manufacturer's Name ____

Type ____ HP ____

WATER LEVELS Land surface elevation above mean sea level ____ ft

Static level 203 ft below top of well Date ____

Artesian pressure ____ lbs per square inch Date ____

Artesian water is controlled by ____ (cap, valve etc)

WELL TESTS Drawdown is amount water level is lowered below static level

Was a pump test made? ☐ Yes ☐ No If yes by whom? ____

Yield ____ gal /min with ____ ft drawdown after ____ hrs

Yield ____ gal /min with ____ ft drawdown after ____ hrs

Yield ____ gal /min with ____ ft drawdown after ____ hrs

Recovery data (time taken as zero when pump turned off) (water level measured from well top to water level)

Time	Water Level	Time	Water Level	Time	Water Level

Date of test ____

Bailer test ____ gal /min with ____ ft drawdown after ____ hrs

Airtest 200 gal /min with stem set at 1260 ft for 1 hrs

Artesian flow ____ gpm Date ____

Temperature of water ____ Was a chemical analysis made? ☐ Yes ☐ No

CONSTRUCTION OR DECOMMISSION PROCEDURE

Formation Describe by color character size of material and structure and the kind and nature of the material in each stratum penetrated, with at least one entry for each change of information indicate all water encountered (USE ADDITIONAL SHEETS IF NECESSARY)

MATERIAL	FROM	TO
Brown Silt	0	4
Sand gravel & cobbles	4	7
Sandy Clay	7	15
Tan sticky clay	15	72
Dark brown coarse sandstone	72	79
Brown clay	79	86
Sandstone & clay layers brown	86	106
Sand & fine gravel brown	106	110
Dark green clay	110	116
Fine gravel & sand black with green clay	116	178
Green clay	178	185
Sandstone dark green	185	190
Fine gravel & sand black with gren clay	190	199
Black sandstone & hard dark green clay layers	199	224
Green clay	224	260
Black sandstone & hard dark green clay	260	397
Light green clay	397	425
Green sandstone	425	450
Fine gravel sand some green clay	450	538
Green clay	538	545
Green sandstone	545	586
Greeen clay	586	598
Green clay & sandstone layers some brown & gray clay	598	630
Green clay & green sandy clay layers	630	846
Gray sandstone	846	864
Fine gravel sand & clay	864	885
Black & green claystone	885	910
Hard gray basalt	910	915
Reddish brown clay & broken rock	915	935
Hard light gray basalt	935	1040

Start Date 6 28 04 Completed Date 7 26 04

WELL CONSTRUCTION CERTIFICATION I constructed and/or accept responsibility for construction of this well and its compliance with all Washington well construction standards Materials used and the information reported above are true to my best knowledge and belief

Driller/Engineer/Trainee Name (Print) Larry McLanahan

Driller/Engineer/Trainee Signature [signature]

Driller or trainee License No 0337

If TRAINEE
Driller's Licensed No
Driller's Signature

Drilling Company BJ Exploration Co Inc

Address 404 North Conway Street

City State Zip Kennewick WA 99336

Contractor's Registration No BJEXPCI132OK Date 8-11-04

Ecology is an Equal Opportunity Employer

ECY 050 1 20 (Rev 2/03)

Please print, sign and return to the Department of Ecology

Nillson Well

Water Well Report

Original – Ecology 1st copy – owner 2nd copy – driller

ECOLOGY

Construction/Decommission

☐ Construction

☐ Decommission *ORIGINAL INSTALLATION Notice of Intent Number* ________

153566

DEPT OF ECOLOGY Received AUG 18 2004 CENTRAL REGION

Current Notice of Intent No W150741

Unique Ecology Well ID Tag No AHP784

Water Right Permit No G4 29667P

Property Owner Name Roy Farms Inc JR

Well Street Address 401 Walters Rd

City Moxee **County** Yakima

Location E ¼ 1/4 SE 1/4 **Sec** 14 **Twn** 12 **R** 20 EWM ☑ or WWM ☐ (circle one)

Lat/Long (s t r still REQUIRED) **Lat Deg** ______ **Lat Min/Sec** ______ **Long Deg** ______ **Long Min/Sec** ______

Tax Parcel No ________

PROPOSED USE ☐ Domestic ☐ Industrial ☐ Municipal ☐ DeWater ☑ Irrigation ☐ Test Well ☐ Other ______

TYPE OF WORK Owner's number of well (if more than one) ______
☐ New well ☑ Reconditioned *Method* ☐ Dug ☐ Bored ☐ Driven
☐ Deepened ☐ Cable ☑ Rotary ☐ Jetted

DIMENSIONS Diameter of well 12 inches drilled 12 & 9 7/8
Depth of completed well 1270 ft

CONSTRUCTION DETAILS

Casing Installed ☑ Welded 12" Diam from +1 ft to 942 ft
☐ Liner installed ______ Diam from ______ ft to ______ ft
☐ Threaded ______ Diam from ______ ft to ______ ft

Perforations ☐ Yes ☑ No
Type of perforator used ______
SIZE of perfs ______ in by ______ in and no of perfs ______ from ______ ft to ______ ft

Screens ☐ Yes ☑ No ☐ K Pac Location ______
Manufacturer's Name ______
Type ______ Model No ______
Diam ______ Slot size ______ from ______ ft to ______ ft
Diam ______ Slot size ______ from ______ ft to ______ ft

Gravel/Filter packed ☐ Yes ☑ No ☐ Size of gravel/sand ______
Materials placed from ______ ft to ______ ft

Surface Seal ☑ Yes ☐ No To what depth? 942 ft
Material used in seal cement
Did any strata contain unusable water? ☐ Yes ☐ No
Type of water? ______ Depth of strata ______
Method of sealing strata off ______

PUMP Manufacturer's Name ______
Type ______ HP ______

WATER LEVELS Land surface elevation above mean sea level ______ ft
Static level 203 ft below top of well Date ______
Artesian pressure ______ lbs per square inch Date ______
Artesian water is controlled by ______ (cap, valve, etc)

WELL TESTS Drawdown is amount water level is lowered below static level
Was a pump test made? ☐ Yes ☐ No If yes by whom? ______
Yield ______ gal/min with ______ ft drawdown after ______ hrs
Yield ______ gal/min with ______ ft drawdown after ______ hrs
Yield ______ gal/min with ______ ft drawdown after ______ hrs

Recovery data (time taken as zero when pump turned off) (water level measured from well top to water level)

Time	Water Level	Time	Water Level	Time	Water Level

Date of test ______
Bailer test ______ gal/min with ______ ft drawdown after ______ hrs
Airtest 200 gal/min with stem set at 1260 ft for 1 hrs
Artesian flow ______ gpm Date ______
Temperature of water ______ Was a chemical analysis made? ☐ Yes ☐ No

CONSTRUCTION OR DECOMMISSION PROCEDURE

Formation Describe by color character size of material and structure and the kind and nature of the material in each stratum penetrated, with at least one entry for each change of information indicate all water encountered (USE ADDITIONAL SHEETS IF NECESSARY)

MATERIAL	FROM	TO
Med hard broken brown & black basalt	1040	1047
Med soft fractured brown basalt & hard green clay		
little water 175psi	1047	1079
Hard green clay	1079	1081
Med hard black basalt	1081	1094
Hard green clay	1094	1095
Med hard black basalt with green clay seams	1095	1147
Med hard black basalt porus	1147	1180
Med hard black basalt & green clay seams	1180	1191
Soft black porus basalt with blue green clay		
Little water 190 psi	1191	1196
Med soft black basalt with green clay seams	1196	1224
Hard green clay	1224	1233
Med hard black basalt	1233	1270
12' casing to 942		
9 7/8 to 1270		

Start Date 6-28 04 Completed Date 7 26 04

WELL CONSTRUCTION CERTIFICATION I constructed and/or accept responsibility for construction of this well and its compliance with all Washington well construction standards Materials and the information reported above are true to my best knowledge and belief

Driller/Engineer/Trainee Name (Print) Larry McLanahan
Driller/Engineer/Trainee Signature *Larry McL*
Driller or trainee License No 0337

If TRAINEE
Driller's Licensed No
Driller's Signature

Drilling Company BJ Exploration Co Inc
Address 404 North Conway Street
City State Zip Kennewick WA 99336
Contractor's Registration No BJEXPCI132OK Date 8-11-04

Ecology is an Equal Opportunity Employer ECY 050 1 20 (Rev 2/03)

The Department of Ecology does NOT Warranty the Data and/or the Information on this Well Report.

Well Construction & Licensing

Home | Laws & Rules | Map Search | Text Search | Forms | Site Info | Contact Well Team | About Ecology

Well Report Map Menu

Search Options | Legend/Laye

County

City

Watershed (WRIA)

Township/Range/Section

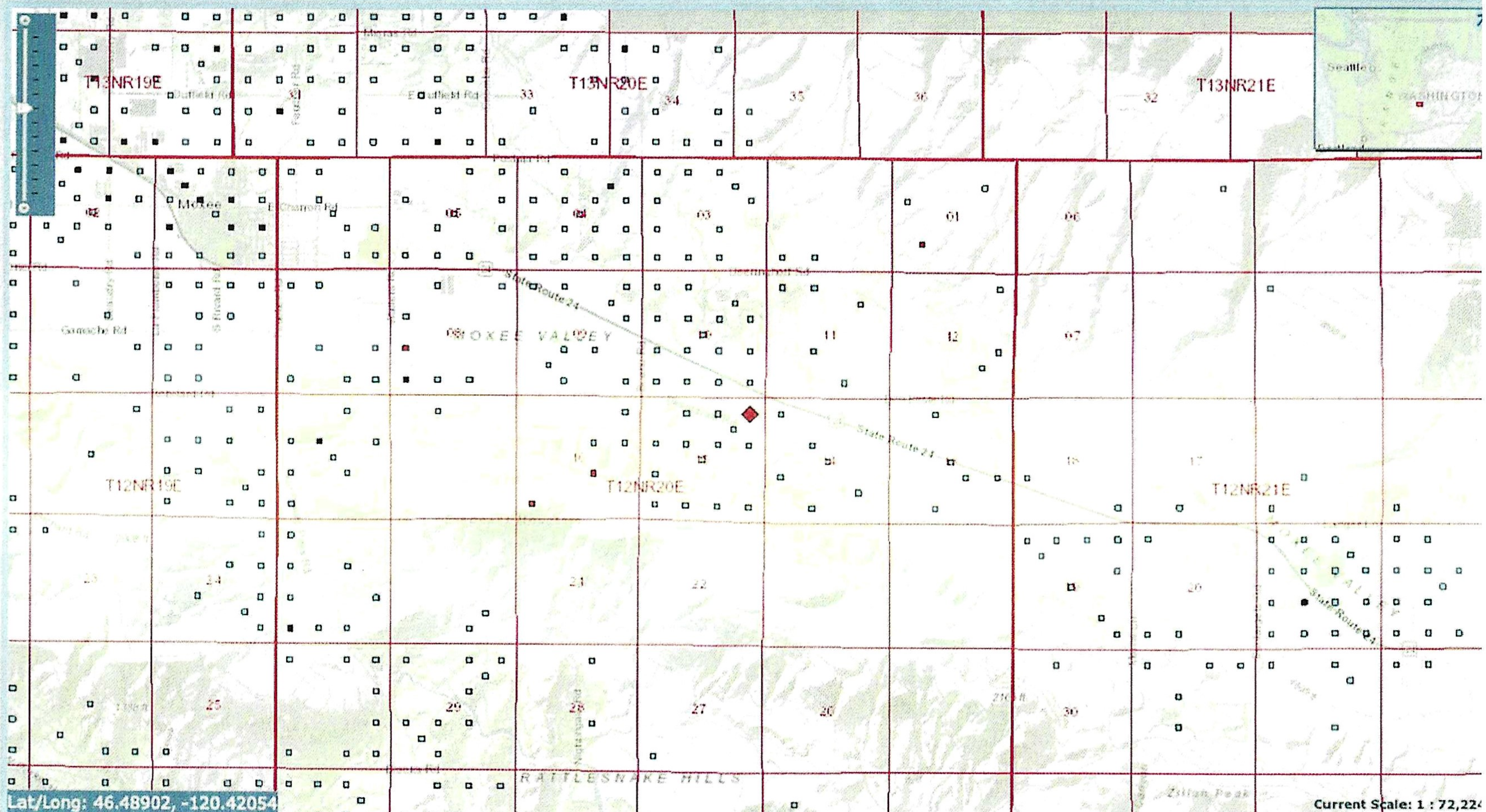
Township

Range

Section *optional*

Address/Location

Zoom in | Zoom out | Pan | Select wells



S. well

DEPARTMENT OF ECOLOGY State of Washington

Water Rights Map Search

Home | Map Search | Record Search | GIS Spatial Data | Contact Us | Data Disclaimer | Help | Privacy Notice | Water Resources

Map Navigation Menu

Search Options | Legend/Layers | Record Details

Record/Document No.: G4-31681

Quantities:
3000.0000 GPM
1188.0000 Irrigated Acres

Purposes:
Frost Protection
Irrigation
Stockwater

Source Names:
Groundwater

Device Types:
Well

Number of Devices: 2

Lattitude/Longtude Point
Township/Range/Section Centroid

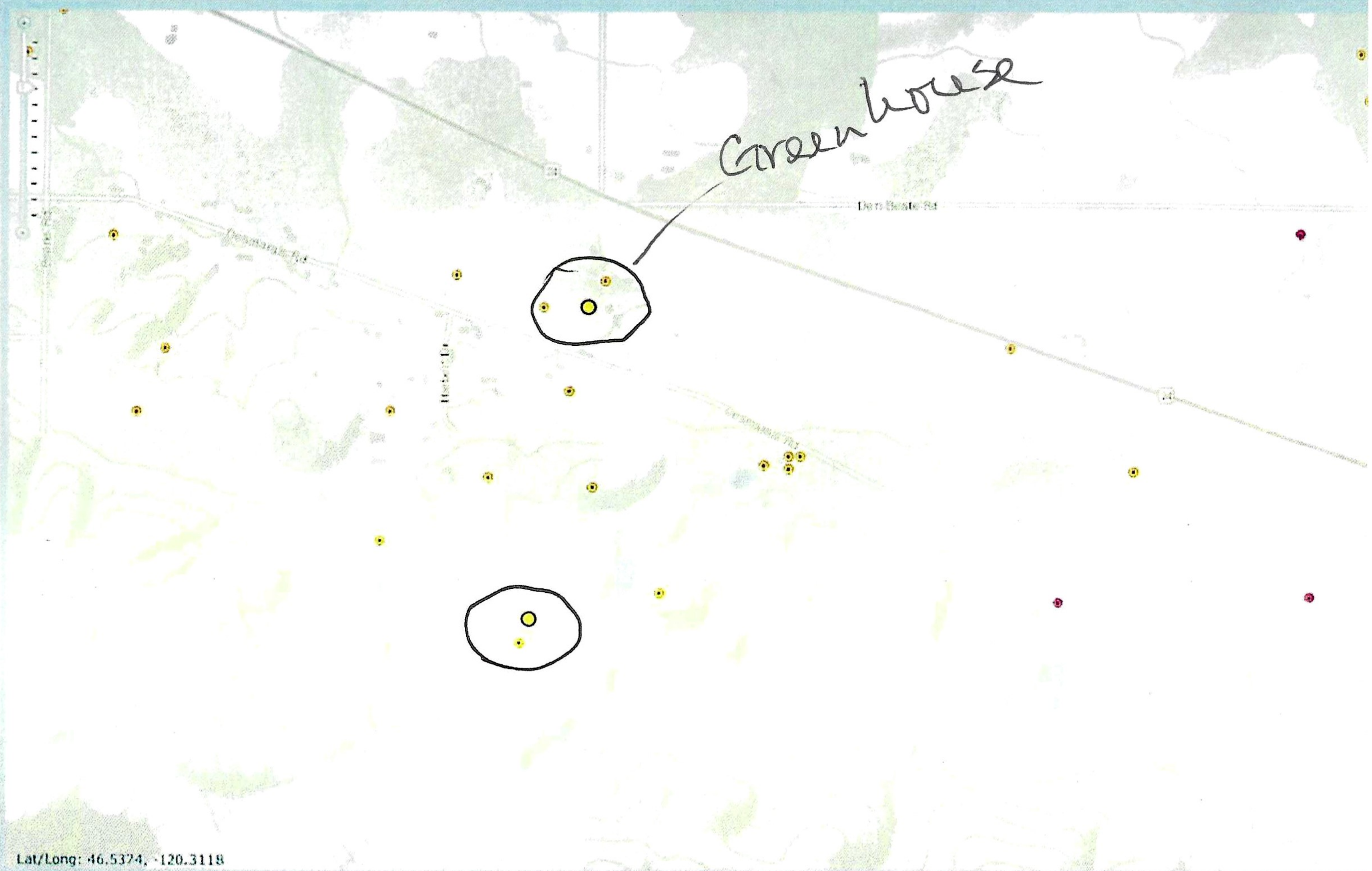
Open Record in WRTS
Submit Record Correction

Images:
Application
Application Supporting Documents
Miscellaneous Reports

Note!

The vicinity of this type of water right location is displayed using a centroid value. Neither the place of use nor the withdrawal points have been mapped to the real location. You can view images for water right documents above when available, which may provide additional location details.

How to Video Clips



Lat/Long: 46.5374, -120.3118

Export Search Result | Display in Text Search Result

View Record	Record/Doc No.	WR Doc ID	Person or Organization	Priority Date/Claim First Use	Phase	Status	Images	Qi	Qa	Open in WRTS
View Details	G4-31681	2086336	Roy Farms Inc *.	01/15/1993	New Application	Active	Yes	3000.0000 GPM	...	Open Record in WRTS

South

WASHINGTON STATE DEPARTMENT OF ECOLOGY

APPLICATION FOR PERMIT
TO APPROPRIATE PUBLIC WATERS OF THE STATE OF WASHINGTON

RECEIVED JAN 15 1993 DEPARTMENT OF ECOLOGY CENTRAL REGION OFFICE

☐ SURFACE WATER ☒ GROUND WATER

$10.00 MINIMUM STATUTORY EXAMINATION FEE REQUIRED WITH APPLICATION

(GRAY BOXES FOR OFFICE USE ONLY)

APPLICATION NO. G 431681 | W.R.I.A. 37 | COUNTY Yakima | PRIORITY DATE 1/15/93 | TIME | ACCEPTED m.a.

APPLICANT'S NAME — PLEASE PRINT: ROY FARMS, INC.

Bus. Tel. 452-3494
Home Tel.
Other Tel.

ADDRESS (STREET) 401 Walters Rd. (CITY) Moxee, (STATE) Wash. (ZIP CODE) 98936

DATE & PLACE OF INCORPORATION IF APPLICANT IS A CORPORATION: Yakima, Washington

1. SOURCE OF SUPPLY

IF SURFACE WATER
SOURCE (NAME OF STREAM, LAKE, SPRING, ETC.) (IF UNNAMED, SO STATE)
TRIBUTARY

IF GROUND WATER
SOURCE (WELL, TUNNEL, INFILTRATION TRENCH, ETC.): 2 EXISTING WELLS
SIZE AND DEPTH: #1 - 2600' deep
#2 - 2100' deep (2 wells)

2. USE

USE TO WHICH WATER IS TO BE APPLIED (DOMESTIC SUPPLY, IRRIGATION, MINING, MANUFACTURING, ETC.): IRRIGATION / FROST PROTECTION / LIVESTOCK / SUPPLEMENTAL

ENTER QUANTITY OF WATER REQUESTED USING UNITS OF: CUBIC FEET PER SECOND (CFS) OR GALLONS PER MINUTE (GPM): 3,000 gpm | ACRE FEET PER YEAR

(irrigation during irrigation season, frost protection, stockwater)

TIMES DURING YEAR WATER WILL BE REQUIRED: Mar. - Oct.

IF IRRIGATION, NUMBER OF ACRES: 808 acres / 380 ac. Primary / Supplemental | IF DOMESTIC USE, NUMBER OF UNITS BY TYPE, E.G. 1-HOME, 1-MOBILE HOME, 2-CAMPSITES, ETC | IF MUNICIPAL USE, ESTIMATED POPULATION 20 YEARS FROM TODAY

DATE PROJECT WAS OR WILL BE STARTED: 1985 | DATE PROJECT WAS OR WILL BE COMPLETED: 1993

3. LOCATION OF POINT OF DIVERSION/WITHDRAWAL

3A. IF IN PLATTED PROPERTY

LOT	BLOCK	OF (GIVE NAME OF PLAT OR ADDITION)	SECTION	TOWN	RANGE	ALSO, PLEASE ENCLOSE A COPY OF THE PLAT AND MARK THE POINT(S) OF WITHDRAWAL OR DIVERSION

(E½ of Sec 15, T 12 N, Range 20 EWM, Yakima County)

3B. IF NOT IN PLATTED PROPERTY

ON ACCOMPANYING SECTION MAPS, ACCURATELY MARK AND IDENTIFY EACH POINT OF DIVERSION. SHOW NORTH-SOUTH AND EAST-WEST DISTANCES FROM NEAREST SECTION CORNER OR PROPERTY CORNER

ALSO, ENTER BELOW THE DISTANCES FROM THE NEAREST SECTION OR PROPERTY CORNER TO THE DIVERSION OR WITHDRAWAL.

LOCATED WITHIN (SMALLEST LEGAL SUBDIVISION)	SECTION	TOWNSHIP N	RANGE (E OR W) W.M.	COUNTY
	15	12	20E	YAKIMA

Well #2 - NE¼ NE¼ Sec 15 • Well #1 - NE¼ SE¼ Sec. 15

4. DO YOU OWN THE LAND ON WHICH THIS SOURCE IS LOCATED. IF NOT, INSERT NAME & ADDRESS OF OWNER: YES

5. LEGAL DESCRIPTION OF PROPERTY *ON WHICH WATER IS TO BE USED*

ATTACH A COPY OF THE LEGAL DESCRIPTION OF THE PROPERTY (ON WHICH THE WATER WILL BE USED) TAKEN FROM A REAL ESTATE CONTRACT, PROPERTY DEED OR TITLE INSURANCE POLICY OR, COPY CAREFULLY IN THE SPACE BELOW

See Maps

PRIMARY USE: ① N½ - Sec 23-12-20 • 320 acres Roy Farms
② ~~(½ E¼ + SW¼) of SW¼~~ (S¾ W½ SW¼) - Sec 14-12-20 60 acres

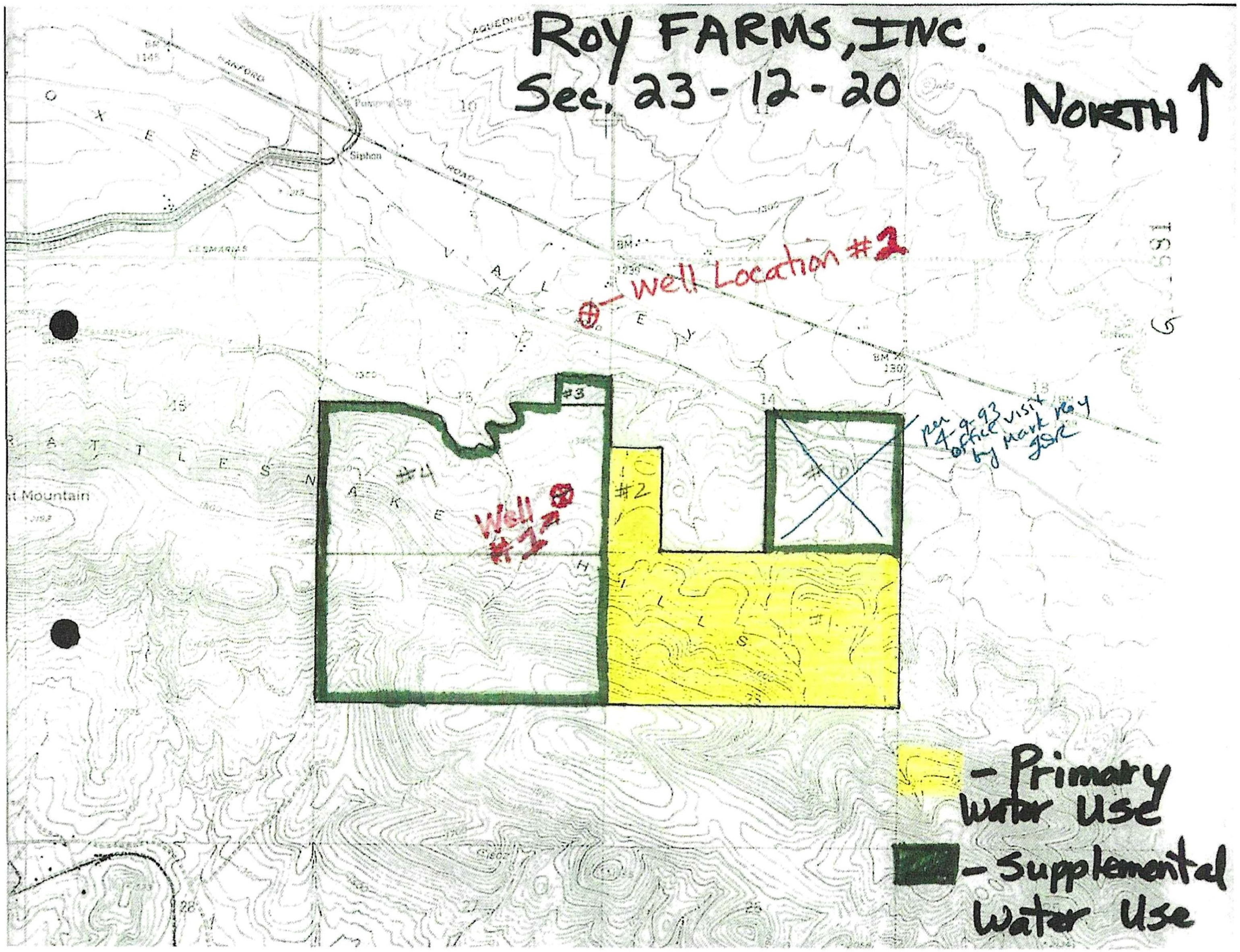
SUPPLEMENTAL USE:
③ Short Plat 79-221 Lot 3+4 - S½ SE¼ NE¼ - Sec. 15-12-20 18 acres Jim Roy
④ S½ Ex. North of Roza Lateral - Sec 15-12-20 310 acres
⑤ N½ - Sec. 22-15-20 22-12-20? 320 acres
⑥ ~~SE¼ - Sec. 14-12-20~~ ~~160 acres~~ Ollie Nilsson

per office visit by Mark Roy 4-9-93 LSR

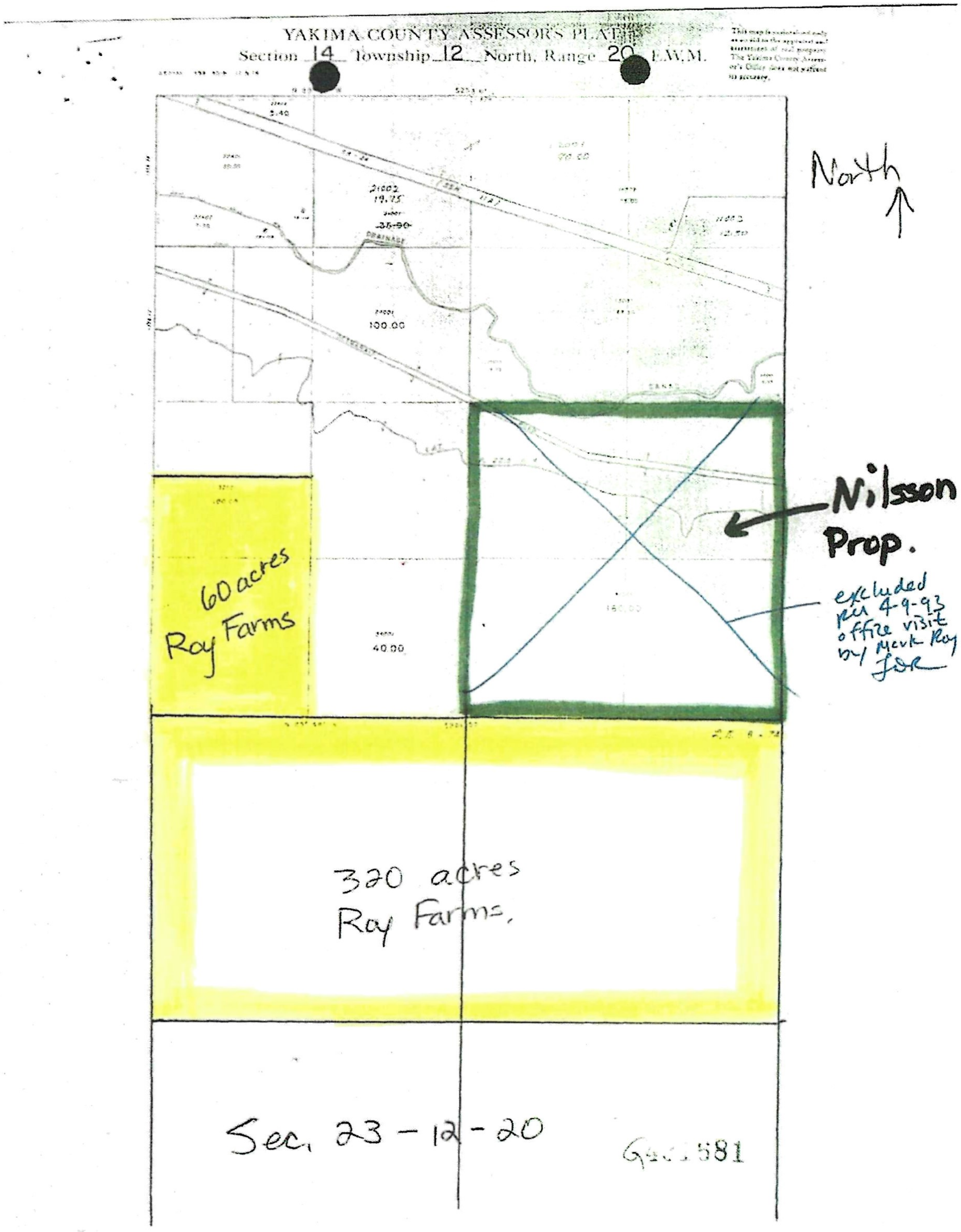
3/18/93 gm

ECY 040-1-14
Rev. 8/91 F

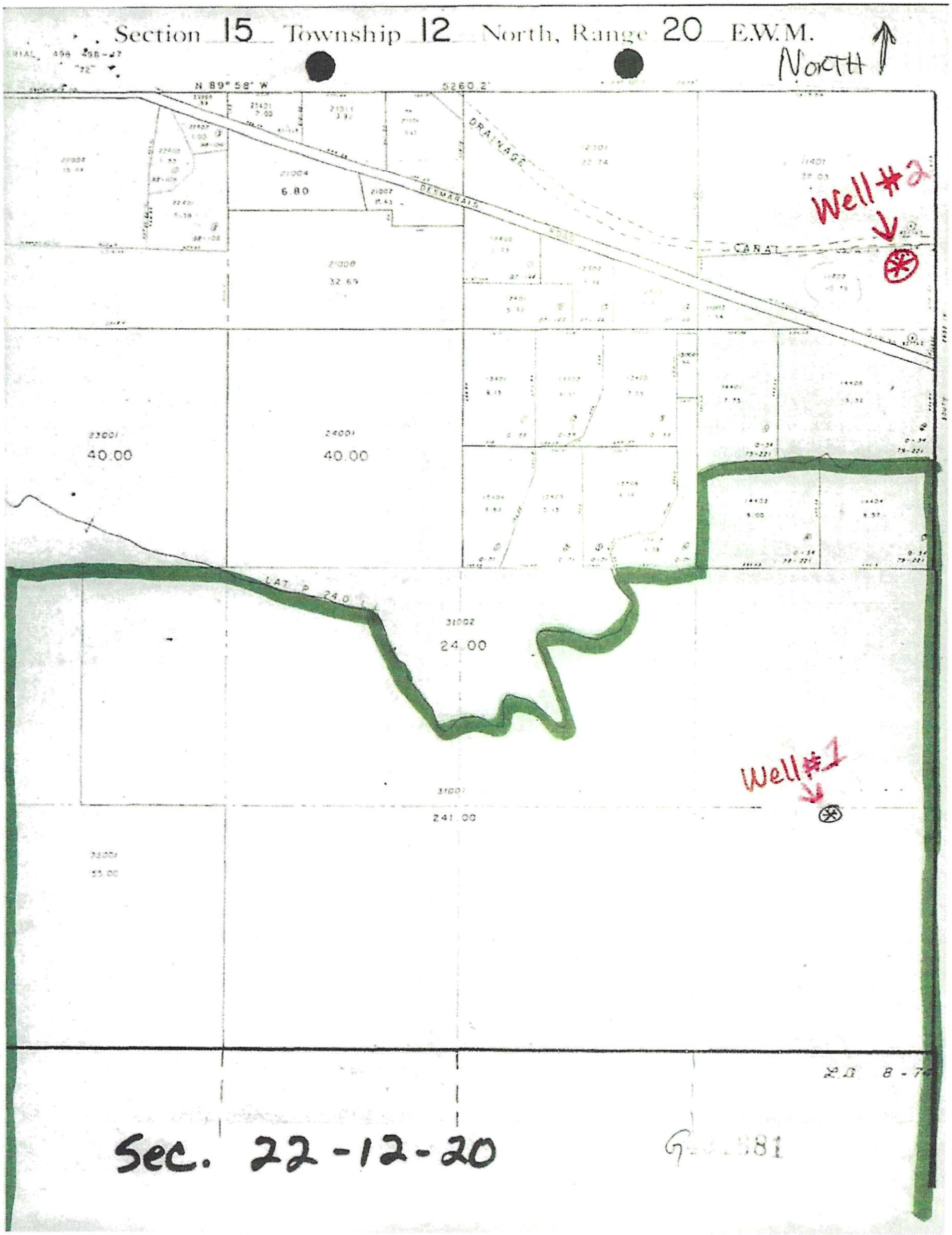
APPLICATION



Roy FARMS, INC.
Sec. 23-12-20
NORTH
Well Location #2
Well #1
#1
#2
#3
#4
per 4-9-93 office visit Mark Roy JSR
- Primary Water Use
- Supplemental Water Use
Rattlesnake Hills
Valley
Siphon



YAKIMA COUNTY ASSESSOR'S PLAT
Section 14 Township 12 North, Range 20 E.W.M.
North
21002
19.75
100.00
Nilsson Prop.
excluded per 4-9-93 office visit by Merk Roy JDR
60 acres Ray Farms
40.00
160.00
320 acres Ray Farms.
Sec. 23 - 12 - 20
G... 581


Section 15 Township 12 North, Range 20 E.W.M.
North
N 89° 58' W
5260.2'
DRAINAGE
DESMARAIS ROAD
CANAL
Well #2
Well #1
21004
6.80
21008
32.69
23001
40.00
24001
40.00
31002
24.00
LAT. P 24.0
31001
241.00
Sec. 22-12-20