In Washington, the Cascade Range snowpack is the state's second largest natural freshwater reservoir. As climate deviates from current conditions, and the type and spatiotemporal distributions of precipitation change, the need to capture and store surplus runoff for later use will increase. Since surface storage methods have a number of drawbacks – cost, environmental issues, land availability, and evaporative losses, to name a few - alternative storage methods are preferable. Aquifer Storage and Recovery (ASR) is an economical water storage option that can be used to supplement freshwater sources and reserves. With the ability to capture and inject water underground during high flow periods for later use, ASR is a viable option to mitigate climatic changes and augment Washington's freshwater supply.

To estimate ASR suitability across Washington, the Office of the Columbia River funded a Master's Thesis at Oregon State University. This study assessed factors such as infrastructure considerations, aquifer characteristics, and regulatory criteria in order to offer insight into the potential for ASR expansion, before having to conduct expensive on-site investigations.

To evaluate ASR feasibility throughout Washington, a desktop suitability assessment, using a modified ASR metric and a modified site suitability assessment, was applied to over 280 locations within Washington's 62 Water Resource Inventory Areas (WRIAs). The modified ASR metric, which is a ratio of the estimated desired volumetric injection rate to the rate at which an aquifer can accept the injected water, indicates 24% and 29% of sites are marginally suitable and suitable for ASR, respectively. Additionally, about 50,000 acre-feet per year of potential storage was realized for WRIAs on the east side of the Cascade Range, which satisfies approximately 17% of predicted 2030 municipal and industrial consumptive use estimates.

The site suitability assessment, which integrates regulatory, hydrogeologic, and infrastructure factors to produce a percentage of ideal conditions suitable for ASR, indicates 51% of the locations evaluated have between 40% to 60% ideal conditions. Furthermore, 32% of marginally suitable and 36% of suitable wells, based on the modified ASR metric, have greater than 60% ideal conditions suitable for ASR. This suggests potential expansion of ASR projects exist in Washington, which could enhance current demand and increase future water storage reservoirs. This assessment provides a course grained evaluation that can be used as a guide to identify locations where more detailed site-specific ASR feasibility studies should be conducted.

A Desktop Suitability Assessment of Aquifer Storage and Recovery (ASR) in Washington State

Report for Washington State Department of Ecology

Oregon State University | College of Earth, Ocean, and Atmospheric Sciences

A Desktop Suitability Assessment of Aquifer Storage and Recovery (ASR) in Washington State

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Prepared for Washington Department of Ecology April 2014

Table of Contents

Figures

Tables

List of Appendices

Appendix A: WRIA 1-62 Maps. Modified ASR metric and site suitability assessment outcome (available upon request).

Appendix B: Spreadsheets. Spreadsheets include modified ASR metric and site suitability assessment results for WRIA 1-62 (available upon request).

Acknowledgments

The authors extend thanks to Washington's local and state staff members, non-government organizations, and consultants that contributed a variety of specialized information. We would like to express gratitude to Bob Patterson for providing feedback and suggestions during the initial phase of this project. We also wish to thank Llyn Doremus for reviewing the draft report and contributing insightful comments and suggestions. The authors are particularly beholden to Dave Nazy for his overall guidance and support. Without his assistance this project would not have been possible.

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Abstract

In Washington, the Cascade Range snowpack is the state's second largest natural freshwater reservoir. As climate deviates from current conditions, and the type and spatiotemporal distributions of precipitation change, opportunities to capture and store surplus runoff for later use will increase. Since surface storage methods have a number of drawbacks – cost, environmental issues, land availability, and evaporative losses, to name a few - alternative storage methods are preferable. Aquifer Storage and Recovery (ASR) is an underground storage option used to supplement freshwater reserves. With the ability to capture and inject water underground during high flow periods for later use, ASR is a viable option to mitigate climatic changes and augment Washington's freshwater supply. To estimate ASR suitability, the assessment of factors such as infrastructure considerations, aquifer characteristics, and regulatory criteria offers insight into the potential for statewide ASR expansion before conducting expensive on-site investigations.

To evaluate ASR feasibility throughout Washington, a desktop suitability assessment, using a modified ASR metric and a modified site suitability assessment, was applied to over 280 locations within Washington's 62 Water Resource Inventory Areas (WRIA). The modified ASR metric, which is a ratio of the estimated desired volumetric injection rate to the rate at which an aquifer can accept the injected water, indicates 24% and 29% of sites are marginally suitable and suitable for ASR, respectively. Additionally, about 50,000 acre-feet per year of potential storage was realized for WRIAs on the east side of the Cascade Range, which satisfies approximately 17% of predicted 2030 municipal and industrial consumptive use estimates. The site suitability assessment, which integrates regulatory, hydrogeologic, and infrastructure factors to produce a percentage of ideal conditions suitable for ASR, indicates 51% of locations have between 40% to 60% ideal conditions. Furthermore, 32% of marginally suitable and 36% of suitable wells, based on the modified ASR metric, have greater than 60% ideal conditions suitable for ASR. This suggests potential expansion of ASR projects exist in Washington, which could enhance current demand and increase future water storage reservoirs. Because of the limited data requirements, the technique can be used elsewhere to provide rapid estimates of ASR suitability. It should prove applicable to developed and developing regions alike.

Introduction

Warmer temperatures, due to changes in climate, will likely have a profound impact on water resources. Consequently, in the Pacific Northwest, the type and timing of precipitation is changing. Using historical averages, Littell et al. (2009) project a 28% decrease in snowpack by the 2020s and 59% by 2080s. Additionally, Elsner et al. (2010) estimate changes in snow water equivalent (SWE), soil moisture, runoff, and stream flow for emission scenarios in the 2020s, 2040s and 2080: the results project a 46% decrease in SWE by 2040; in 2080 SWE is estimated to almost disappear. Therefore, the Pacific Northwest will receive less overall snow accumulation, higher wintertime runoff, earlier spring snowmelt, and lower summertime flows. Additionally, Washington's population is expected to increase from 5.9 million in year 2000 to 8.3 million by year 2030 (WA DOT, 2012). Hence, the need to utilize alternative methods to supplement water supply to capture winter and early springtime runoff will likely increase over time.

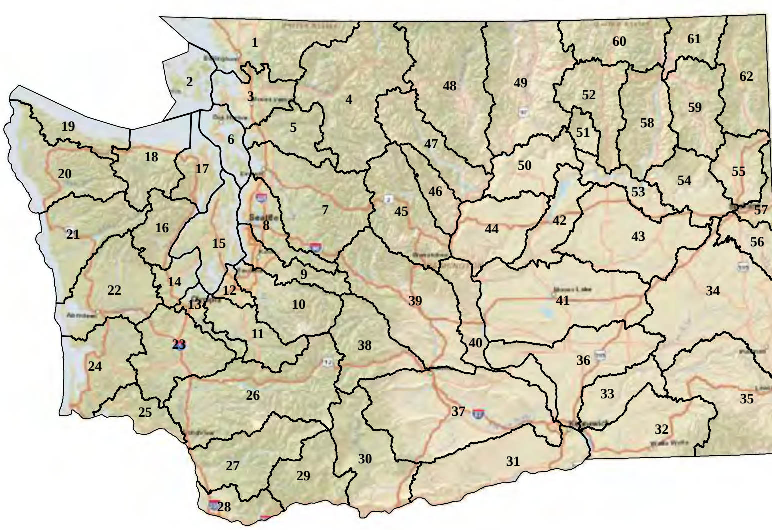
Although used since the 1960s (Pyne, 1995), Aquifer Storage and Recovery (ASR) is considered an alternative water supply method that captures excessive seasonal flow and retains it underground for later use. ASR is the storage of surplus surface water in aquifers via injection wells, and the retrieval of the same, or of similar quality water when demand is at its peak. ASR schemes are typically considered successful when stored water is available when needed. The storage of water in an aquifer is controlled by many factors, the most important being hydrogeologic conditions. Confined aquifers are commonly used (Figure 2b), whereas semi-confined to unconfined (Figure 2a) are less common but can also accept water. Successful ASR projects can also be constrained by infrastructure and regulatory factors. However, the influence of these factors on potential projects can be realized early on with a desktop suitability assessment of available information.

To determine the potential of developing new ASR projects in Washington, a desktop assessment, using a modified site suitability assessment and a modified ASR metric, based on Woody (2007), was conducted within Washington's 62 Water Resource Inventory Areas (WRIA) (Figure 1).

ASR Regulation in Washington

WAC Chapters 173-157

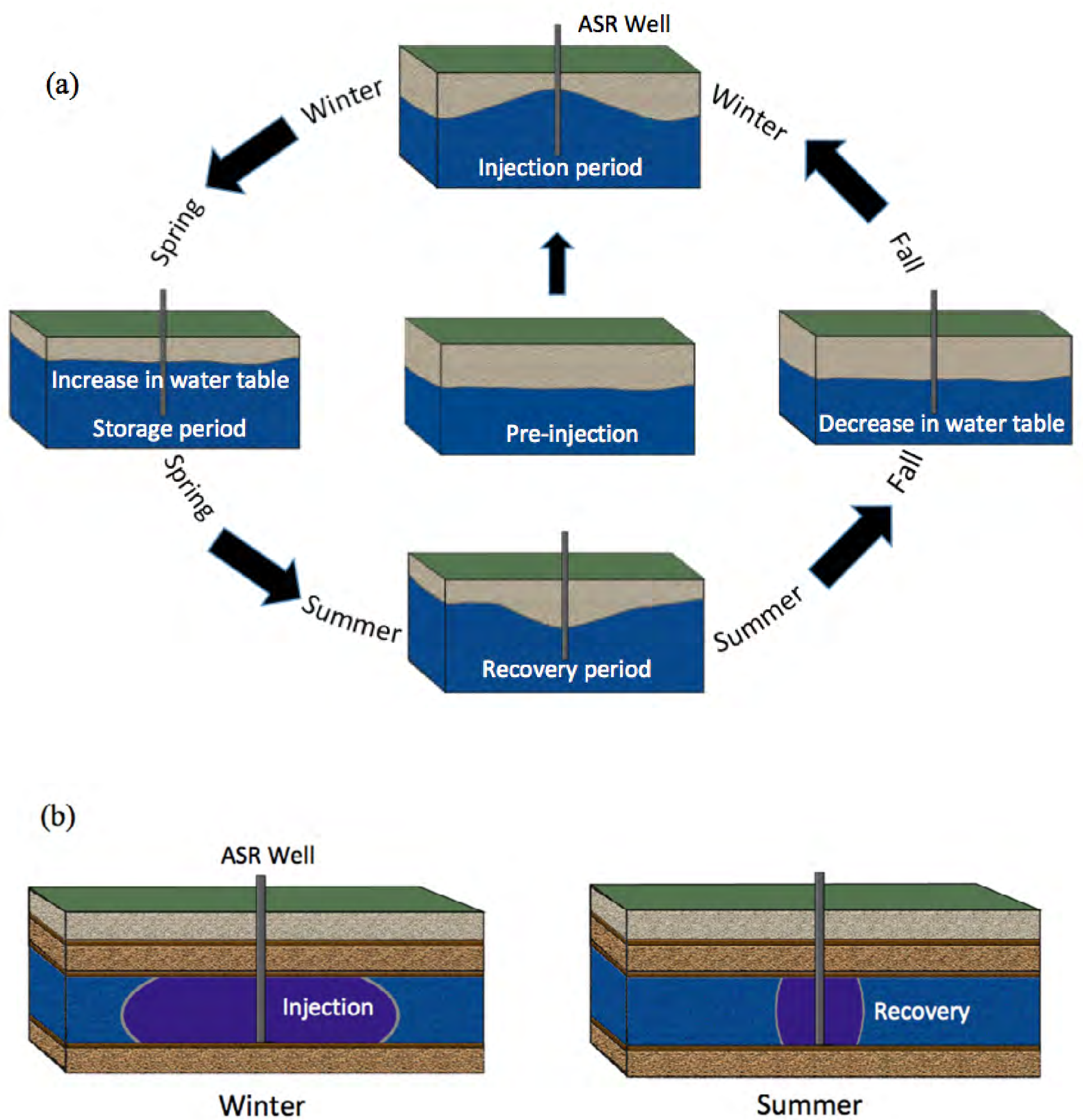
Washington Administrative Code (WAC) Chapters 173-157 establish the standards for review of applications, and when necessary, identify options for mitigation of potential impacts to groundwater quality or the environment for underground artificial storage and recovery projects (Washington State Legislature, 2003).



Data Source: Washington Department of Ecology GIS Data (WA ECY, 2013)

Figure 1. Map of Water Resource Inventory Areas

Figure 2. Conceptual models of ASR in an unconfined (a) and confined aquifer(b). In the unconfined aquifer, injected water mounds near the injection well. Injection occurs during high flow periods. When complete, injected water eventually propagates throughout the aquifer and an increase in the height of the water table is observed. Water is then stored until the summer when demand is high. During recovery, a cone of depression forms until recovery seizes and a lowering of the water table is observed, until the cycle begins again during winter months. If boundary conditions exist such that stored water increases water levels, the water is retrievable when needed. Injected water in a confined aquifer (b) increases pressure within the aquifer temporarily; however, if a density difference in native groundwater exists (i.e. brackish water), injected water will form a "bubble" around the injection well and remain until recovery occurs, at which time the bubble shrinks. Injection typically occurs during winter months and recovery during summer months.



Authorizations or Permits Required

To proceed with an ASR scheme, some or all of the following are required: water rights to source waters, reservoir permit, secondary permit, Underground Injection Control (UIC) registration, and an NPDES permits (Figure 3).

Water Right

Water can only be recovered if a water right permit, certificate, or registered water right claim is on file with the state. However, if the proposed water use is different from that authorized, a secondary permit is required.

Reservoir Permit

To apply for a reservoir permit the applicant must ensure the following is provided (WAC 173-157-110) (Figure 4): a hydrogeologic system description, an operational plan certified by an engineer or a registered geologist, legal framework description, environmental assessment, monitoring plan, and, if requested, a mitigation plan. An extensive feasibility study may be requested if these requirements do not meet the approval of the state.

Defined in WAC 173-157-120, the hydrogeologic system description must contain a conceptual model including source water and the aquifer's physical and chemical conditions. Examples include: transmissivity, porosity, extent of the aquifer, available storage volume, flow direction, geology, chemical composition of source water, etc.

The operation plan must include the following details (WA 173-157-130): availability of source water, rate of injection, storage times, capacity of injection wells, water treatment methods, etc.

The legal framework description (WA 173-157-140) requires documentation of water rights for source water storage, a list of water rights within the project area, instream flow diversion points, and ownership of the operating facility.

The environmental assessment includes (WAC 173-157-150): contaminated areas, current and prior land use, surface flow information, impacts to habitat, surface deformation, slope stability, etc.

Defined in WAC 173-157-160, mitigation plans, if required, must describe actions that will prevent adverse impacts to the environment including methods and evaluations of these measurements.

Figure 3. Authorizations required for an ASR project (Washington State Legislature, 2003)

1. Water rights to source waters:
   a. Any source water you use as part of a project by diverting from a state watercourse or withdrawing state groundwaters, must be obtained under a valid water right permit, certificate, or registered water right claim.
   b. The underlying water right specifies authorized uses. Any proposal to use stored water for different uses will require issuance of a secondary permit.
2. Reservoir permit: When proposing to collect and store water in a naturally occurring underground geological formation for subsequent use as part of an ASR project, you must apply for a reservoir permit in accordance with the provisions of RCW 90.03.370 (2)(a).
3. Secondary Permit: You must apply for a secondary permit in accordance with the provisions of RCW 90.03.370 if you propose to apply the water stored in a reservoir to a beneficial use, except that you are not required to apply for a secondary permit if you already have a water right for the source water that authorizes the proposed beneficial use.
4. UIC Registration: All UIC wells to be utilized as part of an ASR project must be registered with the department in accordance with the provisions of chapter 90.48 RCW. Additionally, the construction and technical aspects of the injection wells must abide by UIC regulations as stated in chapter 173-160 WAC
5. NPDES Permit: Water obtained from an aquifer recharge project and disposed of in surface water or surface water bodies water must meet water quality standards set forth in chapter 173-201A WAC to protect aquatic life.

Figure 4. Reservoir permit application (Washington State Legislature, 2003)

1. A description (conceptual model) of the hydrogeologic system prepared by a hydrogeologist licensed in the state of Washington.
2. A project operation plan with a description of the pilot and operational phases of the ASR project prepared by an engineer or geologist licensed in the state of Washington.
3. A description of the legal framework for the proposed project.
4. An environmental assessment and analysis of any potential adverse conditions or potential impacts to the surrounding ecosystem(s) that might result from the project, along with a plan to mitigate such conditions or impacts. The environmental assessment will establish whether a determination of non-significance or an environmental impact statement is required per SEPA regulations.
5. A project mitigation plan, if required.
6. A project monitoring plan.

Proper monitoring plans include: data, sampling methods, water quality information, etc.

UIC Registration

As mandated by the Environmental Protection Agency (EPA), ASR wells must be registered as Class 5 of the Underground Injection Control Program (UIC). These wells are limited to the injection of non-hazardous fluids to prevent contamination of subsurface waters. All registration forms for Class 5 wells in Washington must be submitted to Washington State Department of Ecology (Ecology).

NPDES

An NPDES permit may be required if water from a recharge project is discharged to surface water or surface water bodies.

Water Quality

Stored water must meet state groundwater quality standards defined in Chapter WAC 173-200 (Washington State Legislature, 1990). The intent of this chapter is, "to maintain the highest quality of the state's groundwaters and protect existing and future beneficial uses of the groundwater through the reduction or elimination of the discharge of contaminants to the state's groundwaters."

The state maintains an antidegradation policy; therefore, if groundwater meets drinking water standards, injected water must be of the same quality. Although, according to WAC 173-157-200, strong consideration will be given to the overriding public interest in its evaluation of compliance with groundwater quality protection standards.

Groundwater Antidegradation Policy

Chapter 90.48 Revised Code of Washington (RCW) of the Water Pollution Control Act and chapter 90.54 RCW of the 1971 Water Resources Act guides the state groundwater antidegradation policy (WAC 173-200-030). The policy is intended to prevent degradation of groundwater and the natural environment (Figure 5).

In cases where injected water contains non-native constituents or contaminants in excess of the groundwater quality criteria set forth in WAC 173-200-040, it must be shown that an overriding consideration of public interest will be served, and an All Known and Reasonable Technologies (AKART) analysis (WAC-200-050) for ensuring injected water meets groundwater standards is required. An engineering report, typically prepared by a licensed engineer, is required to address "All Known and Available". An approved engineer reviews case-by-case decisions on technology-based effluent limits; and an economic reasonableness test defines "Reasonable" (WA ECY, 2011). At the completion of an AKART analysis, if groundwater quality criteria are not met, contaminants must be minimized to a reasonable extent (Nazy, 2014). Enforcement limits may

Figure 5. Washington's groundwater antidegradation policy (Washington State Legislature, 1990)

A. Existing and future beneficial uses shall be maintained and protected and degradation of groundwater quality that would interfere with or become injurious to beneficial uses shall not be allowed.

B. Degradation shall not be allowed of high quality groundwaters constituting an outstanding national or state resource, such as waters of national and state parks and wildlife refuges, and waters of exceptional recreational or ecological significance.

C. Whenever groundwaters are of a higher quality than the criteria assigned for said waters, the existing water quality shall be protected, and contaminants that will reduce the existing quality thereof shall not be allowed to enter such waters, except in those instances where it can be demonstrated to the department's satisfaction that:

i. An overriding consideration of the public interest will be served; and

ii. All contaminants proposed for entry into said groundwaters shall be provided with all known, available, and reasonable methods of prevention, control, and treatment prior to entry.

exceed groundwater quality criteria under certain circumstances listed in WAC 172-200-050.

Inquiry and Use in Washington

Projects involving aquifer storage are on the rise in the Pacific Northwest. Many water distributors and local governments in Washington have taken an active role investigating its use and benefits (Figure 6), and although the degree to which each inquiry varies by source, the overall interest suggests such projects will likely increase in the future. The following is an overview of ASR inquiry and use within various WRIAs. Inquiries that cross WRIA boundaries are discussed separately, followed by details of locations currently operating ASR wells. Though this is an extensive list, it is by no means an all-inclusive one.

Inquiry by WRIA

WRIA 1: Nooksack

City of Blaine and the Birch Bay Water and Sewer considered ASR developments in 1998. GeoEngineers (1998) assessed and determined a feasibility study and pilot project would cost $75,000 to $125,000.

The city of Lynden's Public Works Committee (2009) considered the viability of utilizing ASR. Subsequently, a scope of work was presented to the committee by Associated Earth Services, which discussed initial testing and estimated phase 1 of the project would cost up to $110,000 and included well drilling, geologic, and hydrogeologic assessments.

WRIA 6: Island

The town of Coupeville considered contracting Pacific Groundwater Group to conduct a 10-task feasibility study estimated to cost $132,460 (Coupeville, 2013).

WRIA 9: Duwamish-Green

The city of Kent, located in WRIA 9, submitted copies of major water rights to Lakehaven Utility District to be included in the Optimization of Aquifer Storage for Increased Supply (OASIS) project. The city of Kent is also modifying its Soos Creek well for ASR use. It is estimated the project could add an additional 0.5 million gallons per day (MGD) to their water supply (Pace, 2011).

WRIA 10: Puyallup-White

The city of Bonney Lake concluded suitable ASR conditions might exist within their aquifer and suggested a fatal flaw analysis be conducted (Bonney Lake, 2010).

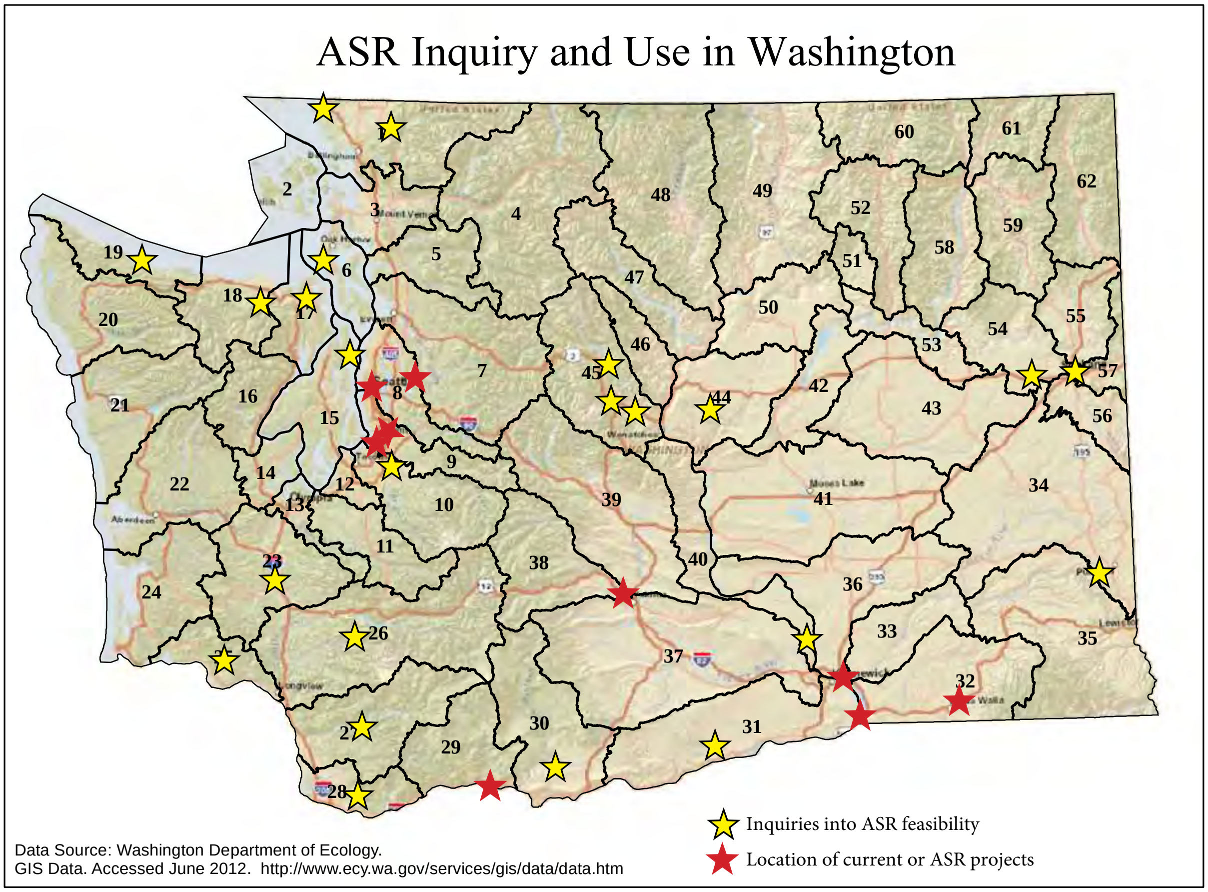
WRIA 15: Kitsap

Golder Associates, Inc. (2005) suggested ASR could offset Kingston Wastewater Treatment Plant costs when compared to various groundwater recharge methods.

WRIA 17: Quilcene-Snow

Pacific Groundwater Group (2007) evaluated sediments in Chimacum Valley and determined a "middle aquifer" could be favorable for ASR and recommended further aquifer tests.

Figure 6. Map of ASR inquiry and use in Washington



WRIA 18: Elwha-Dungeness
Tetra Tech (TTFW, 2003a) conducted a hydrogeologic analysis using a groundwater model to simulate aquifer recharge via irrigation ponds in the Sequim-Dungeness area and found two suitable locations on the east and west side of the Dungeness River. Jefferson County Public Utility District and Pacific Groundwater Group (PGG, 2009) updated TTFW's groundwater model and included 14 scenarios and determined 3 viable options: 2 infiltration scenarios and 1 ASR scenario. The use of ASR would require injecting about 2 cubic feet per second (cfs) of water into deep aquifers from May to July, with subsequent recovery occurring July to September.

WRIA 19: Lyre-Hoko
It was concluded ASR was unsuitable due to lack of distribution means and suitable aquifers (TTFW, 2005)

WRIA 23: Upper Chehalis
Tetra Tech (2003b) states surficial aquifers in this region, including portions of WRIA 22, are unsuitable for ASR; however, the Newaukum confined aquifer, southeast of the city of Centralia, is recommended as the target aquifer for future investigation.

WRIA 25 & 26: Grays-Elochoman and Cowlitz
Although considered unsuitable for ASR, due to the potential of high costs burdening small communities, future evaluations of suitability were recommended (HDR/EES, 2006a).

WRIA 27 & 28: Lewis and Salmon-Washougal
These watersheds were deemed unsuitable for ASR due to abundant groundwater supplies but future evaluations were recommended (HDR/EES, 2006b).

WRIA 30: Klickitat

Aspect Consulting (2003) estimated ASR projects could supplement Swale Creek subbasin flows and water could potentially be stored in the Grande Ronde and Wanapum Basalts. In the Little Klickitat subbasin, Aspect Consulting recommended winter overflow from Goldendale's Simcoe Springs be captured and injected into the Wanapum Basalts.

WRIA 31: Rock-Glade

Aspect Consulting (2007) discussed ASR as a possible storage option for the Horse Heaven area. They estimated the region was hydrogeologically suitable for ASR but potentially not cost effective.

WRIA 34: Palouse

Brown and Wirganowicz, (2007) created an ASR development plan for the city of Pullman. Cost for a single ASR well, which included intake and water treatment, was estimated at $180,000; ASR permitting and planning costs were estimated at $64,000. Both excluded costs for a facility scheme, construction, and initial testing. Although ASR was deemed a viable option for the city, two obstacles will likely prevent the development of these systems: state groundwater antidegradation rules and the city's priority for water reuse (Gardes, 2013).

WRIA 40a: Alkali-Squilchuck

It was determined by RH2 (2007), ASR could be feasible in the southern boundary of this region, but low permeability sandstone and landslide deposits, which underlie most of the watershed, are determined unsuitable for ASR.

WRIA 44: Moses Coulee

The watershed management plan for WRIA 44 and 50 (Foster Creek Conservation District, 2004) indicates 2 infiltration sites, located within the Douglas Creek basin, could prove suitable for ASR.

WRIA 45: Wenatchee

In appendix B of the Montgomery Water Group (2006) water storage assessment, Swope (2005), believes Icicle Canyon, near the city of Leavenworth, would not be feasible for an ASR project due to a lack of confining units, though an infiltration basin would be possible. The city of Cashmere also lacks the proper hydrogeologic conditions suitable for an ASR project, as its confined aquifer is not laterally continuous. Conversely, the Upper Wenatchee region surrounding the city of Plain is potentially suitable for ASR due to the structure of local confining units.

WRIA 54: Lower Spokane

Tetra Tech and GeoEngineers (2007) mention ASR as a structural alternative in the West Plains Project, which encompasses Medical Lake, Fairchild Air Force Base, and Airway Heights. Aquifers potentially suitable for ASR include the Wanapum and/or Grande Ronde Basalts and paleochannel aquifers.

Locations within Multiple WRIAs

Yakima (WRIA 37 & 38):

The city of Yakima conducted an ASR pilot test in 2000 to 2001. The Naches River Water Treatment plant provided source water to the city's Kissell well, which accesses the lower and upper members of the Ellensburg Formation. Following 25 days of injecting approximately 1,200 gallons per minute (gpm), the city recharged 42.4 million gallons, where it remained in storage for 55 days followed by a 30-day recovery period at a rate of 2,000 gpm. Yakima currently plans to add 2 ASR wells, with a capacity of 3.6 MGD to its water system by 2025 (Coleman, 2011).

Spokane (WRIA 54, 55, 56, & 57)

Using MODFLOW, Barber et al. (2011), completed an analysis of the Spokane Valley-Rathdrum Prairie and concluded an alternative method could recharge the aquifer through injection wells and recovery via natural methods to augment summer flows. The hypothetical cost estimate for this project is $90 million.

ASR Projects Operating in Washington

Kennewick
In 2005, Aspect Consulting completed an extensive prefeasibility study for the city of Kennewick. They determined the southwest portion of the water service zone would be the primary ASR target area. The Priest Rapids member within the Wanapum Formation could support additional pressure to accommodate injection into overall ambient groundwater that meets drinking water standards. In 2008, Ecology allocated $1 million to help fund an ASR pilot project (WA ECY, 2008). The ASR system is expected to be fully operational by 2015 (Pitre and Hanson, 2013) and cost $4 million, with $2.4 million provided by Ecology (Pihl, 2013).

Lakehaven Utility District, Federal Way
Located in WRIA 10 and the first of its kind in Washington, the Lakehaven Utility District began investigating the use of ASR in the late 1980s to increase summer supply and address future supply needs. Operating under reservoir application R1-28083A, granted in 2006, the Lakehaven Utility District has 1 ASR well capable of injecting up to 3,000 gpm into the upper member of the Mirror Lake Aquifer (MLA). The MLA is a member of the Salmon Springs Drift glacial unit, and underlies the Redondo-Milton Channel Aquifer (Brown, 2004). The ASR well, initially constructed in 1989, accesses the aquifer at depth intervals of 350 to 360 feet and 375 to 435 feet below ground surface (Armstrong, 1989). The confining unit overlying the MLA is comprised of glacial till, silt, and clay deposits and is a member of the Vashon drift glacial unit. The MLA is estimated to have 29,000 acre-feet of available storage (French, 2013). The district is currently under Phase 1 of the OASIS project, which requires two 6-year pilot phases, eight 6-year operational phases, and incorporates 27 ASR wells (Wood, 2006). Currently, no plans are in place to utilize the ASR well, as additional methods of supply became available to the District. However, as demand is expected to increase, the District predicts it will rely on ASR wells in the future (French, 2013).

Sammamish Plateau Water & Sewer District
Located in WRIA 8 and initiated in 2005, operating under application R1-28192A (Wood, 2003), the District has injected over 700 million gallons as of 2005. With 4 ASR wells accessing the Lower Issaquah Valley Aquifer, injection phase is between November to April, followed by storage of up to 1 month and recovery during June to October (Coffey, n.d.). However, during the recovery phase, the district is not allowed to recover more water than the original water right allows; therefore, recovery of stored water, in addition to current rights, is not permissible.

Seattle Highline Well Field
Located in WRIA 9, Seattle Public Utilities (formerly known as Seattle Water Department) began its ASR program in the Highline well field in 1991. Operating 2 ASR wells, under reservoir application R1-28168 (WA ECY, 2003a), the city injects Cedar River surplus water into the underlying "intermediate" glacial aquifer, presumably the Puget Aquifer, which is bounded by clay aquitards (U.S. Bureau of Reclamation, 2000). The water is subsequently recovered during peak periods and for emergency purposes.

Walla Walla
In the early 1990s, the city of Walla Walla began its ASR program by modifying existing well No. 1, followed by the addition of well No. 6 in 2003. Accessing Columbia River Basalts, the wells have a combined injection capacity of 600-900 million gallons per year. In areas near the injection wells, aquifer levels have increased 20-30 feet per year with an average injection rate of 878 million gallons per year. The city applied for an Oregon ASR permit (S-54483), as the point of diversion is located in Oregon; furthermore, the permit will allow for additional recovery currently limited by existing water rights (HDR Engineering, 2013).

White Salmon
Aspect Consulting (2011) concluded ASR was

a viable option for the city of White Salmon. Although an additional site-specific investigation was recommended, it was proposed the city could inject water obtained from the Buck Creek diversion into the Grande Ronde basalt aquifer. They estimated a current well could be retrofitted and used for injection between November through April. Subsequently, Ecology's Office of Columbia River provided the city with a grant to begin constructing such a system (WA ECY, n.d)

WRIA 32: Walla Walla

The Boise White Paper Plant in Wallula plans to use ASR to inject winter flows to store water for summer cooling purposes. Barr Engineering Company created a groundwater flow model, which indicated the surficial aquifer could be used for ASR, although the high transmissivity of the sand and gravel aquifer could allow some captured water to escape the storage zone (Boise White Paper LLC, 2008). Supporting a multi-phase plan, GSI Water Solutions, Inc. and HDR Engineering, Inc. drilled wells to determine hydrogeologic conditions, created a quality assurance project plan, and provided recommendations for additional work (GSI Water Solutions and HDR Engineering, 2010).

Desktop Suitability Studies

Conducting an ASR desktop suitability study provides an understanding of the basic factors that might impede an ASR project. According to Maliva and Missimer (2010), an ASR desktop study is the process of reviewing the following information prior to extensive fieldwork: water supply and demand, water quantity, hydrogeology, utility infrastructure, and regulatory requirements. Although there is intrinsic subjectivity to this approach, it allows for inexpensive large-scale suitability assessments centering on parameters deemed important to those interested in implementing such projects.

As discussed by Maliva and Missimer (2010), CH2M Hill (1997) conducted an ASR desktop suitability study at the request of the St. Johns River Water Management District in Florida. Creating a feasibility screening tool divided into feasibility factors, cost factors, and regulatory factors, the bulk of this tool was dedicated to technical factors that were subdivided into: facility, hydrogeologic, design, and operational factors. A numerical scoring system of the following seven criteria calculated a total score and feasibility level: storage-zone confinement; storage-zone transmissivity; storage-zone gradient and direction; recharge water quality; native water quality; overall physical, geochemical and design interactions; and interfering uses and impacts. Once the total score and resulting feasibility level of low, moderate, or high confidence was determined, a corresponding detailed (evaluate impact of critical factors), focused (investigate specific factors), or general (confirm assumptions) study was recommended.

As part of the Comprehensive Everglades Restoration Plan, Brown et al. (2005) conducted an ASR feasibility study, which involved the development of an ASR site selection suitability index and the use of a Geographical Information System (GIS) to determine potential ASR locations suitable to aid in wetland replenishment. After applying the following initial pass/fail criteria in GIS - distance to source water is less than 3 miles, minimum project size of 5 acres, and land use is not urban subdivisions, lakes, wetlands, coastal habitat, or landfills - the areas that passed this evaluation were subdivided into polygons and a secondary evaluation was performed. Within each polygon, scores were assigned to the following factors: ecological suitability, well density, source water quality, groundwater quality, road density, proximity to power lines, transmissivity, and distance to source water. Normalizing scores from 0 to 1, after applying weighting factors to each criterion, with values based on agreement among contributors, Brown et al. successfully confirmed the suitability of 4 previously recognized ASR pilot locations, in addition to highlighting regions most suitable for ASR schemes.

Woody (2007) used an adapted version of Brown et al. (2005) selection index to conduct an ASR suitability of Oregon's 18 state-designated watersheds. To make it applicable for municipal use, Woody eliminated the minimum project size of 5 acres from the initial pass/fail screening and altered the secondary site evaluation by: modifying scores for distance to source water, removing road density and proximity to power lines, and adding hydraulic gradient and aquifer thickness criteria. Scores were totaled and divided by the highest achievable score, representing a percentage of ideal conditions suitable for ASR. As suggested by this study, the calculations of these parameters can provide insight into the possibility of improving specific scores through economic investment. However, unlike Brown et al., due to the scale of the study area, developing GIS maps with polygons indicating ASR suitability throughout the breadth of each watershed was infeasible, as transmissivity, hydraulic gradient, and other statewide detailed information was not available.

In addition, Woody (2007) quantitatively assessed the suitability of ASR using an ASR metric equation, which was derived from the Theis (1935) and Cooper-Jacob (1946) non-equilibrium equations. Utilizing pump test information, static water level data, calculated or predetermined transmissivity values, and water rights or estimated recharge rates, the metric evaluated the estimated desired water injection rate to the aquifer injection rate capacity. The metric value indicated the potential suitability: 1 indicated marginal suitability; greater than 1 indicated potential suitability; and less than 1 indicated unlikely suitability.

Methods

To assess the suitability of ASR within each WRIA, a modified site selection suitability assessment and a modified ASR metric were used (Woody, 2007). Only wells that passed the initial site selection pass/fail screening - distance to source water is less than 3 miles and land use is not lakes, wetlands, landfill, and protected habitat - were evaluated by the modified ASR metric equation and then the site selection assessment. Various sources were used in each method to determine variables (Table 1).

Although these methods provide an indication of the potential for an ASR project at point locations within each watershed, the scale of the study area excludes evaluation of other factors such as cost, geochemical compatibility, geologic structures, leakage, aquifer boundaries, etc.

Well Selection Process

Point locations within each watershed were selected based on water well logs containing well test and static water information: wells with pump test data greater than 24 hours were favored, and well tests based solely on bailer or airlift data were rejected.

Due to the likelihood of obtaining necessary water well log information, an extensive search for municipal and water association well logs for each WRIA was requested through Ecology's online well log database (WA ECY, 2003b), at which time the results were downloaded in csv format and imported into an Excel spreadsheet. Searching the well log database by well ID number, wells without one of the following - open interval, static water level, yield, drawdown, drawdown time, depth, and lithology information - were deleted.

The well log spreadsheet was then imported into GIS, which contained the following layers obtained from Ecology's online GIS data (WA ECY, 2013): WRIA boundaries, city and urban growth areas, and national hydrography's major water feature dataset. Subsequently, wells mapped within water bodies or multiple wells identified in one point location were deleted, as were any wells located beyond 3 miles from major streams and fresh water bodies; the remaining wells were assigned a well name representing the owner or the closest source water.

Modified Site Suitability Assessment

Description

Using the same 8 secondary criteria as Woody (2007) - well density, recharge water quality, groundwater quality, distance to source water, threatened species, transmissivity, hydraulic gradient, and aquifer thickness - the site suitability assessment also included the likelihood predicted water supply exceeds demand for 4 winter months in year 2030 (WSU, 2011). Furthermore, each criterion was categorized by infrastructure, regulatory, and hydrogeologic factors (Table 2). Once a criterion was scored, a percent of ideal conditions was calculated for each factor based on total scores within each category, divided by the total possible score within the respective category. This approach provided a better understanding of the effects each factor had on the overall percent of ideal conditions suitable for ASR within each WRIA.

Infrastructure (Table 2)

Subdivided into well density, recharge water quality, ambient groundwater quality and distance to source water. Infrastructure factor is one category in which financial investment could potentially improve a score.

Well Density

An excessive number of wells, accessing the same aquifer and located within a 1-mile radius of a potential ASR scheme pose a risk, as these wells could capture stored water; therefore the numerical rating score is: 0 if more than 5 wells are present, 1 if 1 to 5 wells are present, and 2 if no wells are present. Creating a 1-mile buffer around the study well in GIS, scores were derived by counting the number of wells in this zone that contain similar open intervals as the study well. The risk associated with well density could be reduced if the depth of the ASR well was greater than that of the surrounding wells.

Recharge Water Quality and Ambient Groundwater Quality

Water quality scores were based on the extent to which groundwater and surface water met drinking water standards. A score of 0 indicated no water quality standards were met, a score

Table 1. Variables used in study with respective source(s)

Method	Variable	Source
Modified Site Suitability	Well Density	Water Well Logs (WA ECY, 2003b); WA Ecology (2013) GIS Data
	Recharge Water Quality	WTC location, WA DOH (2012) and/or Reported Values
	Distance to Source Water	WA Ecology (2013) GIS Data
	Groundwater Quality	WA DOH (2012) and/or Local Information
	Transmissivity	Reported Values or Well Logs (WA ECY, 2003b)
	Horizontal Hydraulic Gradient	Reported Values
	Aquifer Thickness	Well Logs (WA ECY, 2003b)
	Threatened Species	Fish Critical Basins (WA ECY, n.d) and Available Studies
	Predicted Supply Sufficiently Exceeds Demand during 4 Winter Months	Washington State University (2011) WRIAs 29-62
Modified ASR Metric	Headspace in Well	Well Logs (WA ECY, 2003b)
	Injection Rate	Water Treatment Capacity, Surface Water Right, or Assumed Rate (Sources Vary)
	Transmissivity	Reported Values or Specific Capacity Estimated from Well Log (WA ECY, 2003b)

of 1 indicated some water quality standards were met, and a score of 2 indicated all water quality standards were met. A well received a recharge water quality score of 2 if found to be owned by distributors that operate a water treatment facility, assuming surface water would be treated prior to injection. Due to the scale of the study area, determining the proximity of the study well to water supply distribution infrastructure was rarely feasible and was not used in the scoring scheme.

When available, scores were obtained from watershed water quality studies. When unavailable, additional information was obtained from the Washington State Department of Health's Office of Drinking Water System database (WA DOH, 2012). Study wells identified as Group B water systems in the database, defined as systems serving fewer than 15 connections and less than 25 people per day, earned a score of 2 if water from the well was not treated prior to distribution, as it was assumed all water quality standards were met. As noted by Woody (2007), poor groundwater quality can not be mitigated; however, if sufficient density differences are present between injected and native water, a bubble of high quality water can exist within the vicinity of the ASR well; therefore, aquifers with poor groundwater quality should not be immediately dismissed as a possible option for storage when considering ASR projects.

Distance to Source Water

Due to financial constraints caused by water conveyance costs, all study wells outside a 3-mile distance from source water were eliminated. Using GIS, scores were derived based on proximity of source water to the study well: source water closer than a 1-mile radius to the well received a score of 2 and source water between a 1- and 3-mile radius received a score of 1.

Regulatory Criteria (Table 2)

Regulatory aspects were subdivided into threatened species presence and whether predicted water supply exceeds demand. Scores assigned within this category could potentially be improved on depending upon changes in current or future water management methods.

Threatened and Endangered Species

The threatened and endangered species criterion is the likelihood an ASR project could negatively impact a protected species. In 2003, Washington began a water acquisition program, which encourages the selling, leasing, or donating of water in locations where salmon and trout are most vulnerable. Sixteen fish-critical basins were identified as locations where low flows are impacting salmon populations (WA ECY, n.d.). Wells located within these basins were scored 0, as it is assumed any withdrawals will likely affect these species. Scores in other basins are as follows: 0 if an ASR project will negatively affect threatened species, a score of 1 if an ASR project might affect threatened species, and a score of 2 if an ASR project will not affect threatened or endangered species. Scores were based on various watershed studies.

Predicted Water Supply Exceed Demand

In 2011, Washington State University completed a water supply and demand forecast for Ecology (WSU, 2011), which contained modeled results for year 2030 for the Columbia River Basin WRIAs 29 through 62. Each chart compared monthly surface water supply, surface water irrigation demands, and municipal demands for each WRIA. For our purposes, these charts were used to determine if average year supply exceeded demand for at least 4 out of 5 winter months (November through March), assuming an ASR scheme could inject excess supply throughout this period. Due to insufficient data, scores were given only to watersheds with modeled results; watersheds without data were not assigned scores nor used in determining regulatory or overall percent of ideal conditions suitable for ASR. A score of 0 was assigned if demand exceeded supply for 4 out of 5 winter months or a score of 2 was assigned if supply exceeded demand for at least 4 winter months.

Table 2. Site selection criteria and scores. Adapted from Woody (2007)

Secondary Site Selection Criterion	Numerical Rating System
Infrastructure	
Well Density: The likelihood an ASR project could affect water levels of nearby wells	0 = more than 5 wells within 1 mi radius 1 = 1 to 5 wells within 1 mi radius 2 = no wells within 1 mi radius
Recharge Water Quality: The degree to which surface water meets drinking water standards	0 = does not meet standards 1 = meets some standards 2 = meets all standards
Groundwater Quality: The degree groundwater meets drinking water standards	0 = does not meet standards 1 = meets some standards 2 = meets all standards
Distance to Source Water: The most cost effective feasible distance between source water and an ASR well.	0 = distance = 3 mi 1 = 1 mi < distance to source < 3 mi 2 = distance to source < 1 mi
Regulatory Criteria	
Threatened/Endangered Species: The likelihood an ASR project could negatively affect a protected species or habitat	0 = very likely 1 = somewhat likely 2 = not likely
Predicted Water Supply Exceeds Demand: Estimated supply vs. demand for at least 4 winter months	0 = demand exceeds predicted supply 2 = predicted supply exceeds demand
Hydrogeologic	
Transmissivity: Characterizes the ability of the aquifer to transmit water through-out its entire thickness.	0 = < 5,000 ft^2/day or > 25,000 ft^2/day 2 = 5,000 ft^2/day < T < 25,000 ft^2/day
Horizontal Hydraulic Gradient: Gradient suitable to maintain water near injection well	0 = gradient is steep (> 0.01) 1 = gradient is moderate (0.01 to 0.001) 2 = gradient is shallow (< 0.001)
Aquifer Thickness: The likelihood stored water will escape the influence of the injection well	0 = aquifer < 25 ft thick 2 = aquifer >= 25 ft thick

<u>Hydrogeologic (Table 2)</u>

These aspects were subdivided into transmissivity, hydraulic gradient, and aquifer thickness. Scores in this category should be regarded as an indication of the aquifer properties until additional on-site field investigations are conducted.

Transmissivity

Transmissity (T) characterizes the ability of the aquifer to transmit water through the entire thickness. The following transmissivity scores were based on the scoring scheme in Woody (2007) and Brown et al. (2005): 0 if T was less than 5,000 ft^2/day or greater than 25,000 ft^2/day and 2 if T was determined to be equal to or within these values. Transmissivity values were determined by: (1) local aquifer studies; or (2) based on the Razack and Huntley (1991) method, which relies on specific capacity values obtained from pump test information typically located on water well logs.

Hydraulic Gradient

To prevent injected water from moving outside the zone of recharge, Brown (2005) concluded shallow regional hydraulic gradients less than or equal to 0.01 were most suitable for ASR. As in the Woody (2007) study, the same scoring was used. Steep gradients (greater than 0.01) scored 0, moderate gradients (between 0.01 and 0.001) scored 1, and shallow gradients (less than 0.001) scored 2. Gradients were determined by regional aquifer studies; however, more often than not, gradients for specific locations could not be identified; therefore, locations without data were not assigned scores nor used in determining hydrogeologic or overall percent of ideal conditions suitable for ASR.

Aquifer Thickness

To prevent the movement, piracy, and limit the radius of stored water, Woody (2007) suggests aquifer thickness greater than 25 feet is most suitable for an ASR project. As determining aquifer thickness in large-scale ASR suitability studies is not feasible, thickness was assumed as the length of the open interval of the water well. For water well logs with multiple openings, the largest value was used. An aquifer thickness under 25 feet scored 0 and equal to or greater than 25 feet scored 2.

Modified ASR Metric

The ASR metric (Woody, 2007) determines the quantitative relationship between an aquifer's potential storage rate to a desired storage injection rate:

$$\text{ASR Metric} = \frac{\Delta h_{max}}{\Delta h} \qquad (1)$$

Where:

Δh_{max} = free space in the well determined by well log information

Δh = head change at the well based on a desired injection rate

The numerator is the available headspace in the well (Figure 7). Obtained from well logs, available headspace in the well was calculated as the distance from the static water level to, where available, the ground surface. The denominator is the head change at the well based on a desired injection rate. The desired injection rate, used in this study, equaled a municipality's maximum water treatment capacity up to 1.94 MGD or a municipality's surface water right up to 3 cfs. A flow rate of 3 cfs reflects the median value obtained from Table 3. As a conservative measure, if water treatment capacity and water right information was unavailable, a flow rate of 2 cfs was used.

Rounding to the nearest whole number, an ASR metric result greater than 1 (Figure 8) indicates the hydrogeologic conditions of the aquifer will accommodate such rates. A result equal to 1 (Figure 9) indicates marginal suitability and may not be advantageous as it suggests groundwater levels have been raised to the surface. A metric less than 1 (Figure 10) indicates the aquifer is unsuitable and groundwater levels will exceed the maximum possible head change available in the well, increasing the likelihood of undesired affects.

Derivation of Modified ASR Metric

The denominator in equation 1 is rooted in the Cooper-Jacob (1946) non-equilibrium equation, a modified version of the Theis (1935) equation, which assumes the aquifer is of uniform thickness, confined, horizontal, homogeneous, and of infinite extent:

$$\Delta h = \frac{2.3Q}{4\pi T}\log\left[\frac{2.25Tt}{r^2S}\right] = \frac{2.3Q}{4\pi T}F \qquad (2)$$

Where:
T= Transmissivity (L^2/t)
Q= Rate of injection (L^3/t)
S= Storativity (dimensionless)
r = Well radius (L)
t =Time

Woody (2007), using information obtained from ASR case studies, used the following values to calculate a conservative value for F:
Thus,

$$F = \log\left[\frac{2.25Tt}{r^2S}\right] = 12.48 \qquad (3)$$

Where:
T = 70,000 ft^2/day; maximum transmissivity in ASR case studies
S = 0.0001; minimum storativity in ASR case studies
r = 0.25 feet; radius of well; minimum value in ASR case studies
t = 120 days; assumes injection will take place during 4 winter months

Therefore, equation 2 becomes:

$$\Delta h = \frac{2.3Q}{4\pi T} * 12.48 = \frac{2.28Q}{T} \qquad (4)$$

Where:
T= Transmissivity (L^2/time)
Q= Rate of injection (L^3/time)

While Woody (2007) chose to multiply F by an engineering safety factor of 2, we have modified this equation and eliminated the safety factor, in an effort to include additional suitability information. Thus, substituting equation 3 into 1 results in the following modified metric:

$$\text{Modified ASR Metric} = \frac{T*\Delta h_{max}}{2.28Q} \qquad (5)$$

Where:
Δh_{max} = maximum open interval or maximum screened interval obtained from well log (L)

T = Transmissivity obtained from specific capacity (Razack and Huntley, 1991), except where regional aquifer data exist (L^2/t)
Q = Desired injection rate (L^3/t)

To validate the modified ASR metric, the metric was used to determine the suitability of historical ASR wells (Table 4). Of the 12 wells surveyed, 3 were determined marginally suitable, while the remaining were determined suitable.

Results

Two hundred and eighty four wells in Washington were evaluated for ASR suitability. Of those wells, 51% have between 40 to 60 % of ideal conditions suitable for ASR. Furthermore, the results from the modified ASR metric indicate 24% of wells were marginally suitable and 29% suitable for ASR.

Modified Site Suitability Assessment

Although the overall results indicate variable ranges of suitability, the majority of sites with greater than or equal to 60% of ideal conditions are located throughout the Columbia River Basalt region (Figure 33). Distribution of statewide results for total percent of ideal conditions is represented in Figure 11. Distribution is as follows: of the 284 wells evaluated, 2% have 20% ideal conditions suitable for ASR; 23% have between 20 to 40% ideal conditions suitable for ASR; 51% have between 40 to 60% ideal conditions suitable for ASR; 23% have between 60 to 80%

Table 3. Historical ASR injection rate per well

Location	System	Aquifer type	Injection rate	Notes	Source
			cfs		
Denver	WWD	Siliciclastic	2.7	p. 427	Maliva and Missimer, 2010
Arizona	Chandler Tumbleweed	Siliciclastic	3.6	P. 434	Maliva and Missimer, 2010
Nevada	Las Vegas	Siliciclastic	8.2	p. 438	Maliva and Missimer, 2010
Oregon	The Dalles	Basalt	3.3	p. 476	Maliva and Missimer, 2010
Oregon	Salem	Basalt	1.9	p. 476	Maliva and Missimer, 2010
Oregon	Tualatin	Basalt	3.6		Woody, 2007
Oregon	Pendleton	Basalt	2.5		Woody, 2007
Oregon	Baker City	Basalt	1.8		GSI, 2006
		Mean	**3.5**		

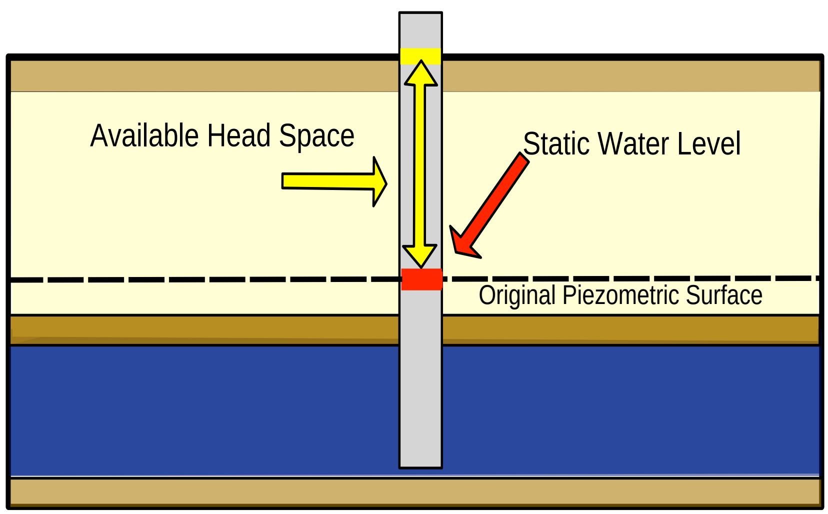


Figure 7. ASR Metric Prior to Injection. Aquifer under confined conditions prior to injection: headspace (yellow arrow) in well is determined by the distance from the static water level to, when possible, ground surface.

Figure 8. ASR Metric: > 1
As injection occurs, the potentiometric surface and water level in the well rises. If the desired injection rate is less than the rate of the aquifer's ability to accept water, the potentiometric surface and water level will not rise to the surface.

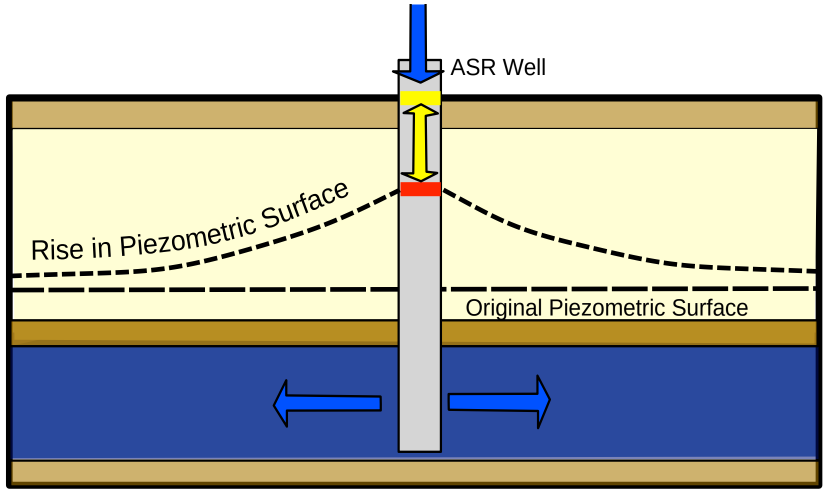


Figure 9. ASR Metric: = 1
If desired injection rate equals the aquifer's capacity to accept this rate, the potentiometric surface and water level will rise to the surface, indicating marginal suitability.

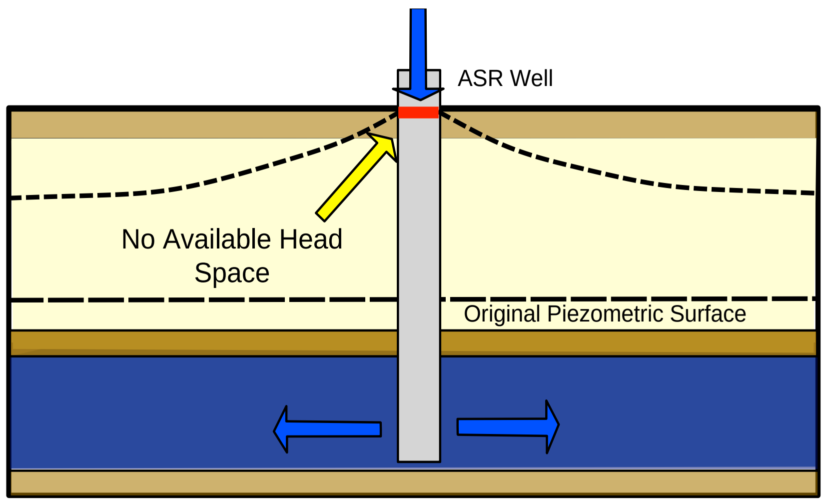


Figure 10. ASR Metric: < 1
If the desired injection rate is greater than the aquifer's capacity to accept this rate, the potentiometric surface will rise above the ground indicating unsuitable conditions; thereby increasing, the possibility of developing fractures within the aquifer, artesian springs, and flowing wells.

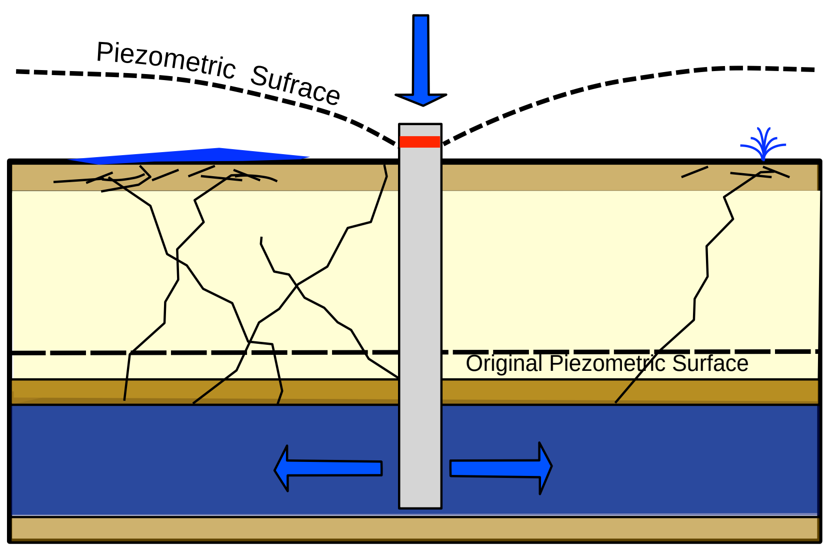


Table 4. Modified ASR metric of notable ASR projects

WRIA	Transmissivity	Maximum head change	Injection rate	Rate capped at 1.938 MGD	Injection rate conversion	ASR Metric	Source
	ft^2/d	ft	MGD	MGD	ft^3/d		
Sammamish, WA Plateau Well 13R	4.8×10^3	530	2.8	1.9	25.9×10^4	4.4	Coffey,n.d;. Schneider Equipment, 2006
Walla Walla, WA Well 1	9.7×10^3	90	2.3	1.9	25.9×10^4	1.5	HDR, 2006
Sammamish, WA Plateau Well, 12R	2.3×10^4	133	0.6	0.6	77.0×10^3	17.1	Wood, 2003; Charon Drilling, 1999
Lakehaven, WA	7.6×10^4	286	2.8	1.9	25.9×10^4	36.7	Wood, 2006; Armstrong Drilling, 1989 (test phase)
Salem, OR	1.4×10^4	311	19.8	1.9	25.9×10^4	7.6	Woody, 2007
Beaverton, OR	6.6×10^4	183	2.3	1.9	25.9×10^4	20.3	Woody, 2007
Baker City, OR	9.8×10^2	196	1.1	1.1	14.3×10^4	0.6	Woody, 2007
Dallas, OR	1.3×10^3	623	0.2	0.2	32.1×10^3	11.4	Woody, 2007
Charleston, SC	2.2×10^2	400	0.0	0.0	53.5×10^2	7.2	Woody, 2007
El Paso, TX	1.3×10^4	107	0.7	0.7	97.4×10^3	6.4	Woody, 2007
Yakima, WA Kissel Well	8.0×10^3	107	2.3	1.9	25.9×10^4	1.4	Woody, 2007
Clackamas, OR	1.8×10^3	400	0.8	0.8	10.6×10^4	2.9	Woody, 2007

ideal conditions suitable for ASR; and 1% have 80% or greater ideal conditions suitable for ASR (Figure 12).

Percent of Ideal Regulatory, Infrastructure, and Hydrogeologic Conditions

The results for overall percent of ideal conditions were subdivided into infrastructure, regulatory, and hydrogeologic factors for each location. Distribution of the results are summarized in Table 5.

Modified ASR Metric

Results for the modified ASR metric were sporadic throughout Washington (Figure 13). Of the 284 wells selected for this study, 48% were determined unsuitable, 24% were determined marginally suitable, and 29% were determined suitable for ASR. Within the 62 WRIAs, 52 contained point locations suitable and/or marginally suitable for ASR, equaling a combined minimum storage potential of 86,000 acre-feet per year (76 MGD) Storage potential was calculated by multiplying injection rates by 120 days, which is assumed to be the number of injection days typical for an ASR project.

Combined Result

A statewide review of combined results indicate 36% of suitable wells, based on the modified ASR metric, have greater than 60% ideal conditions suitable for ASR. Wells are located within 16

Figure 11. Statewide distribution of modified site suitability assessment. Each dot on map represents a well and the percent to which it is suitable for ASR.

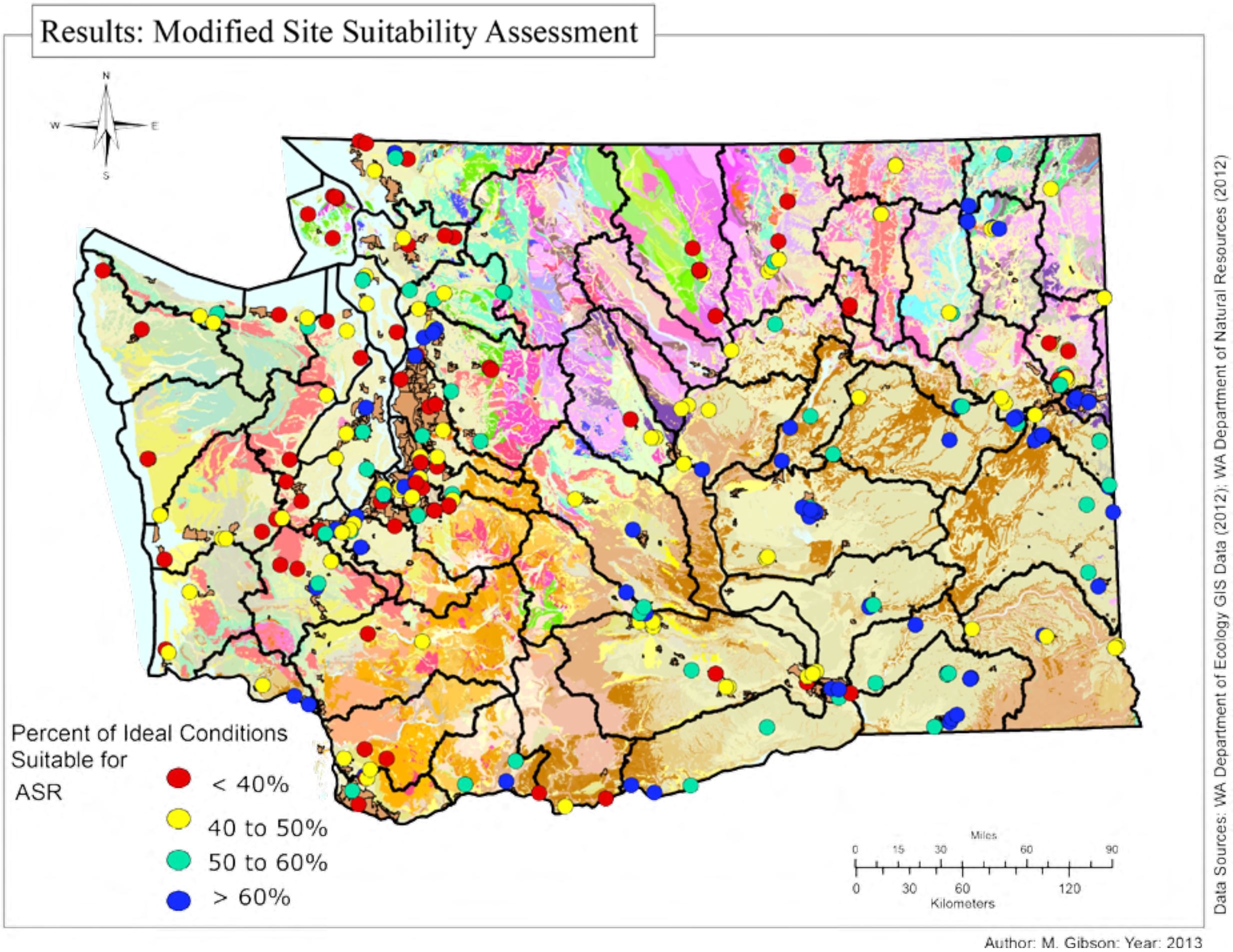
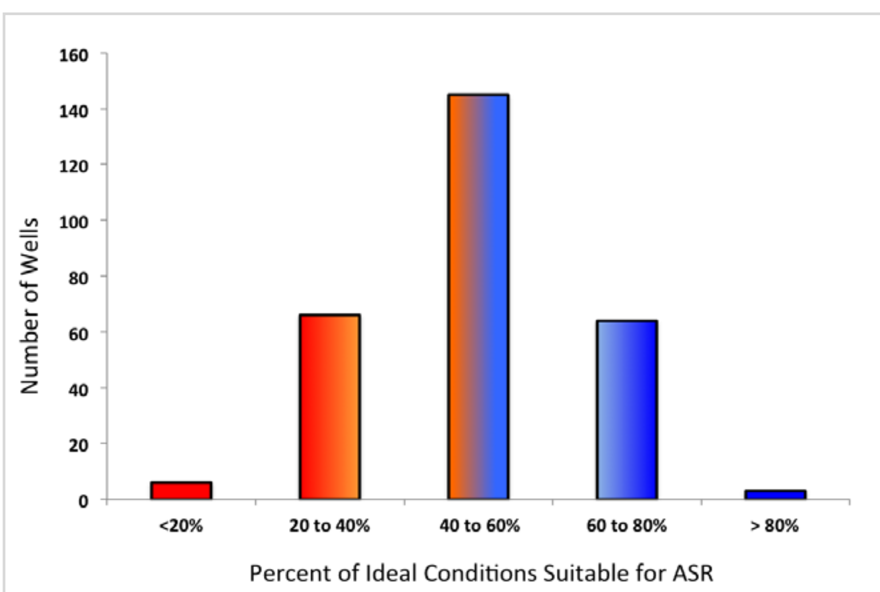


Figure 12. Distribution of modified site suitability assessment



WRIAs (Figure 14) and respective well scores are listed in Table 6.

Discussion

Lane (2009) indicated total freshwater use, both self and public-supplied, equaled about 5,780 MGD, with surface water accounting for 74% and groundwater accounting for 26%. After comparing these values with potential storage estimates for the state of Washington, based on the modified ASR metric, it was determined ASR could potentially meet 2% surface water needs and 5% groundwater needs (Table 7).

Lane (2009) also subdivided use based on public supply, domestic, irrigation, livestock, aquaculture, industrial, mining, and thermoelectric. Table 8 is a comparison of these rates, combined potential ASR storage rates, and the percent ASR could satisfy estimated use. Washington State University (2011) estimated consumptive municipal and industrial demand use for year 2030 within WRIAs 29 through 62. Comparing these estimates with yearly storage volume potential, obtained by the modified ASR metric, it was determined that ASR could possibly satisfy up to 17% of total demand or 50,000 acre-feet per year on the east side of the Cascade Range. Furthermore, results in 18 WRIAs indicate ASR use could potentially meet more than 20% of demand (Table 9).

Combined Results: Watersheds with Highly Suitable Wells

As mentioned above, of the wells with 60% ideal conditions suitable for ASR, 36% were estimated to have a metric value greater than 1. Therefore, the most promising locations suitable for ASR are located in 16 WRIAs (Figure 14). The following is a discussion of these wells and watersheds.

Figure 13. Modified ASR Metric outcome and state geologic map. Colored dot represents study well.

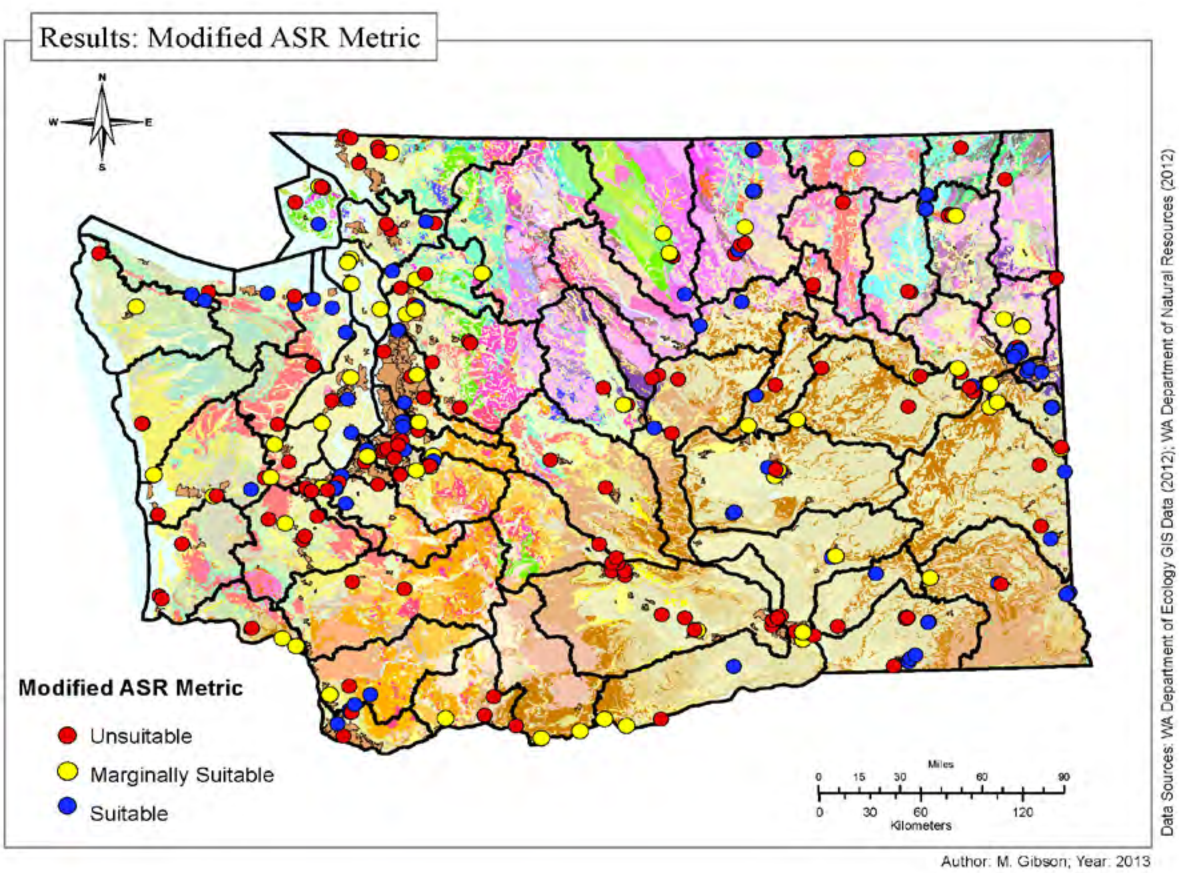


Table 5. Distribution of percent of ideal regulatory, infrastructure, and hydrogeologic conditions suitable for ASR

Percent of ideal conditions suitable for ASR	Regulatory	Infrastructure	Hydrogeologic
	Number of wells		
< 20%	85	6	81
20 to 40%	22	60	9
40 to 60%	99	93	125
60 to 80%	76	114	9
> 80%	2	11	60

Figure 14. Map of WRIAs, wells favorable for ASR, and ASR projects

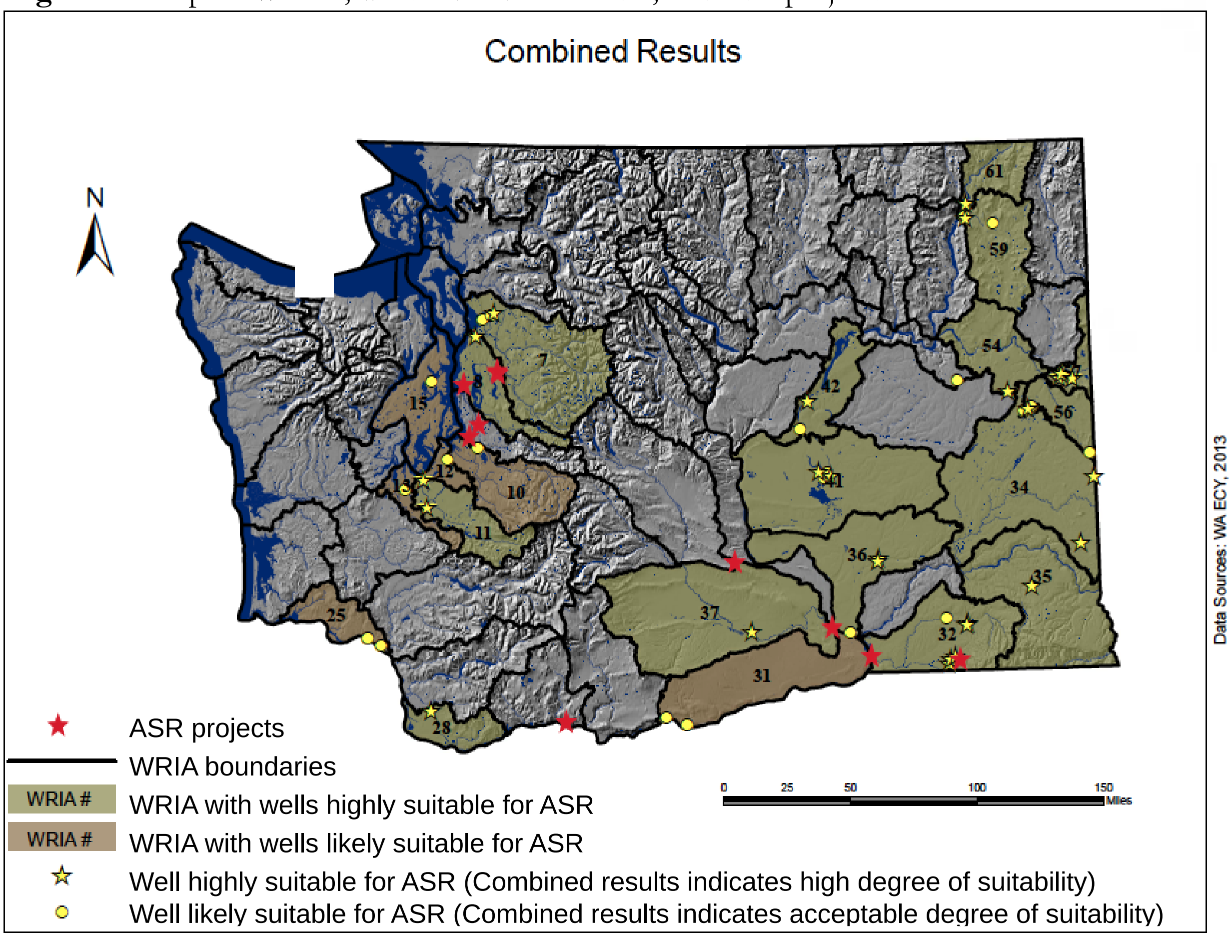


Table 6. Highly suitable wells, within select WRIAs, determined by the modified metric and modified site suitability assessment.

WRIA	WRIA Name	Well name (owner-WRIA-well #)	Modified ASR Metric	Percent of ideal conditions suitable for ASR
7	Snohomish	Marysville-7-2	4	64%
8[a]	Cedar-Sammamish	Everett-8-2	2	64%
11	Nisqually	Dupont-1	5	79%
11	Nisqually	Yelm-1	3	71%
28	Salmon-Washougal	Battle Ground-1	2	64%
32[a]	Walla Walla	Walla Walla-1	2	78%
32[a]	Walla Walla	Walla Walla-2	2	78%
32[a]	Walla Walla	Walla Walla-3	3	72%
32[a]	Walla Walla	Waitsburg-1	20	63%
32[a]	Walla Walla	Waitsburg-2	14	63%
32[a]	Walla Walla	Waitsburg-3	15	63%
33	Lower Snake	*Lake Herbert-1	7	75%
34	Palouse	Farmington-1	3	75%
34	Palouse	Pullman-1	5	83%
35	Middle Snake	Pomeroy-1	5	63%
36	Esquatzel Coulee	Connell-1	2	69%
36	Esquatzel Coulee	Connell-2	10	88%
37	Lower Yakima	Grandview-1	2	61%
41	Lower Crab	Moses-2	2	78%
41	Lower Crab	Moses-5	2	83%
42	Grand Coulee	Blue Lake-1	2	69%
54	Lower Spokane	Medical Lake-1	7	75%
56	Hangman	Cheney-2	2	69%
57	Middle Spokane	Spokane-57-1	18	61%
57	Middle Spokane	Spokane-57-2	16	61%
57	Middle Spokane	Spokane Valley-1	43	67%
57	Middle Spokane	Spokane Valley-2	41	67%
59	Colville	Kettle Falls-2	3	67%
61	Upper Lake Roosevelt	Marcus-1	3	69%

[a]WRIAs that contain current ASR wells

*non-municipal well

Table 7. Freshwater use by type (Lane, 2009) compared to cumulative storage potential rate. Storage rate was calculated using results obtained from the modified ASR metric. The cumulative storage rate represents the minimum combined storage potential, as individual well injection rates were capped.

Freshwater use type	Estimated freshwater use by type (Lane, 2009)	Cumulative statewide ASR storage potential	Percent ASR could satisfy use
	MGD		
Groundwater	1490	76.3	5%
Surface Water	4280	76.3	2%

Table 8 . Water use by type (Lane, 2009) and percent ASR could satisfy specified use. Water use is not absolute. Storage rate was calculated using results obtained from the modified ASR metric. The cumulative storage rate represents the minimum combined storage potential, as individual well injection rates were capped.

Type	Total (MGD)	Cumulative statewide ASR storage potential (MGD)	Percent ASR could satisfy specified use
Public Supply	990	76.3	8%
Domestic	648	76.3	12%
Irrigation	3520	76.3	2%
Livestock	30.7	76.3	249%
Aquaculture	211	76.3	36%
Industrial	520	76.3	15%
Mining	26.6	76.3	287%
Thermoelectric Power	456	76.3	17%

Table 9. Estimated municipal and industrial consumptive use for year 2030 (WSU, 2011) and percent ASR could satisfy demand (WRIA 29-61). Storage rates represent minimum combined storage potential.

WRIA	WRIA Name	Number of suitable ASR wells in WRIA	Predicted municipal and industrial consumptive use-year 2030 (WSU, 2011)	Potential ASR storage rate	Percent ASR could meet 2030 demand
			Acre-feet per year		
29	Wind-White Salmon	1	643	480	74%
30	Klickitat	2	4,690	950	20%
31	Rock-Glade	4	6,041	2100	35%
32	Walla Walla	7	11,896	3450	29%
33	Lower Snake	1	2,066	480	23%
34	Palouse	3	13,435	1670	12%
35	Middle Snake	5	10,759	2560	24%
36	Esquatzel Coulee	4	15,331	2855	19%
37	Lower Yakima	2	42,577	1430	3%
38	Naches	0	12,090	0	0%
39	Upper Yakima	0	18,190	0	0%
40	Alkali-Squilchuck	0	3,842	0	0%
41	Lower Crab	6	28,124	3800	14%
42	Grand Coulee	2	2,102	950	45%
43	Upper Crab-Wilson	1	6,453	480	7%
44	Moses Coulee	1	99	700	721%
45	Wenatchee	1	9,266	700	8%
46	Entiat	0	422	0	0%
47	Chelan	1	1,968	480	24%
48	Methow	5	1,586	3330	210%
49	Okanogan	6	3,524	3090	88%
50	Foster	1	2,594	480	18%
51	Nespelem	0	27	0	0%
52	Sanpoil	1	176	700	406%
53	Lower Lake Roosevelt	1	1,211	700	59%
54	Lower Spokane	2	6,005	1060	18%
55	Little Spokane	13	14,732	6660	45%
56	Hangman	7	3,641	4280	118%
57	Middle Spokane	4	49896	2860	6%
58	Middle Lake Roosevelt	0	1,688	0	0%
59	Colville	3	5,596	2140	38%
60	Kettle	1	1,053	480	45%
61	Upper Lake Roosevelt	1	7,559	480	6%
62	Pend Oreille	1	1645	480	29%
		Total	**290,927**	**50,000**	**17%**

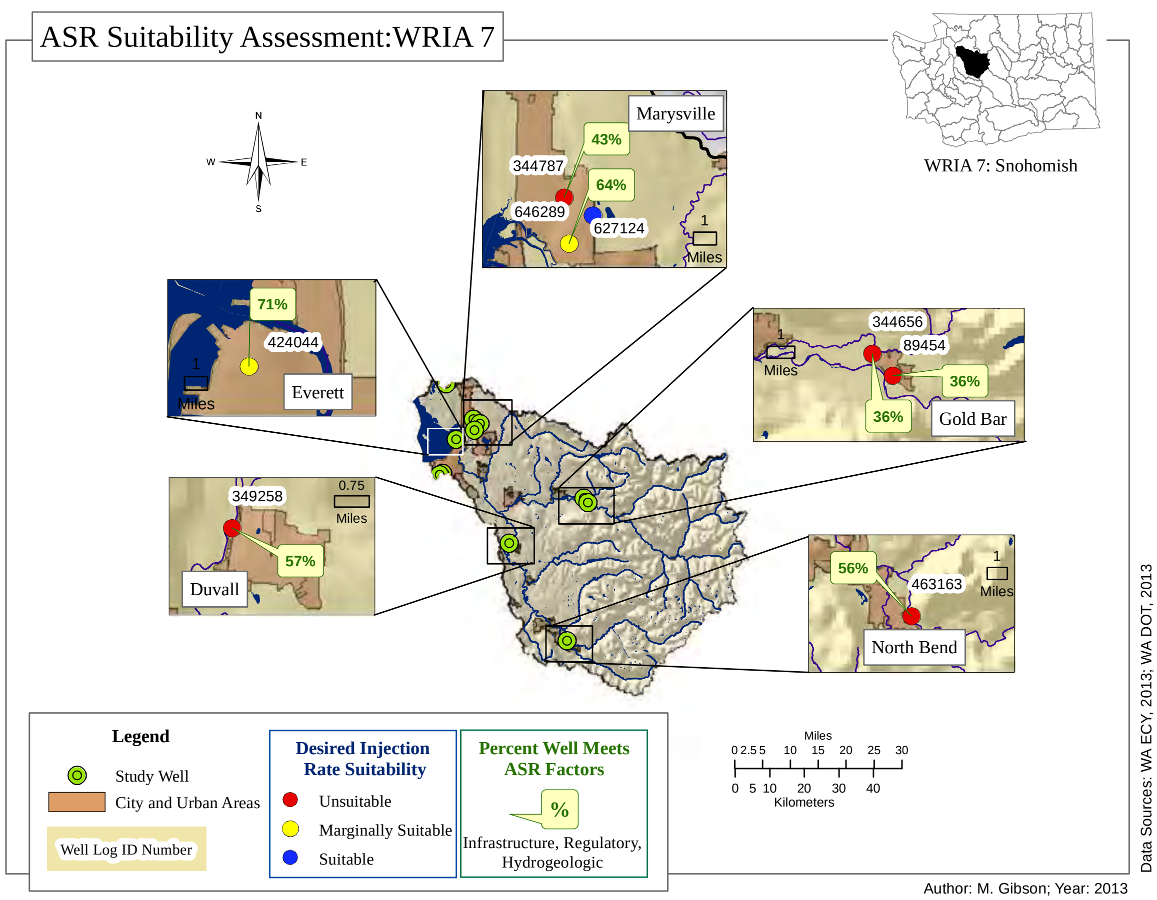
WRIA 7: Snohomish (Figure 15)

Marysville-7-2 (Table 10) is likely located in Quaternary glacial till of the Vashon Stade (Jones, 1999). Accessing the aquifer at 226 to 272 feet below ground surface, it is estimated to have a transmissivity of 14,500 ft^2 per day, based on specific capacity, and is probably located within the Puget Aquifer. Although no localized faults or folds are present (WA DNR, 2013), transmissivity values are within the target range for ASR. This watershed is located in a fish-critical basin (WA ECY, n.d.), which could negatively impact water availability; however, it has 100% hydrogeological conditions and 63% infrastructure conditions suitable for ASR. The city of Marysville's population increased 481.1% from 1990 to 2010 (WA OFM, 2012; U.S. Census, 2010) and has water rights of 27.1 MGD on an annual basis (Marysville, 2011). This study estimated Marysville-7-2 could, at a minimum, potentially accept 3 cubic feet per second for 120 days or 710 acre-feet per year of supplemental supply. Since the Snohomish watershed is currently under the Instream Resources Protection Program, obtaining a new year-round surface water right might prove difficult (WA ECY, 2012a), but will likely not be a problem for the purpose of seasonal injection.

Table 10. Well(s) compatible with ASR within WRIA 7

Well Name	Well ID	Percent of Ideal Conditions				ASR Metric
		Infrastructure	Regulatory	Hydrogeologic	**All Factors**	
Marysville-7-2	646289	63%	0%	100%	**64%**	**3.7**

Figure 15. ASR suitability assessment: WRIA 7

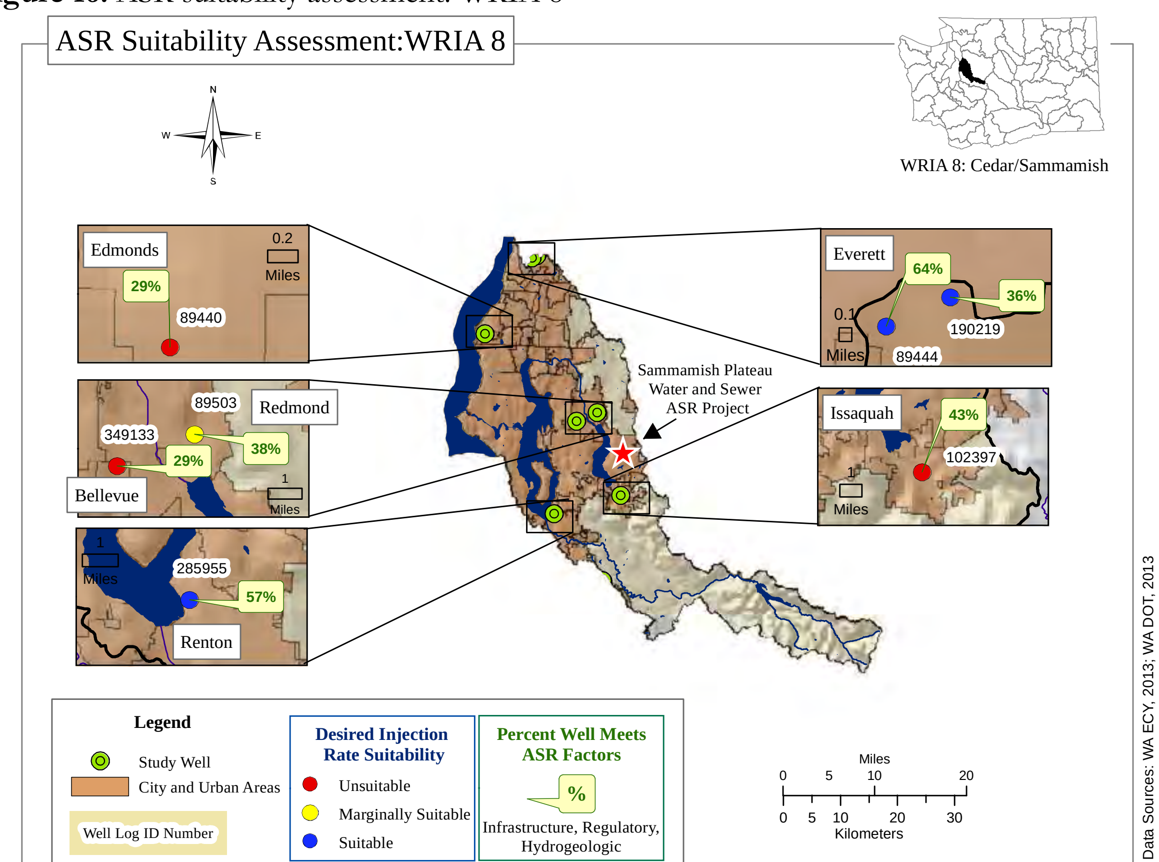


WRIA 8: Cedar-Sammamish (Figure 16)
Everett-8-2 (Table 11) is located in WRIA 8. Completed at a depth of 381 feet, it has an open interval at 296 to 368 feet below ground surface. Calculated from specific capacity, the aquifer's transmissivity is estimated at 5,000 ft^2 per day, which is at the lower end of the target range. Located within Quaternary glacial drift of the Fraser and/or the Puget Aquifer (Jones, 1999), the well is within 6 miles of an anticline (WA DNR, 2012). ASR projects located within an anticline are not advantageous unless boundary conditions and aquifer characteristics exist to prevent injected water from escaping; however, the distance and lack of additional information prohibits estimating the potential for ASR based on local structural characteristics. Furthermore, this well is located in a fish-critical basin (WA ECY, u.d.), which could make acquiring additional surface water rights, if needed, difficult. Moreover, the city of Everett had a 47.3% increase in population from 1990 to 2010 (WA OFM, 2012; U.S. Census, 2010), and although eight water systems provide service to Everett (2012), the addition of an ASR scheme to current infrastructure could aid in meeting increasing demand. This WRIA is also under the Instream Resources Protection Program rule WAC 173-508 for WRIA 8 (WA ECY, 2012b); however, obtaining a seasonal surface water right, if needed, should be feasible.

Table 11. Well(s) Compatible with ASR within WRIA 8

Well Name	Well ID	Percent of Ideal Conditions				Metric
		Infrastructure	Regulatory	Hydrogeologic	**All Factors**	
Everett 8-2	190219	63%	0%	100%	**64%**	**1.8**

Figure 16. ASR suitability assessment: WRIA 8



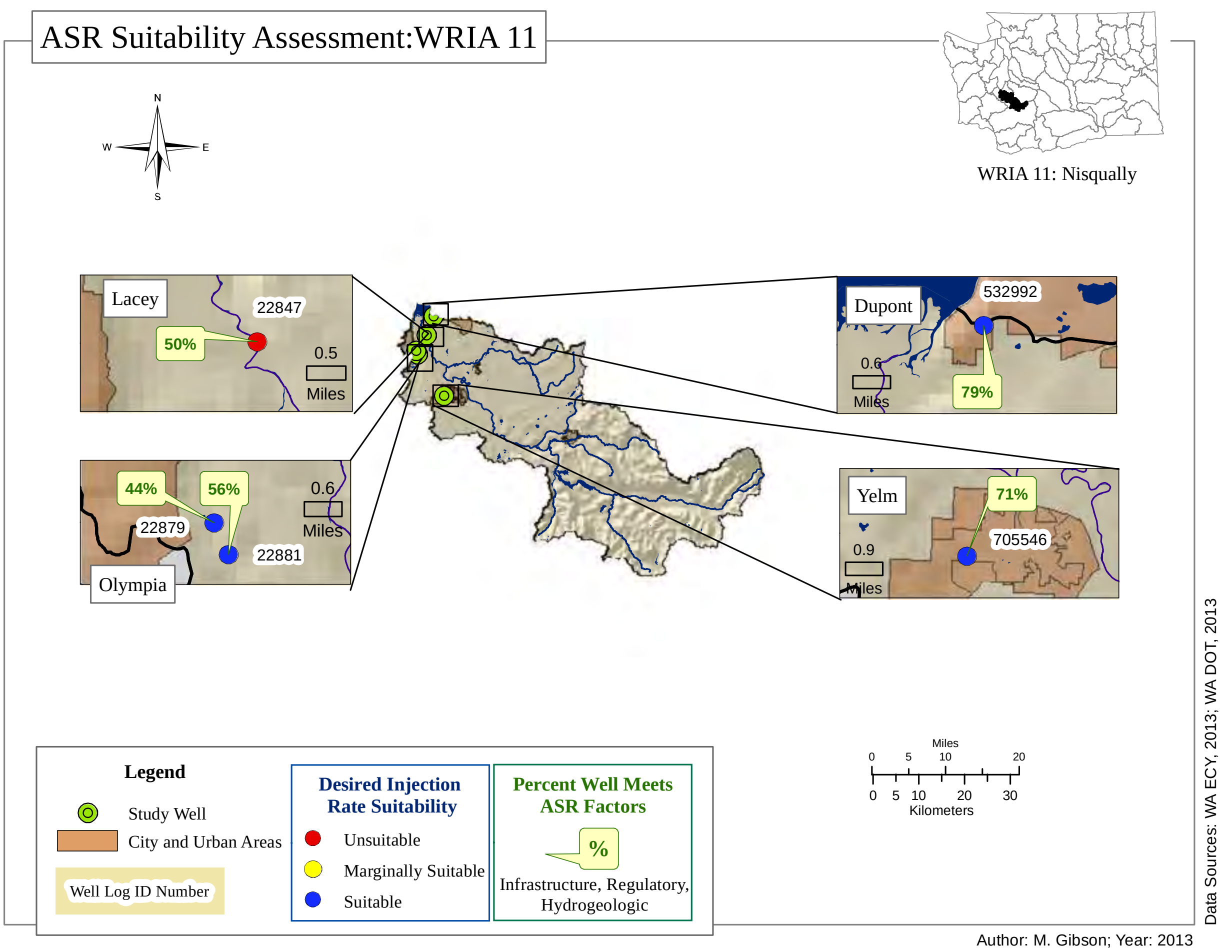
Author: M. Gibson; Year: 2013

WRIA 11: Nisqually (Figure 17)
DuPont-11-1 (Table 12) is DuPont city well #2 and was completed to a depth of 388 ft and accesses the aquifer at 295-355 feet below ground surface. Estimated to be within Quaternary glacial drift and accessing the Fraser Aquifer and/or the Puget Aquifer (Jones, 1999), transmissivity, calculated using specific capacity, was determined to be 12,600 ft^2 per day, which is within the target ASR range. No surficial structural features are known; therefore, additional information will be required to determine if it is located within a confining unit suitable for ASR. With a well depth of 633 feet below ground surface, Yelm-11-1 (Table 12) accesses the aquifer in multiple locations, with the greatest interval occurring at 369 to 437 feet below ground surface and is estimated to withdrawal from the Fraser and/or Puget Aquifer. Transmissivity, based on specific capacity, was estimated at 10,000 ft^2 per day, which is within the range suitable for ASR.

Table 12. Well(s) compatible with ASR within WRIA 11

Well Name	Well ID	Percent of Ideal Conditions				Metric
		Infrastructure	Regulatory	Hydrogeologic	**All Factors**	
Dupont-1	532992	75%	50%	100%	**79%**	**4.7**
Yelm-1	705546	63%	50%	100%	**71%**	**2.6**

Figure 17. ASR suitability assessment: WRIA 11



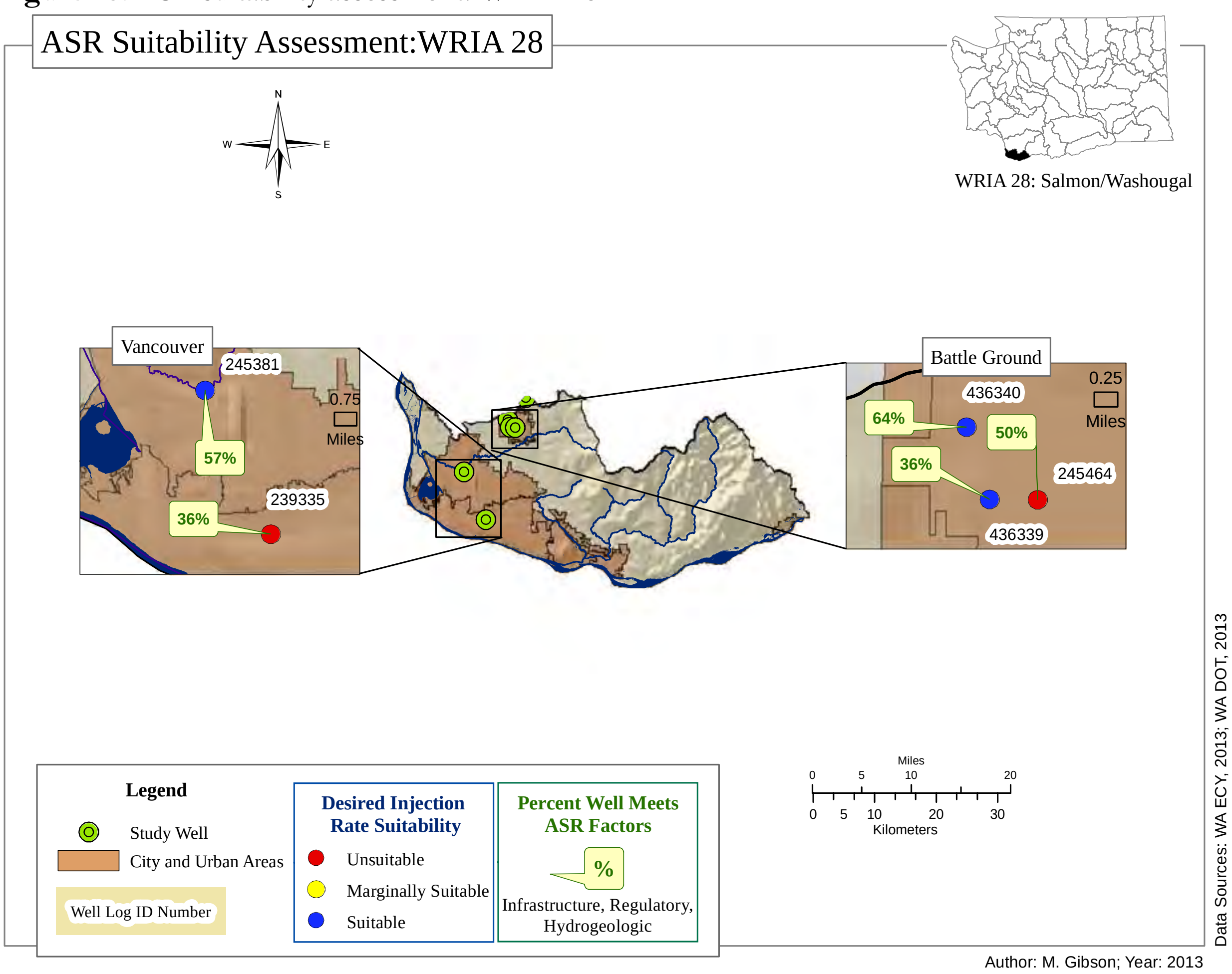
WRIA 28: Salmon-Washougal (Figure 18)

Battle Ground-1 well (Table 13) is 379 feet deep and has an open interval at 286-379 feet below ground surface. Located in the Pleistocene outburst flood deposits (WA DNR, 2013), transmissivity, based on specific capacity, was estimated at 6,000 ft^2 per day, which is within target ASR range. Although the city of Battle Ground had a 367.6% increase in population from 1990 to 2010 (WA OFM, 2012; U.S. Census, 2010), HDR and EES (2006b) it was determined ASR is unsuitable for this watershed as it contains an abundant supply of groundwater, but recommended revisiting ASR use in the future.

Table 13. Well(s) compatible with ASR within WRIA 28

Well Name	Well ID	Percent of Ideal Conditions				Metric
		Infrastructure	Regulatory	Hydrogeologic	**All Factors**	
Battle Ground-1	436340	50%	50%	100%	**64%**	**2.1**

Figure 18. ASR suitability assessment: WRIA 28



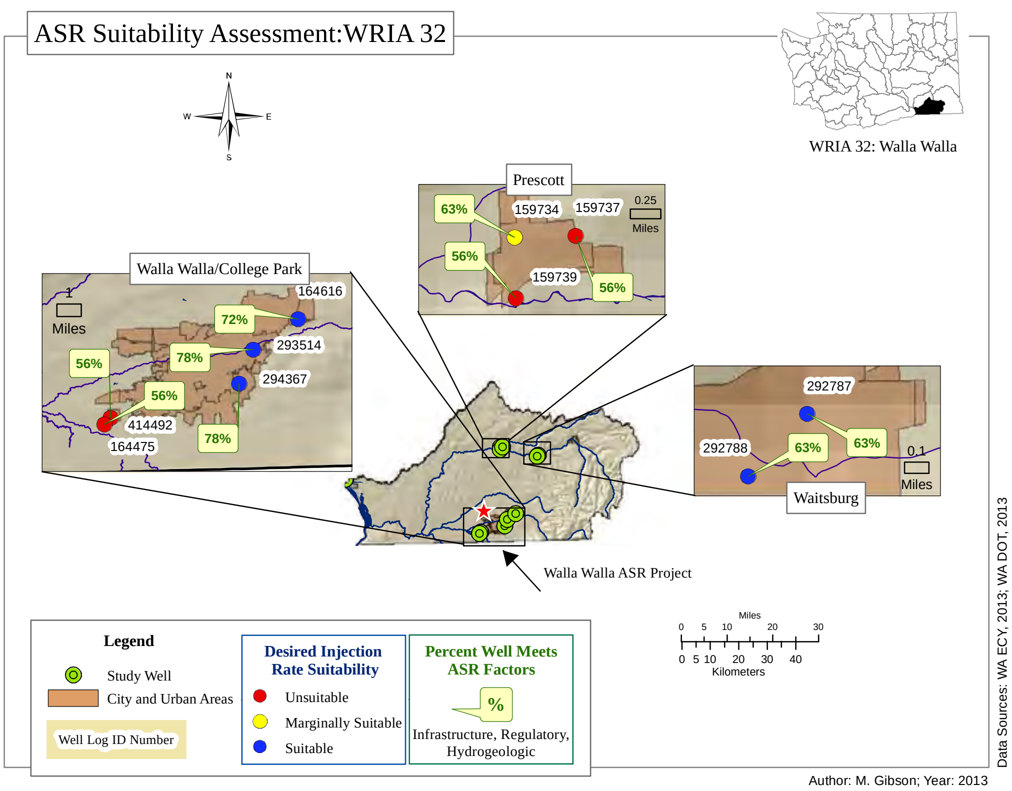
WRIA 32: Walla Walla (Figure 19)

Six wells in the Walla Walla watershed have greater than 60% ideal conditions suitable for ASR and an ASR metrics greater than 1 (Table 14). Three wells are owned by the city of Walla Walla, which has a current ASR scheme, and three wells are owned by the city of Waitsburg. All wells access the Columbia River Basalts. Transmissivities for Walla Walla wells range from 7,800 to 13,000 ft^2 per day, based on the city's comprehensive water system plan (HDR Engineering, 2006). Transmissivity, based on specific capacity, for the Waitsburg's wells range from 15,000 to 21,000 ft^2 per day, which is within the target range for ASR. The open intervals, accessing the aquifer, range from 75 to 357 ft below the surface. As most ASR schemes in Oregon are located in the Columbia River Basalts, hydrogeological conditions are potentially viable for injection and recovery; however, this watershed is a fish-critical basin (WA ECY, u.d.), which could potentially prohibit additional ASR projects if seeking new surface water rights.

Table 14. Well(s) compatible with ASR Within WRIA 32

Well Name	Well ID	Percent of Ideal Conditions				Metric
		Infrastructure	Regulatory	Hydrogeologic	**All Factors**	**Metric**
Walla Walla-1	294367	88%	50%	83%	**78%**	**1.9**
Walla Walla-2	293514	88%	50%	83%	**78%**	**2**
Walla Walla-3	164616	75%	50%	83%	**72%**	**2.9**
Waitsburg-1	292786	50%	50%	100%	**63%**	**20.4**
Waitsburg-2	292787	50%	50%	100%	**63%**	**13.6**
Waitsburg-3	292788	50%	50%	100%	**63%**	**14.9**

Figure 19. ASR suitability assessment: WRIA 32



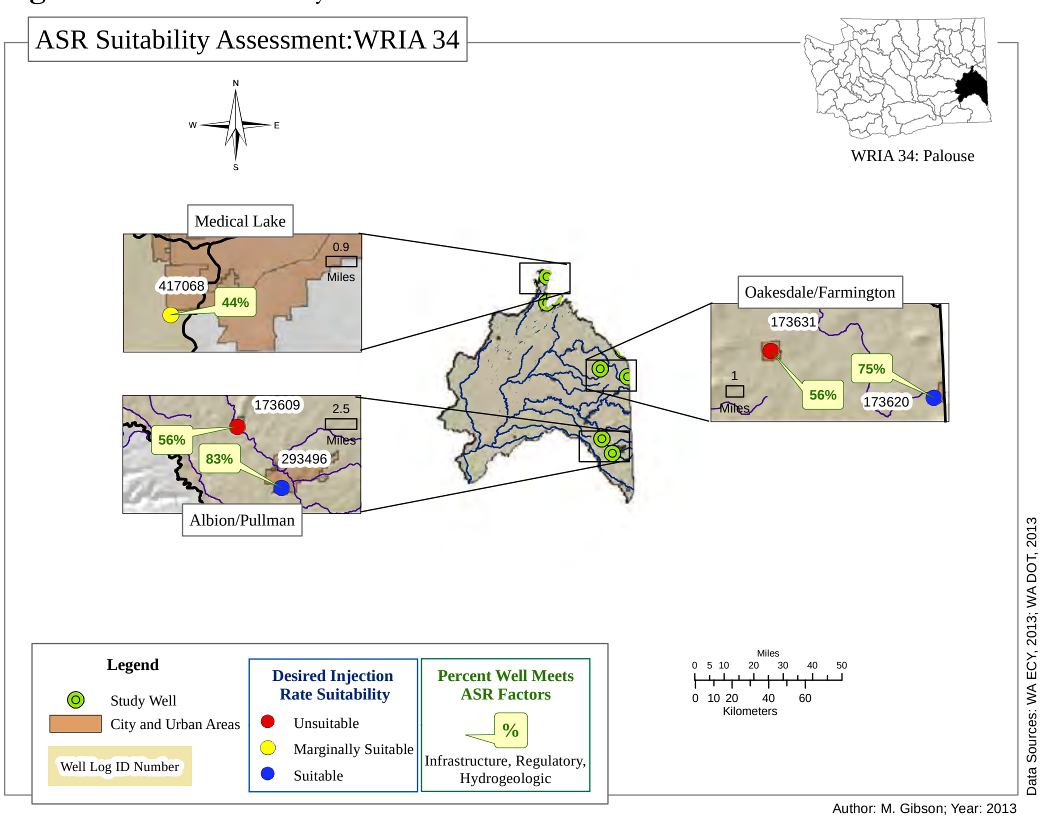
WRIA 34: Palouse Basin (Figure 20)

Two wells in the Palouse watershed indicate potential for ASR use (Table 15). Farmington-1 and Pullman-1 both access confining units of the Columbia River Basalts Group (CRBG) (Figure 33). Transmissivity of Farmington-1, based on specific capacity, is 5,000 ft^2 per day, which is at the lower target zone for ASR. Also based on specific capacity, Pullman-1 has a transmissivity of 14,700 ft^2 per day, which is within the target range for ASR. Furthermore, the majority of the watershed has been appropriated and seasonal closure from June 15 to September 1 for selected water bodies are in effect (WA ECY, 2012c). Moreover, the Palouse Basin Aquifer is comprised of two major aquifers: Wanapum and Grande Ronde basalts of the CRBG (Douglas et al., 2007) and is considered a sole-source aquifer; therefore, any groundwater degradation could seriously impact drinking water quality and consequently injection of water would be highly regulated. Additionally, the city of Pullman conducted an ASR feasibility study and determined ASR operation is compatible with their needs; however, according to Gardes (2013), water reuse is a higher priority for the city, and ASR would be difficult for the city to implement due to Washington's groundwater antidegradation policy.

Table 15. Well(s) compatible with ASR Within WRIA 34

Well Name	Well ID	Percent of Ideal Conditions				Metric
		Infrastructure	Regulatory	Hydrogeologic	**All Factors**	
Farmington-1	173609	50%	75%	33%	**75%**	**3.4**
Pullman-1	293496	88%	75%	83%	**83%**	**5**

Figure 20. ASR suitability assessment: WRIA 34



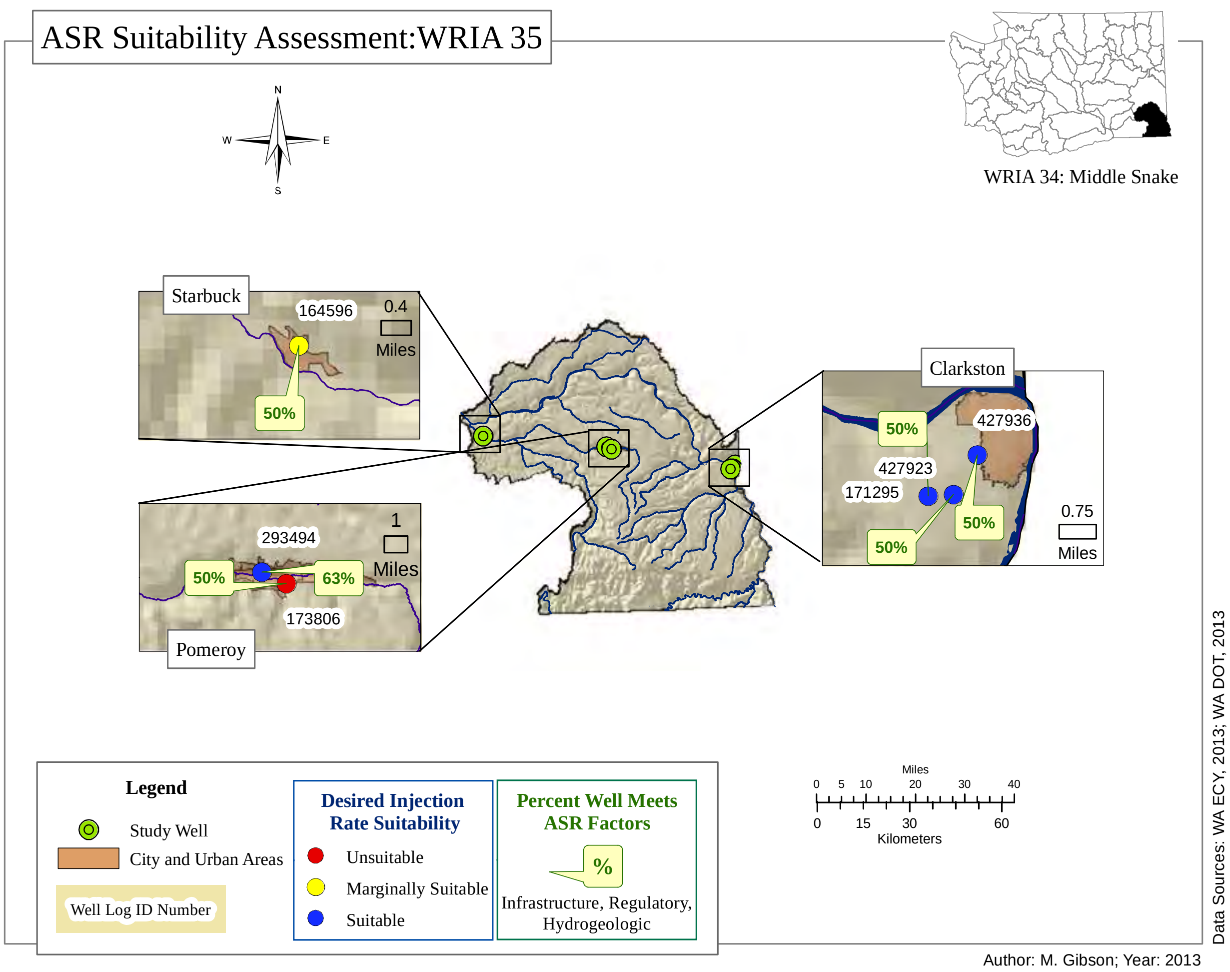
WRIA 35: Middle Snake (Figure 21)

Pomeroy is located next to Patah Creek, a tributary to the Snake River. The city has water rights totaling approximately 0.76 cfs from local springs (WA ECY, 2012d). Pomeroy-1 (Table 16) has a transmissivity, based on specific capacity, of 7,700 ft^2 per day, which is within the ASR suitability range and accesses the Columbia River Basalts at a depth of 69 to 997 feet below the surface. A monocline to the west and normal fault to the east of the city appear to be boundary conditions that could enhance ASR suitability; however, further on-site investigation would be required before a determination of suitability is confirmed. Additionally, the city of Pomeroy had a 2.3 percent population increase from 1990 to 2010 (WA OFM, 2012; U.S. Census, 2010); therefore, demand for additional water supply is not expected to substantially increase at this time.

Table 16. Well(s) compatible with ASR Within WRIA 35

Well Name	Well ID	Percent of Ideal Conditions				Metric
		Infrastructure	Regulatory	Hydrogeologic	**All Factors**	
Pomeroy-1	293494	50%	50%	67%	**63%**	**5**

Figure 21. ASR suitability assessment: WRIA 35

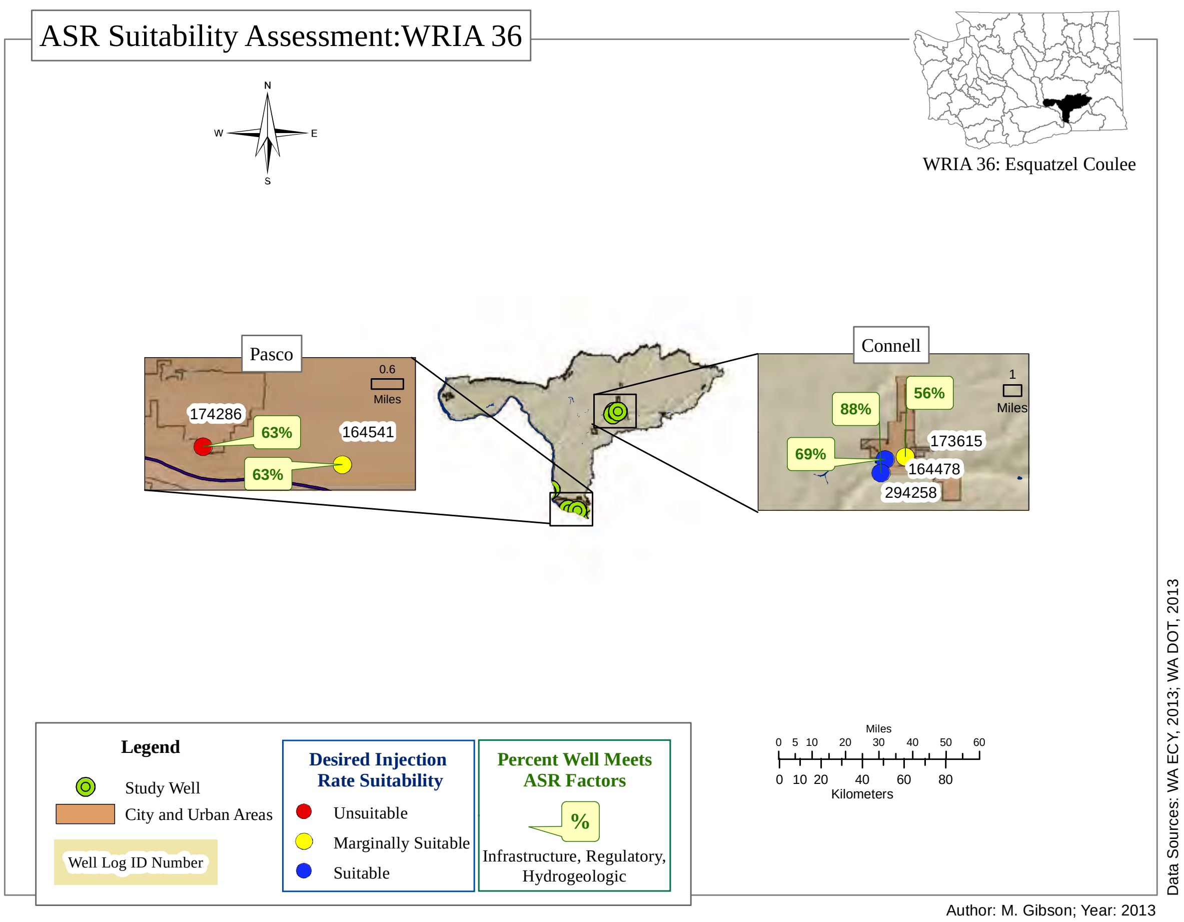


WRIA 36: Esquatzel Coulee (Figure 22)
Two wells within the city of Connell were estimated as highly suited for ASR (Table 17). The Connell wells access the Columbia River Basalts (Figure 33) at a range of 420 to 800 ft below ground surface. Transmissivity of Connell-1, estimated from specific capacity, is 3,300 ft^2 per day, which is below the lower range for ASR. Connell-2 is calculated at 13,200 ft^2 per day and is within the target range for ASR. The city of Connell population increased 109% from 1990 to 2010 (WA OFM, 2012; U.S. Census, 2010) and peak water demand is estimated at 5 MGD (GWMA et al., 2012). Therefore, converting both wells for ASR use could, at a minimum, potentially increase supply by about 1,400 acre-feet per year. Obtaining seasonal surface water rights might be difficult, as this watershed is under Surface Source Water Limitations and restrictions imposed by the U.S. Bureau of Reclamation (WA ECY, 2012e), however this should not be considered a limiting factor, as the watershed is not officially closed to new water uses.

Table 17. Well(s) Compatible with ASR within WRIA 36

Well Name	Well ID	Percent of Ideal Conditions				Metric
		Infrastructure	Regulatory	Hydrogeologic	**All Factors**	
Connell-1	294258	75%	75%	50%	**69%**	**1.9**
Connell-2	164478	88%	75%	100%	**88%**	**9.9**

Figure 22. ASR suitability assessment: WRIA 36



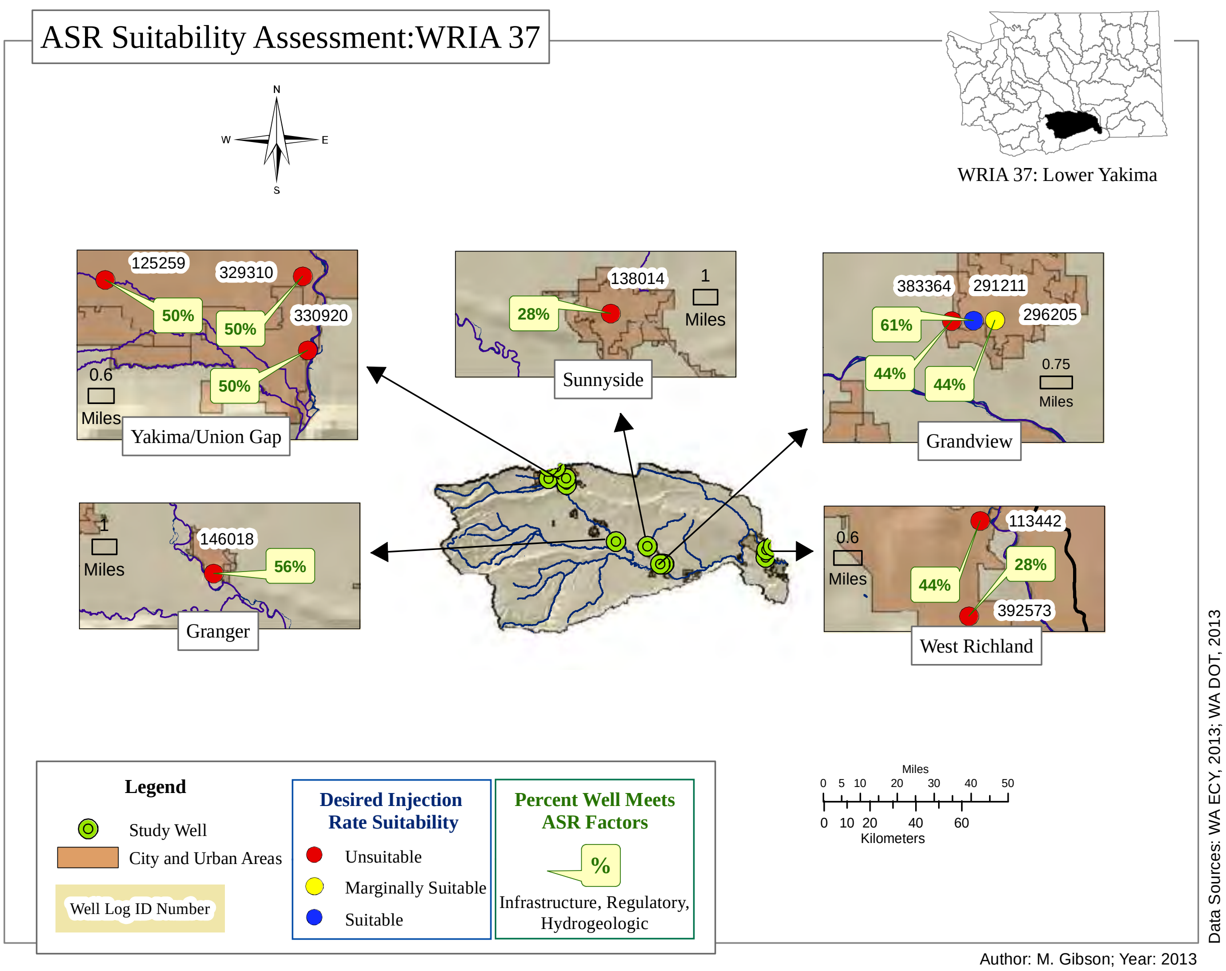
WRIA 37: Lower Yakima (Figure 23)

Grandview-1 (Table 18) is compatible for ASR. Accessing the Columbia River Basalts (Figure 33) at a depth of 739 to 1294 feet below ground surface, transmissivity, estimated from specific capacity is 8,100 ft^2 per day, which is within the target range. The potential limiting factors for ASR in the Lower Yakima watershed are that average year predicted demand exceeds supply during winter months (WSU, 2011), and that the basin is under adjudication and, therefore, unavailable for new appropriations (WA ECY, 2012f).

Table 18. Well(s) compatible with ASR Within WRIA 37

Well Name	Well ID	Percent of Ideal Conditions				Metric
		Infrastructure	Regulatory	Hydrogeologic	**All Factors**	
Grandview-1	291211	75%	0%	100%	**61%**	**2.2**

Figure 23. ASR suitability assessment: WRIA 37



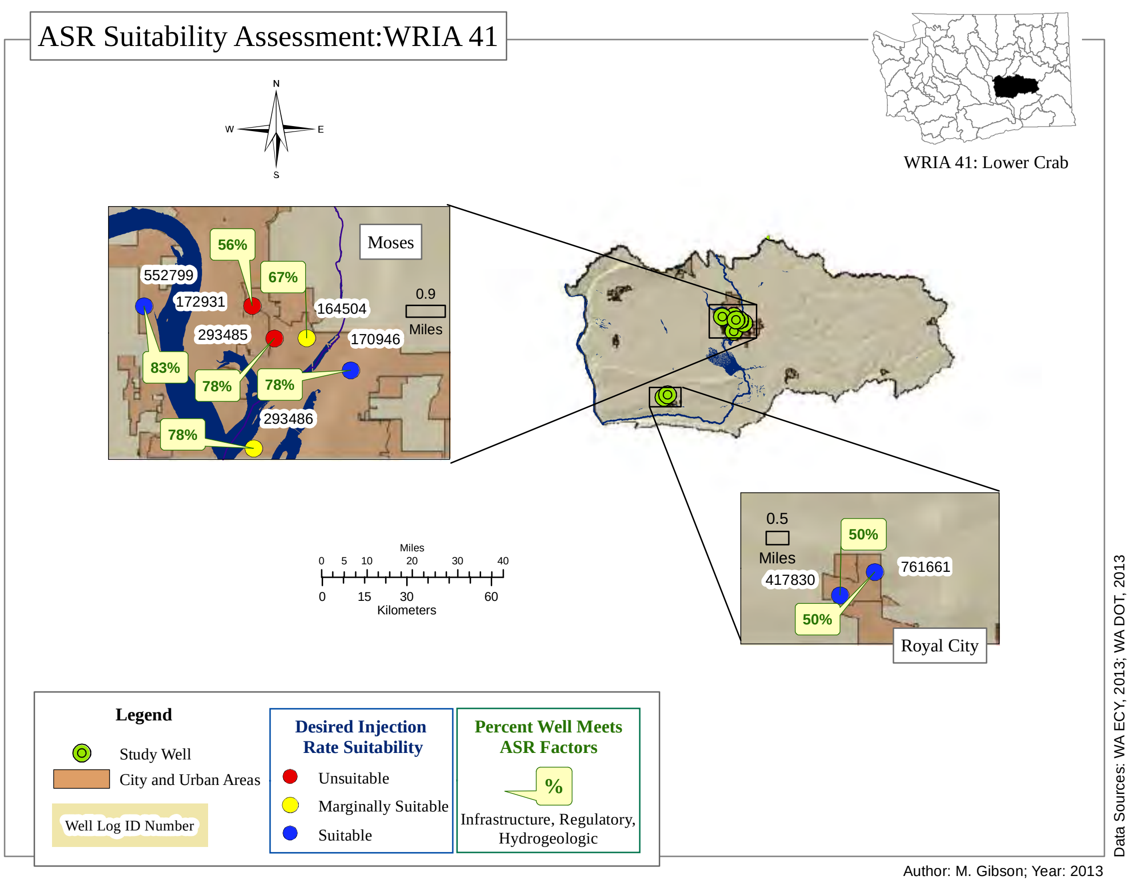
WRIA 41: Lower Crab Watershed (Figure 24)

It is estimated the city of Moses Lake own two municipal wells (Table 19) that are compatible for ASR use. Both access the Columbia River Basalts (Figure 33), have open intervals ranging from 365 to 755 feet below ground surface and transmissivity values, estimated from specific capacity from 8,000 (Moses-5) to 15,700 ft^2 per day (Moses-1), which are within the ASR target zone. Population for the city of Moses increased 81.2% from 1990 to 2010 (WA OFM, 2012; U.S. Census, 2010). With the addition of two ASR wells, the potential realized water supply is, at a minimum, estimated at 1,400 acre-feet per year. However, the U.S. Bureau of Reclamation is examining the utilization of unappropriated waters of the Columbia River and its tributaries above Priest Rapids until December of 2014, thus limiting future appropriations in this watershed. Furthermore, adjudication of Moses Lake is complete (WA ECY, 2012g) and water availability is limited, which could prohibit acquiring additional surface water rights.

Table 19 Well(s) compatible with ASR within WRIA 41

Well Name	Well ID	Percent of Ideal Conditions				Metric
		Infrastructure	Regulatory	Hydrogeologic	**All Factors**	
Moses-2	170946	75%	75%	83%	**78%**	**2.3**
Moses-5	552799	88%	75%	83%	**83%**	**1.8**

Figure 24. ASR suitability assessment: WRIA 41



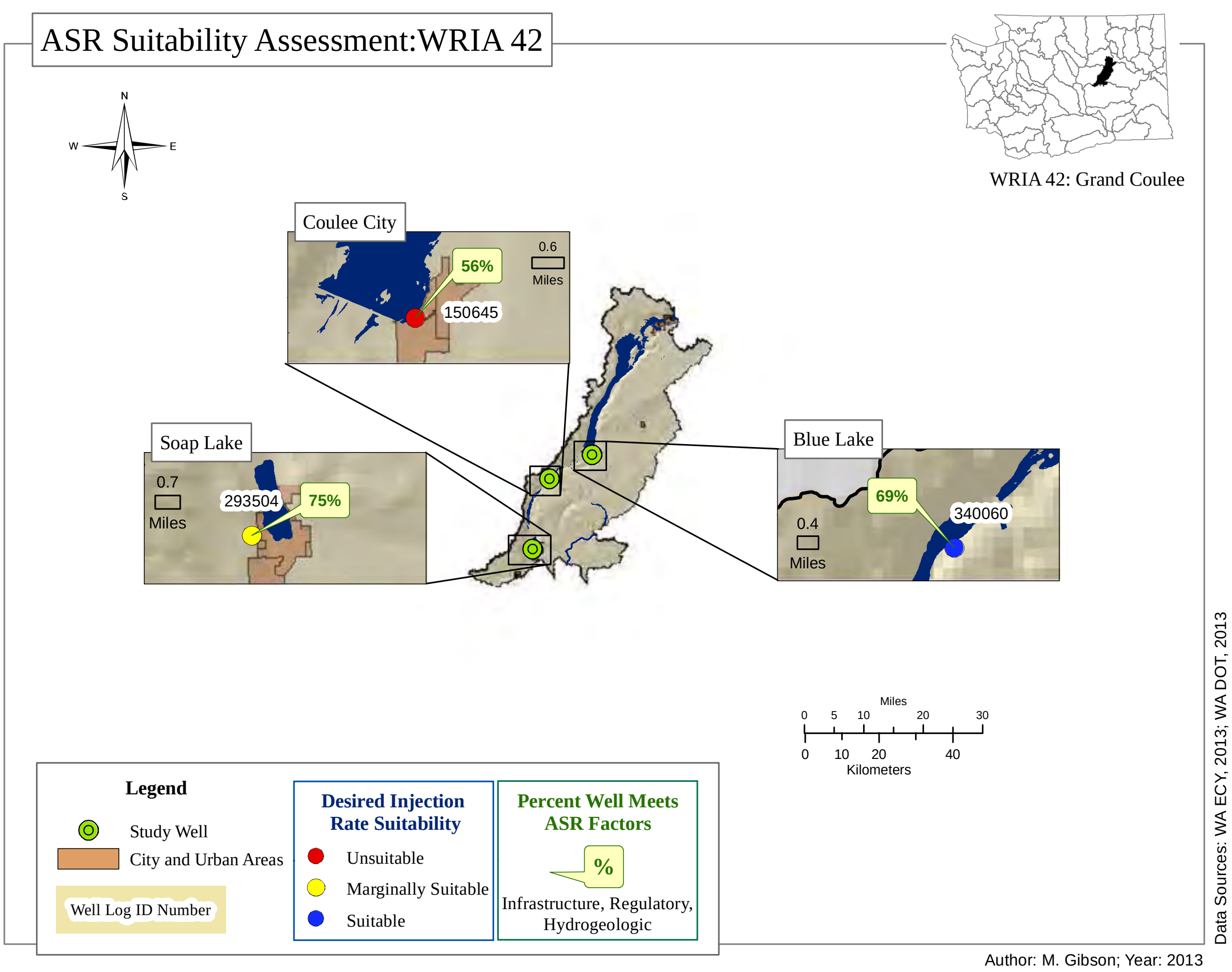
WRIA 42: Grand Coulee (Figure 25)

Blue Lake Water Users Association owns one well that is suitable for ASR (Table 20). Accessing the Columbia River Basalts at a depth of 65 to 240 feet below ground surface, transmissivity, based on specific capacity, is 6,800 ft^2 per day, which is within the target range for ASR. It is estimated this well, retrofitted for ASR, could, at a minimum, add 480 acre-feet per year to the Association's supply. However, this watershed has Surface Water Source Limitations, in addition to restrictions applied by the U.S. Bureau of Reclamation (WA ECY, 2012h); therefore, obtaining surface water rights, if needed, for ASR use could prove difficult.

Table 20 Well(s) compatible with ASR within WRIA 42

Well Name	Well ID	Percent of Ideal Conditions				Metric
		Infrastructure	Regulatory	Hydrogeologic	**All Factors**	
Blue Lake-1	340060	50%	75%	100%	**69%**	**1.6**

Figure 25. ASR suitability assessment: WRIA 42



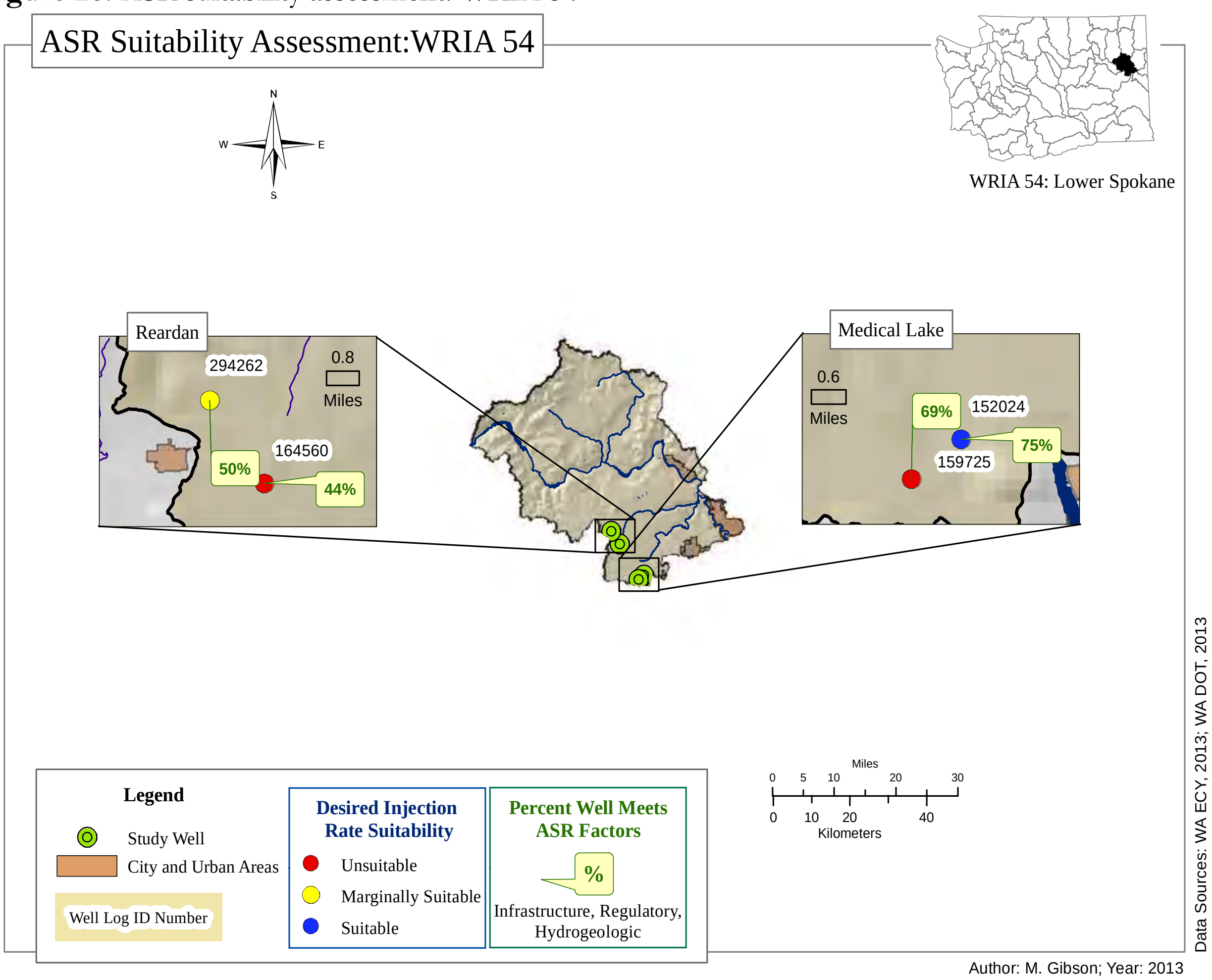
WRIA 54: Lower Spokane (Figure 26)

Medical Lake municipal wells are located within the Wanapum and Grande Ronde Basalts (Medical Lake, 2012). Medical Lake-1, considered suitable for ASR (Table 21), is screened at a depth of 129 to 440 feet below ground surface and transmissivity, based on specific capacity is 22,800 ft^2 per day. The city had a population increase of 38.1% from 1990 to 2010 (WA OFM, 2012; U.S. Census, 2010). Although within this watershed water supply exceeds demand during winter months (WSU, 2011), Source Water Surface Limitations and restrictions imposed by the U.S. Bureau of Reclamation (WA ECY, 2012i) limit available water rights, which could prohibit consideration of ASR projects, if new surface water rights are needed.

Table 21 Well(s) compatible with ASR within WRIA 54

Well Name	Well ID	Percent of Ideal Conditions				Metric
		Infrastructure	Regulatory	Hydrogeologic	**All Factors**	
Medical Lake-1	152024	63%	75%	100%	**75%**	**6.5**

Figure 26. ASR suitability assessment: WRIA 54



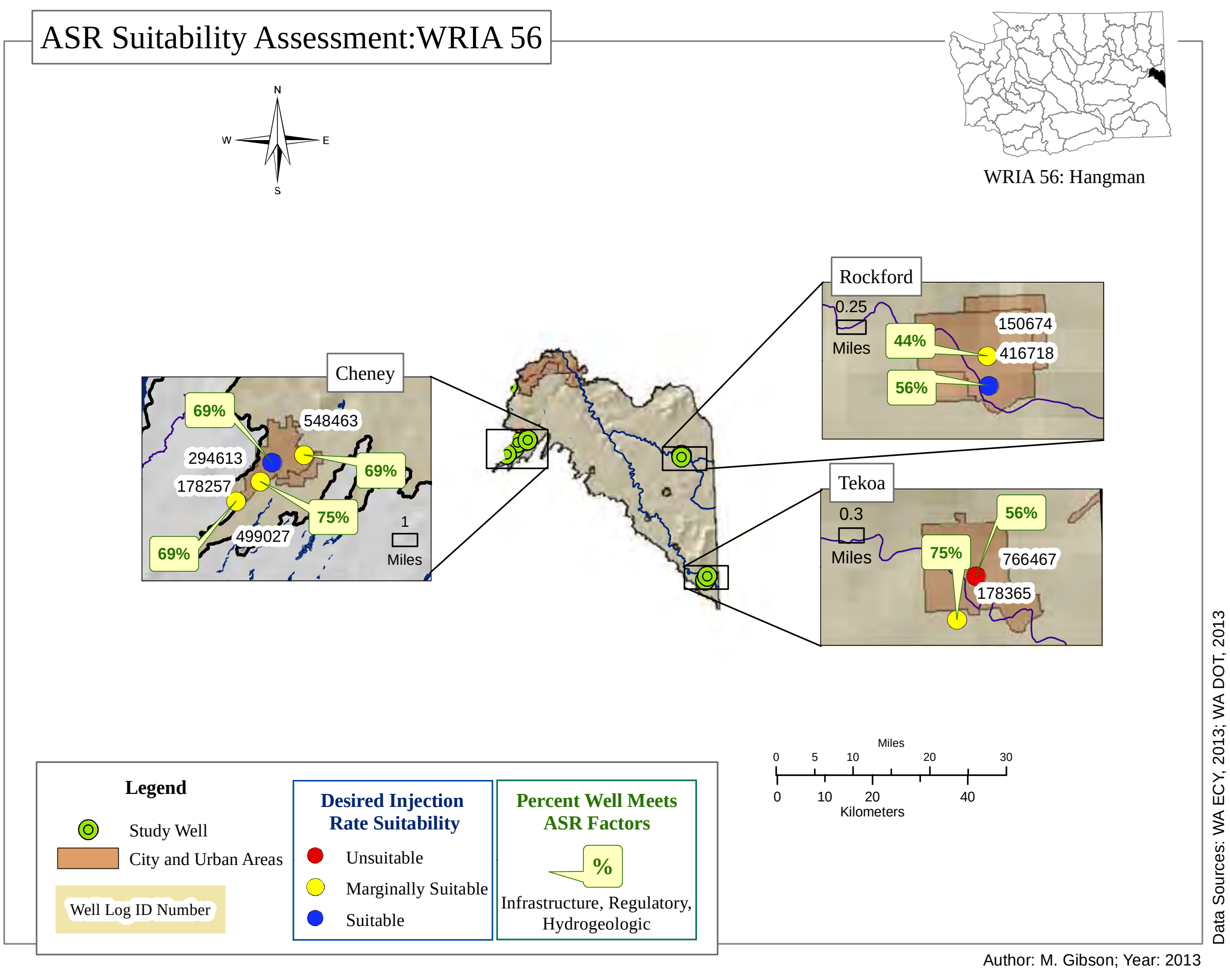
WRIA 56: Hangman (Figure 27)

Municipal well Cheney-2 (Table 22) is estimated to be suited for ASR. Although located in the Columbia River Basalts, transmissivity, based on specific capacity, of 4,400 ft^2 per day is below the target ASR range. The city experienced a population increase of 37.1% during 1990 to 2010 (WA OFM, 2012; U.S. Census, 2010) and significant growth is expected (WA ECY, 2012j). Currently, peak water demand for the city of Cheney is estimated at 2.7 MGD (Cupps and Morris, 2005); therefore, retrofitting Cheney-2 for injection could, at a minimum, add 700 acre-feet per year of additional supply. However, this watershed is under Surface Water Source Limitations and U.S. Bureau of Reclamation restrictions (WA ECY, 2012j).

Table 22. Well(s) compatible with ASR within WRIA 56

Well Name	Well ID	Percent of Ideal Conditions				Metric
		Infrastructure	Regulatory	Hydrogeologic	**All Factors**	
Cheney-2	294613	75%	75%	50%	**69%**	**1.9**

Figure 27. ASR suitability assessment: WRIA 56



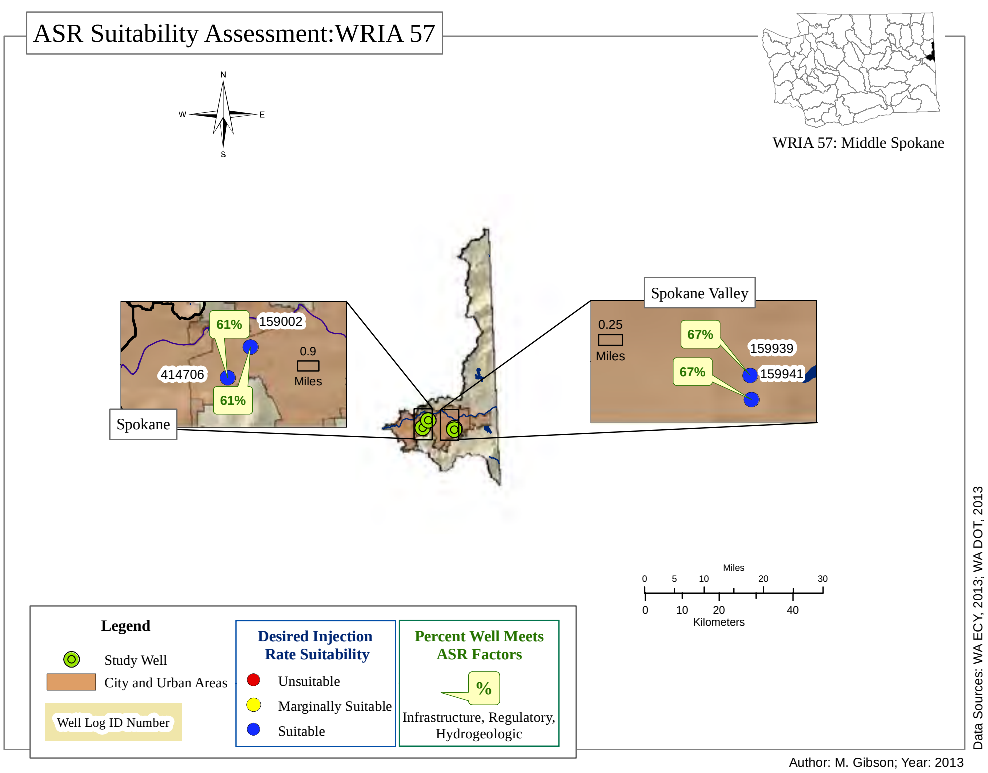
WRIA 57: Middle Spokane (Figure 28)

Wells evaluated in the Middle Spokane watershed are well suited for ASR (Table 23). Each well could potentially add a minimum of 700 acre-feet per year of additional water supply. Although transmissivity of each well, based on specific capacity, were beyond the target range for ASR (107,200 to 224,000 ft^2 per day). Local hydraulic gradient was estimated at 0.0065 to 0.0039 (Golder, 2004), which reduces the potential of injected water escaping the ASR well (Woody, 2007). All wells likely access Quaternary outburst flood deposits (WA DNR, 2012) and are within the Spokane Valley Rathdrum Prairie Aquifer, which is considered highly connected to the Spokane River and lies in Washington and Idaho. Designated a sole source aquifer, strict antidegradation rules apply to injected water. Additionally, the study completed by Barber et al. (2011), found the most promising method for recharging the aquifer by injection and recovery via natural methods would cost $90 million, which is likely cost prohibitive. Furthermore, the Middle Spokane watershed is under Surface Water Source Limitations, the U.S. Bureau of Reclamation restrictions (WA ECY, 2012k), and bi-state water management.

Table 23. Well(s) compatible with ASR within WRIA 57

Well Name	Well ID	Percent of Ideal Conditions				Metric
		Infrastructure	Regulatory	Hydrogeologic	**All Factors**	
Spokane-57-1	414706	63%	75%	50%	**61%**	**18**
Spokane-57-2	159002	63%	75%	50%	**61%**	**15.7**
Spokane Valley-1	159939	75%	75%	50%	**67%**	**42.5**
Spokane Valley-2	159941	75%	75%	50%	**67%**	**40.5**

Figure 28. ASR suitability assessment: WRIA 57



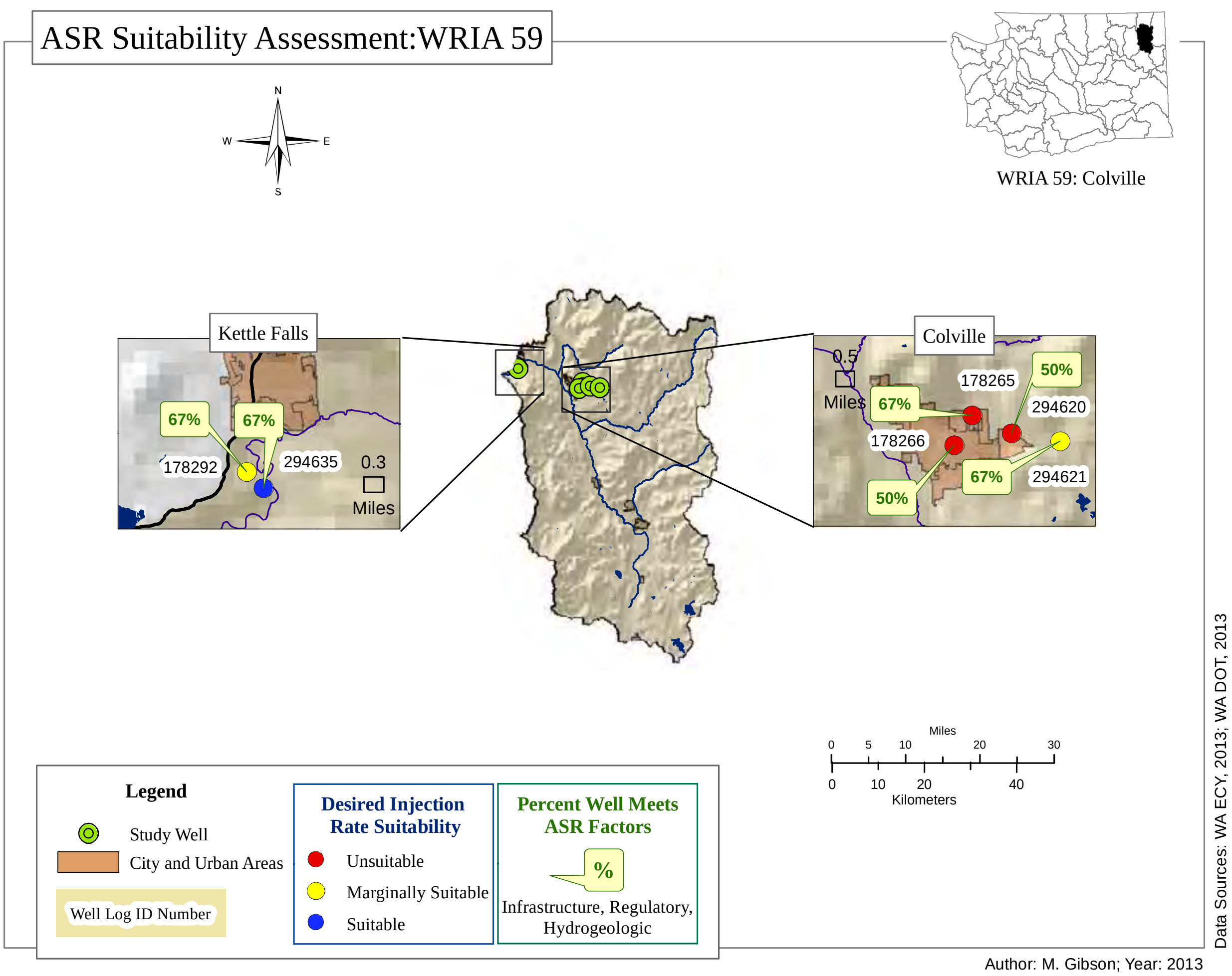
WRIA 59: Colville (Figure 29)

Kettle Falls-2 (Table 24) is considered well suited for ASR. Located in Quaternary glacial drift, it accesses the aquifer at 165 to 157 feet below ground surface. Transmissivity, based on specific capacity, is 10,800 ft^2 per day, which is within the target range for ASR. However, hydraulic gradient estimated from Ely and Kahle (2004) range from 0.011 to 0.037 and is not considered ideal for an ASR scheme (Woody, 2007), as the injected water could migrate away from the ASR well. Additionally, this well is possibly located in an unconfined aquifer and likely hydraulically connected to the Colville River (Ely and Kahle, 2004). Unless local boundary conditions exist, which could prevent the migration of water, retrofitting this well for ASR use would not be an advantageous pursuit.

Table 24. Well(s) compatible with ASR within WRIA 59

Well Name	Well ID	Percent of Ideal Conditions				Metric
		Infrastructure	Regulatory	Hydrogeologic	**All Factors**	
Kettle Falls-2	294635	63%	75%	67%	**67%**	**2.5**

Figure 29. ASR suitability assessment: WRIA 59



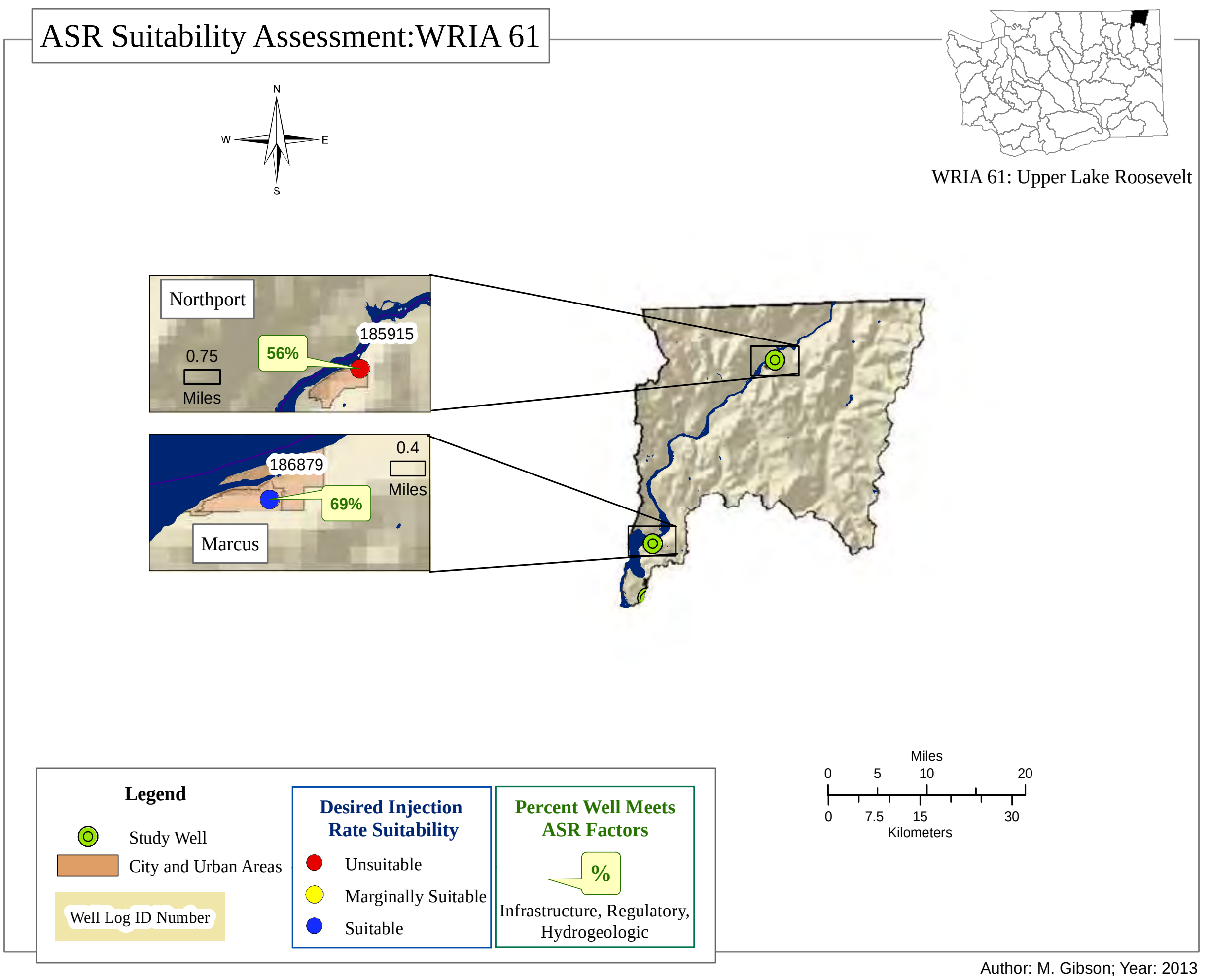
WRIA 61: Upper Lake Roosevelt (Figure 30)

Marcus-1 (Table 25), owned by the town of Marcus, is likely located in Quaternary glacial till (WA DNR, 2012). At a depth of 212 feet, with an open interval of 172 to 212 feet below ground surface, this well is likely hydraulically connected to the Columbia River. Transmissivity, based on specific capacity, is estimated at 10,200 ft^2 per day, which is within the target ASR range. As pumped water from this well is not treated prior to distribution (WA DOH, 2013), groundwater is considered high quality. Although ASR seems viable for the town of Marcus, with a population of 183 (U.S. Census, 2010), it is unlikely a need exists for the development of an ASR scheme in this watershed.

Table 25. Well(s) compatible with ASR within WRIA 61

Well Name	Well ID	Percent of Ideal Conditions				Metric
		Infrastructure	Regulatory	Hydrogeologic	**All Factors**	
Marcus-1	294635	50%	75%	100%	**69%**	**3.3**

Figure 30. ASR suitability assessment: WRIA 61



Statewide Prospects for ASR

Based on the results of this study, potential ASR locations, west of the Cascade Range, are likely located in the Fraser Aquifer and/or Puget Aquifer of the north-central and southern Puget Sound Lowlands. East of the Cascade Range, ASR suitability is highest within the Columbia River Basalts (Figure 31).

Fraser Aquifer

The Fraser Aquifer (Figure 32) is the hydrogeologic unit of the Vashon Stade, which formed during the Fraser Glaciation (20,000 to 10,000 years ago). The Vashon Stade is the last substantial glacial advance into the Puget Sound region; consequently, the Fraser Aquifer is comprised mostly of advance outwash and proglacial deposits. Modeled lateral gradients range from 0.0004 to 0.01, with an average of 0.003 (Vaccaro et al., 1998), which is within the satisfactory rage for ASR (less than or equal to 0.01) (Woody, 2007). The Fraser Aquifer is unconfined to semi-confined (Vaccaro et al. 1998) and is used for municipal, domestic, and agricultural purposes. This being a water table aquifer, the potential for ASR use is unlikely unless local aquifer characteristics exist which would improve suitability.

Puget Aquifer

The Puget Aquifer, consisting of undifferentiated glacial and interglacial deposits, and underlies the Olympia interglacial confining unit. Found at depths greater than 150 feet (USGS, n.d.), thickness of the aquifer ranges from 400 to 1,000 ft and thickens to the north (Jones, 1999). Modeled lateral gradients of the Puget Aquifer range 0.0002 to 0.004, with an average gradient of 0.002, which is acceptable for ASR (Woody, 2007). Lateral extent of the aquifer is unknown in the Puget Sound Lowlands; however, it is believed, it has an areal extent of 70 to 80% (Vaccaro et al., 1997). Due to water availability in the upper aquifers, the Puget Aquifer is not heavily utilized as a groundwater source. Current ASR wells likely accessing this

Figure 31. Map of surficial aquifers, WRIAs, and combined results

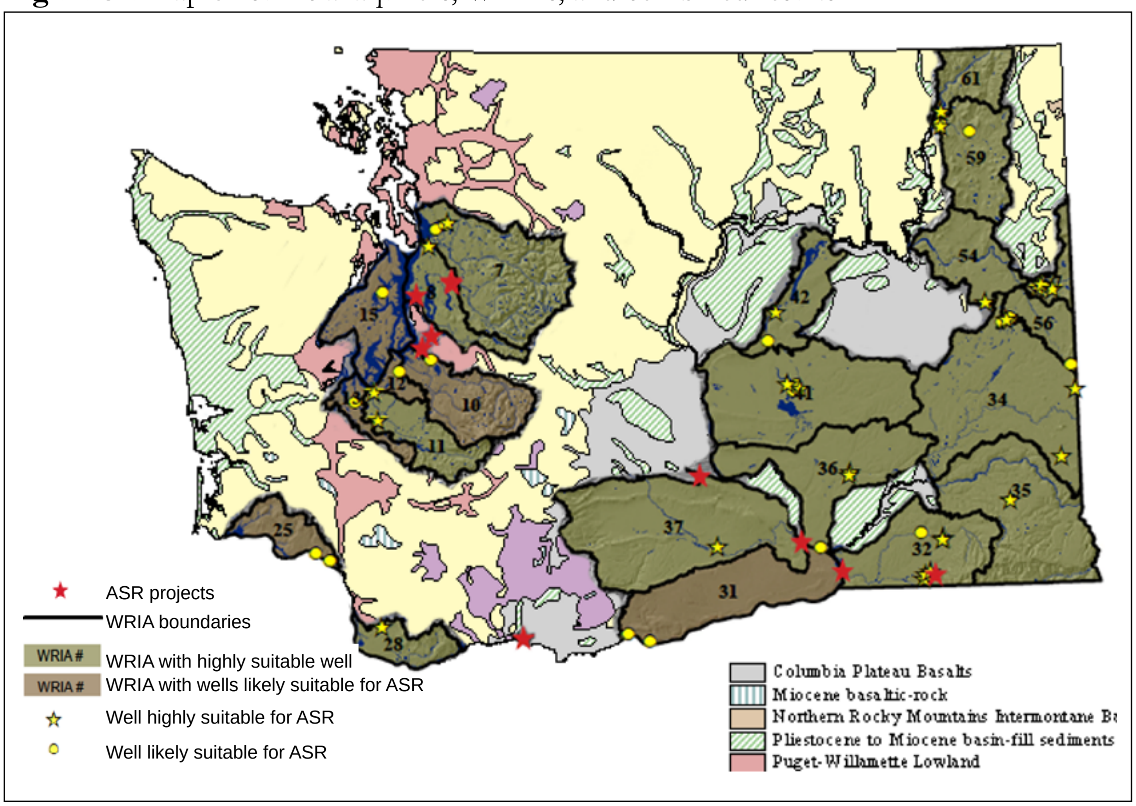
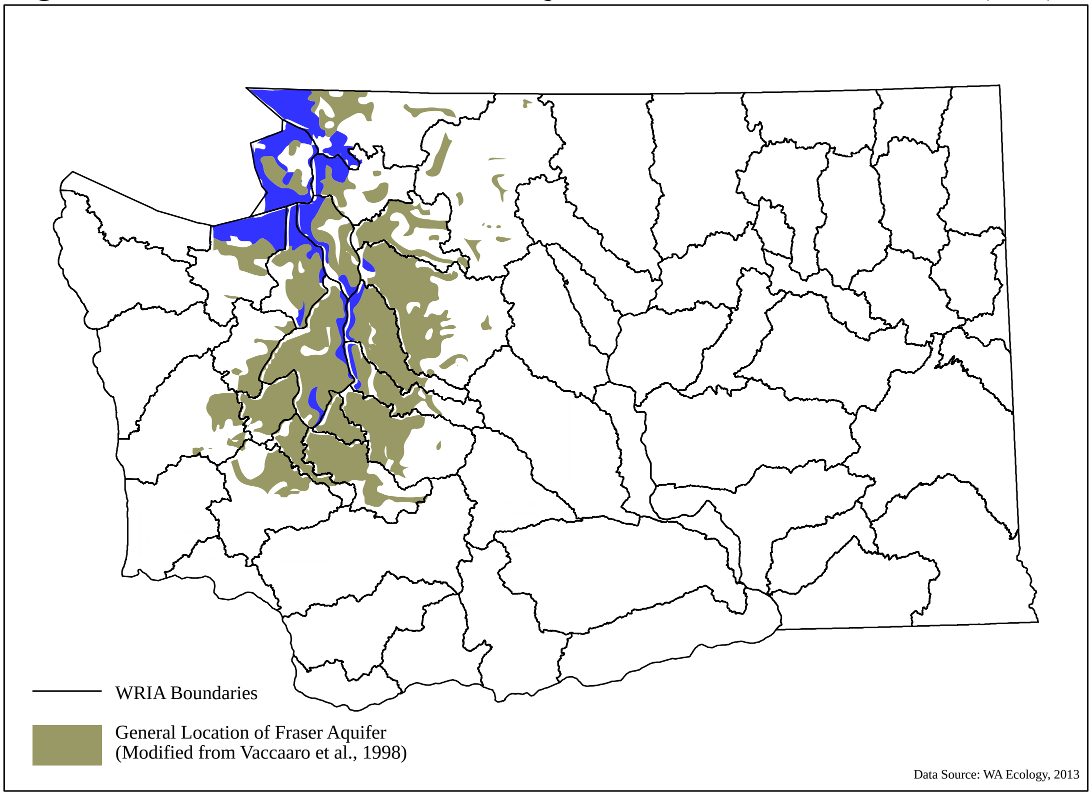


Figure 32. General extent of the Fraser Aquifer modified from Vaccaro et al. (1998)



aquifer are operated by Seattle Public Utilities and are located in the Seattle Highland well field.

Columbia River Basalt Group

The Columbia River Basalt Group (CRBG) (Figure 33) contains more than 300 continental tholeiitic flood basalt sheet flows that cover an area of over 63,000 square miles. The CRBG is overlain by loess to alluvium Quaternary sediments and unconformably underlain by Pre-Tertiary rocks (Tolan et al., 1989). The CRBG includes the following 4 formations (youngest to oldest): Saddle Mountain Basalt, Wanapum Basalt, Grande Ronde Basalt, and Imnaha Basalt. These comprise the Columbia River Regional Aquifer System, which are stacked confined interflow zones. The largest of these formations are the Grande Ronde Basalt, which can exceed a thickness of 3000 feet (Kennedy/Jenks, 2005). Additional geologic and hydrogeologic details are summarized in Table 26 and Table 27 respectively.

Recommended Investigations

The Lakehaven Utility District, located in the city of Federal Way, operates 1 ASR well within the

Figure 33. Areal extent of the Columbia River Basalt Group in Washington (Modified from USGS, 2013)

Mirror Lake Aquifer (MLA), which is a member of the Salmon Springs drift glacial unit (French, 2013). Within the Puget Sound Lowlands (Jones, 1999) the MLA is likely located within the Puget Aquifer. WRIAs in the Puget Sound Lowlands, with wells accessing the Fraser and Puget Aquifers, indicate potential ASR suitability. We recommend these aquifers be considered when initiating ASR suitability investigation within this region.

In Walla Walla, ASR wells are located in the CRBG. The city of Yakima determined ASR is suitable in the Ellensburg Formation, the city of White Salmon is developing ASR in the Grande Ronde basalt, and the majority of ASR wells in Oregon are located in the CRBG interflow zones (Woody, 2007). This study identified 4 WRIAs within the CRBG that could potentially be suitable for ASR. Therefore, ASR investigations east of the Cascade Range should focus on locations within these basalts.

Table 26. Geologic details of the CRBG (HDR and GSI Water Solutions, 2009)

Geologic Details			
Group	Formation	Age of Emplacement	Thickness (ft)
Columbia River Basalt Group	17.5 Ma to 6.6Ma		
	Saddle Mountain Basalt	13.5 to 6.5 Ma	
	Wanapum Basalt	15.5 to 14.5 Ma	< 300
	Grande Ronda Basalt	16.5 to 15.6 Ma	3000 +
	Imnaha Basalt	17.5 to 16.6 Ma	
	Ellensburg Formation (interbedded in CRBG, most notably in Saddle Mountains Basalt)		

Table 27. Hydrogeologic details of the CRBG. Information pertains to WRIA 35: Middle Snake (Kennedy/Jenks, 2005)

CRBG Hydrogeologic Information				
	Saddle Mountain	Wanapum	Grande Ronde	Ellensburg Interbeds
Location	Laterally Extensive	Laterally Extensive	Laterally Extensive	
Description		Disconformably underlies Saddle Mountain Basalts/ Dips away from Blue Mountains to the West	Disconformably underlies Wanapum	
Horizontal Hydraulic Conductivity				$1x10^{-6}$ to 1 ft/day
Vertical Hydraulic Conductivity	$7x10^{-3}$ to 200ft/ day	$7x10^{-3}$ to 5,200 ft/day	$5x10^{-3}$ to 2,500 ft/day	
Notes				Storage coefficient ~0.0002

Conclusion

The present study was designed to determine suitability of ASR within Washington's WRIAs through desktop methods. Although findings suggest ASR is a viable option to supplement current storage within many watersheds, results merely imply suitability and provide locations where local field investigations could be examined.

Limitations

Inherent limitations exist when results are based on an ensemble of various sources. To accurately determine suitability of ASR at a particular location requires on-site investigations to identify regulatory, hydrogeologic, infrastructure and other constraints.

Local Conditions

Local conditions affecting suitability were not incorporated into the method employed. Examples include aquifer boundary conditions, vertical hydraulic gradients, seasonal variability in static water levels, etc. Consequently, a site rendered favorable or unfavorable could be deemed unsuitable or suitable when incorporating these variables.

Water Well Data

Well locations are based on GIS data and are approximate; well log coordinates are derived from calculated quarter-quarter, quarter, and section centroids. Well log information is also limited by the well driller's ability to correctly record this information (WA ECY, 2003c).

Modified ASR Metric

Suitability estimated by the modified ASR metric equation is influenced by transmissivity, desired injection rates, and headspace in the well. Injection rate based on an assumed value, transmissivity based on specific capacity, and maximum headspace based on static water level obtained from well logs limit the assessment outcome of ASR suitability; therefore, results could vary accordingly.

Modified ASR metric results represent the combined total of one ASR well per location with a cap on the desired injection rate. Due to these constraints, potential storage represents the minimum value ASR could accommodate. Higher storage could be realized by incorporating ASR well fields versus that of one well.

Modified Site Suitability Assessment

Due to the large area of the study locations no weighting factors were assigned. A local desktop suitability assessment would likely include weighting factors to ensure those factors affecting suitability are ranked in such a way to accurately describe local conditions.

The methods are a tool for others interested in conducting ASR desktop suitability investigations. The flexibility to change desired injection rates or add or remove ASR factors can help increase confidence when deciding whether a project investigation should proceed or be abandoned. By subdividing the modified site suitability assessment outcome into regulatory, infrastructure, and hydrogeologic factors, one can easily determine which category needs the greatest focus when choosing to move forward with such projects. The desktop method is a reconnaissance method and not a substitute for detailed, site-specific investigations. As presented here, it tends to produce minimum storage amounts. Due to its flexibility and limited data requirements it is suitable for developed and developing regions alike.

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