A Preliminary Assessment of Hydrogeologic Suitability for Aquifer Storage and Recovery (ASR) in Oregon

by
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ABSTRACT

An ASR metric and site rating index applied to over 120 municipal and agricultural locations across Oregon, combined with comparison to case study data from existing ASR sites, indicate that more than 50% of selected sites are hydrogeologically suitable for ASR. The ASR metric is a ratio of aquifer storage to the rate at which surface water is available for injection, with a result greater than one indicating sufficient aquifer storage. The site rating index evaluates aquifer hydraulic parameters as well as economic and engineering factors, and produces a percentage of ideal conditions. While economic and engineering factors can determine ASR feasibility, transmissivity, depth to static groundwater level and the desired injection rate are the controlling hydraulic parameters for hydrogeologic ASR suitability. However, these factors have a flexible relationship; for example, high transmissivity can compensate for small depth to groundwater and vice versa.

In Oregon, most existing ASR sites target Columbia River Basalt interflow zones, where transmissivity is high and native groundwater quality is generally suitable for drinking water. These units are also prone to groundwater decline due to over-pumping, which essentially creates storage for ASR. Results show that suitable potential sites correspond predominantly with Columbia River Basalt, Quaternary and late Tertiary sediments. Potential aquifer storage identified by this study is approximately equal to Oregon's annual public water supply in the year 2000, or 5×10^8 m^3 (160 billion gallons or 502,809 ac-ft). This suggests that ASR expansion in Oregon can significantly increase public supply and provide flexibility in the timing of water availability.

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TABLE OF CONTENTS

Chapter Page

1. INTRODUCTION…….……...…….....2

Purpose and Scope……....…….....5
How to Use This Thesis……....…….....6

2. ASR CASE STUDIES: LESSONS LEARNED……...…....…..…….....8
Oregon ASR Case Studies……....…….....8
ASR Outside of Oregon…….....……....21

3. ASR SITE SCREENING METHODS……...….…….…....…….30

Brown's Site Rating System .....……...…...30
ASR Metric Analysis……....……...…….37

4. DESCHUTES BASIN……...……...47
Basin Hydrology……...…….…….....47
Hydrogeologic Units……..…….……..…..50
ASR Assessment ……...…….…..……..53
Madras…….…….....……55
Redmond…….....…….....……56
Sisters…….....…….……57
Bend…….....…….....……..58
La Pine…….....…….....……...59

5. GOOSE AND SUMMER LAKES BASIN…….…....….60
Basin Hydrology…….….....60
Hydrogeologic Units……..…....……63
ASR Assessment ……...…....……65
Christmas Valley…….....…..….67
Paisley……..…..….67
Plush……...……..…….68
Lakeview……...……...…..….69

6. GRANDE RONDE BASIN…….....……..71
Basin Hydrology……..…….....71
Hydrogeologic Units……....…….…..73

TABLE OF CONTENTS (continued)

Page

ASR Assessment ……75
La Grande……77
Elgin……78
Wallowa……79
Enterprise……79

7. HOOD BASIN……81
Basin Hydrology……81
Hydrogeologic Units……84
ASR Assessment……86
Cascade Locks……88
Hood River……89
Mosier……90
The Dalles……91
Durfur……92

8. JOHN DAY BASIN……93
Basin Hydrology……93
Hydrogeologic Units……96
ASR Assessment ……98
Arlington……100
Condon……101
Fossil……102
John Day……102

9. KLAMATH BASIN……104
Basin Hydrology……104
Hydrogeologic Units……107
ASR Assessment ……109
Lenz……110
Fort Klamath……111
Klamath Falls……112
Pinehurst……113
Bly……114
Merrill……114
Malin……115
Chemult……116
Chiloquin……117

TABLE OF CONTENTS (continued)

Page

10. MALHEUR LAKE BASIN…….....……..…....…….119
Basin Hydrology…….....……..…….....119
HydrogeologicUnits…….....…….…….....122
ASR Assessment ……..……....……..…...…….....123
Burns…….....……...……....125
Crane……...…….....……...…….....126
Riley…….....…...……....127
Diamond……...…….....……...……....127

11. MALHEUR RIVER BASIN…....…….....….....129
Basin Hydrology..…….....……...…….....129
Hydrogeologic Units…….....…….…….....132
ASR Assessment …….....…….....……....133
Ontario…….....….…….....135
Ironside…….....….....….……136
Drewsey……..…….....….…….…137
Harper……..….....….…….…..138

12. MID COAST BASIN……...…….....…....139
Basin Hydrology……..……...…….....….……....139
Hydrogeologic Units…….....….……....…142
ASR Assessment …….....…….....144
Florence……....……....……146
Yachats……...…….....146
Waldport……...…….....147
Newport……...…….....148
Lincoln City…….……...…….....149
Alsea……...…….....150

13. NORTH COAST BASIN……...……151
Basin Hydrology…….....……....…….....…….151
Hydrogeologic Units……....……...……...…….…….....151
ASR Assessment ……..…....…….....156
Warrenton……...…….....158
Clatskanie.....159
Gearhart.....159
Cannon Beach.....160
Manzanita.....161
Tillamook.....161
Pacific City.....162

TABLE OF CONTENTS (continued)

Page

14. OWYHEE BASIN…….....163
Basin Hydrology…….....163
Hydrogeologic Units…….....167
ASR Assessment …….....168
Adrian…….....170
Rome…….....170
Basque…….....171
Jordan Valley…….....172

15. POWDER BASIN…….....173
Basin Hydrology…….....173
Hydrogeologic Units…….....176
ASR Assessment …….....178
North Powder…….....180
Unity…….....181
Halfway…….....181
Huntington…….....182

16. ROGUE BASIN…….....184
Basin Hydrology…….....184
Hydrogeologic Units…….....187
ASR Assessment …….....189
Medford…….....191
Grants Pass…….....192
Ashland…….....193
Cave Junction…….....194
Prospect…….....195
Gold Beach…….....195

17. SANDY BASIN…….....197
Basin Hydrology…….....197
Hydrogeologic Units…….....200
ASR Assessment …….....202
Sandy…….....204
Troutdale…….....205
Welches, Wemme, Zigzag…….....206

TABLE OF CONTENTS (continued)

Page

18. SOUTH COAST BASIN……207
Basin Hydrology……207
Hydrogeologic Units……210
ASR Assessment ……211
Brookings……213
Port Orford……214
Bandon……215
Coos Bay……216
North Bend……217

19. UMATILLA BASIN……218
Basin Hydrology……218
Hydrogeologic Units……221
ASR Assessment ……223
Umatilla……224
Hermiston……225
Heppner……226
Boardman……227
Pilot Rock……227
Weston……228
Milton-Freewater……229
Stanfield……229

20. UMPQUA BASIN……230
Basin Hydrology……230
Hydrogeologic Units……233
ASR Assessment ……235
Reedsport……237
Drain……237
Sutherlin……238
Roseburg……239
Myrtle Creek……240
Canyonville……241

TABLE OF CONTENTS (continued)

Page

21. WILLAMETTE BASIN…….....…….....……242
Basin Hydrology…….....…….....……..……242
Hydrogeologic Units……..…….....…..……245
ASR Assessment …….....…….....……248
Milwaukie …….……..….....……250
Oregon City…….……..…….…….....……251
Estacada.....252
Canby……..…….....253
Woodburn…....……....…….....253
Mt. Angel……..…….....254
Sherwood……..…..…….....255
McMinnville……....…….....256
Amity……....……..…….....256
Independence……..…….....257
Sweet Home……...…….....258
Corvallis…….……..…….....258
Eugene……..…….....259
Cottage Grove …….…….…….....260

22. SUMMARY AND CONCLUSIONS....……..261

REFERENCES…….....…….....266

APPENDICES…….....277
Appendix A: ASR Case Study Data Table..... 278
Appendix B: Well Data.....279
B-1. Deschutes Basin Well Data.....279
B-2. Goose and Summer Lakes Basin Well Data.....281
B-3. Grande Ronde Basin Well Data.....281
B-4. Hood Basin Well Data.....282
B-5. John Day Basin Well Data.....283
B-6. Klamath Basin Well Data.....284
B-7. Malheur Lake Basin Well Data.....285
B-8. Malheur River Basin Well Data.....285
B-9. Middle Coast Basin Well Data.....286
B-10. North Coast Basin Well Data.....287.
B-11. Owyhee Basin Well Data.....288
B-12. Powder Basin Well Data.....288
B-13. Rogue Basin Well Data.....289
B-14. Sandy Basin Well Data.....290
B-15. South Coast Basin Well Data.....291

TABLE OF CONTENTS (continued)

Page

B-16. Umatilla Basin Well Data.....291
B-17. Umpqua Basin Well Data.....293
B-18. Willamette Basin Well Data.....294

Appendix C: Brown's Site Rating System Results.....297
C-1. Deschutes Basin Brown's System.....297
C-2. Goose and Summer Lakes Basin Brown's System.....297
C-3. Grande Ronde Basin Brown's System.....298
C-4. Hood Basin Brown's System.....298
C-5. John Day Basin Brown's System.....298
C-6. Klamath Basin Brown's System.....299
C-7. Malheur Lake Basin Brown's System.....299
C-8. Malheur River Basin Brown's System.....300
C-9. Middle Coast Basin Brown's System.....300
C-10. North Coast Basin Brown's System.....300
C-11. Owyhee Basin Brown's System.....301
C-12. Powder Basin Brown's System.....301
C-13. Rogue Basin Brown's System.....301
C-14. Sandy Basin Brown's System.....302
C-15. South Coast Basin Brown's System.....302
C-16. Umatilla Basin Brown's System.....302
C-17. Umpqua Basin Brown's System.....303
C-18. Willamette Basin Brown's System.....303

Appendix D: ASR Site Assessment Results Table.....304

LIST OF FIGURES

Figure Page

1-1. ASR System illustration.....2
1-2. AR System illustration.....3
1-3. Primary vs. Secondary Research.....6
1-4. Oregon Hydrologic Basins.....7
2-1. Existing ASR sites in Oregon.....9
2-2. Columbia River Basalt Schematic.....12
2-3. ASR Case Studies in the U.S.....21
3-1. Case Studies' Results from Brown's Site Rating System.....36
3-2. ASR Metric Methodology Illustration.....40
3-3. Case Studies' Results from ASR Metric Analysis.....42
3-4. Error Associated with Transmissivity Estimation.....45
3-5. ASR Site Screening Decision Tree.....46
4-1. Deschutes Basin Location Map.....48
4-2. Deschutes Basin Geology Map.....49
4-3. Deschutes Basin ASR Metric Results.....54
4-4. Deschutes Basin Brown's Rating System Results.....55
5-1. Goose and Summer Lakes Basin Location Map.....61
5-2. Goose and Summer Lakes Basin Geology Map.....62
5-3. Goose and Summer Lakes Basin ASR Metric Results.....66
5-4. Goose and Summer Lakes Basin Brown's Rating System Results.....66
6-1. Grande Ronde Basin Location Map.....72
6-2. Grande Ronde Basin Geology Map.....73
6-3. Grande Ronde Basin ASR Metric Results.....76
6-4. Grande Ronde Basin Brown's Rating System Results.....77
7-1. Hood Basin Location Map.....82
7-2. Hood Basin Geology Map.....83
7-3. Hood Basin ASR Metric Results.....87
7-4. Hood Basin Brown's Rating System Results.....88
8-1. John Day Basin Location Map.....94
8-2. John Day Basin Geology Map.....95
8-3. John Day Basin ASR Metric Results.....99
8-4. John Day Basin Brown's Rating System Results.....100
9-1. Klamath Basin Location Map.....105
9-2. Klamath Basin Geology Map.....106
9-3. Klamath Basin ASR Metric Results.....109
9-4. Klamath Basin Brown's Rating System Results.....110
10-1. Malheur Lake Basin Location Map.....120
10-2. Malheur Lake Basin Geology Map.....121
10-3. Malheur Lake Basin ASR Metric Results.....124
10-4. Malheur Lake Basin Brown's Rating System Results.....125
11-1. Malheur River Basin Location Map.....130

LIST OF FIGURES (continued)

Figure Page

11-2. Malheur River Basin Geology Map……...…….....131
11-3. Malheur River Basin ASR Metric Results.....134
11-4. Malheur River Basin Brown's Rating System Results.....135
12-1. Middle Coast Basin Location Map……..…….....140
12-2. Middle Coast Basin Geology Map…….....141
12-3. Middle Coast Basin ASR Metric Results.....145
12-4. Middle Coast Basin Brown's Rating System Results.....145
13-1. North Coast Basin Location Map…….....152
13-2. North Coast Basin Geology Map……...…….....153
13-3. North Coast Basin ASR Metric Results.....157
13-4. North Coast Basin Brown's Rating System Results.....158
14-1. Owyhee Basin Location Map…….....164
14-2. Owyhee Basin Location Geology Map…….....165
14-3. Owyhee Basin ASR Metric Results.....169
14-4. Owyhee Basin Brown's Rating System Results.....169
15-1. Powder Basin Location Map…….....174
15-2. Powder Basin Location Geology Map……..…….....175
15-3. Powder Basin ASR Metric Results.....179
15-4. Powder Basin Brown's Rating System Results.....179
16-1. Rogue Basin Location Map…….....185
16-2. Rogue Basin Location Geology Map…….....186
16-3. Rogue Basin ASR Metric Results.....190
16-4. Rogue Basin Brown's Rating System Results.....191
17-1. Sandy Basin Location Map…….....198
17-2. Sandy Basin Location Geology Map…….....199
17-3. Sandy Basin ASR Metric Results.....203
17-4. Sandy Basin Brown's Rating System Results.....204
18-1. South Coast Basin Location Map…….....208
18-2. South Coast Basin Geology Map…….....209
18-3. South Coast Basin ASR Metric Results.....212
18-4. South Coast Basin Brown's Rating System Results.....213
19-1. Umatilla Basin Location Map…….....219
19-2. Umatilla Basin Geology Map…….....220
19-3. Umatilla Basin ASR Metric Results.....223
19-4. Umatilla Basin Brown's Rating System Results.....224
20-1. Umpqua Basin Location Map…….....231
20-2. Umpqua Basin Geology Map…….....232
20-3. Umpqua Basin ASR Metric Results.....236
20-4. Umpqua Basin Brown's Rating System Results.....237
21-1. Willamette Basin Location Map…….....243
21-2. Willamette Basin Geology Map…….....244

LIST OF FIGURES (continued)

Figure Page
21-3. Willamette Basin ASR Metric Results.....249
21-4. Willamette Basin Brown's Rating System Results.....250
22-1. ASR Metric Results.....262
22-2. Brown's Site Rating System Results.....262
22-3. ASR Metric Results and Geologic Map.....264
22-4. Distribution of Results.....263
22-5. Potential Cumulative ASR Capacity in Oregon.....263

LIST OF TABLES

Table Page

2-1. Summary of Oregon ASR Sites.....10
3-1. Brown's Site Rating System.....31
3-2. Determination of F factor in ASR metric.....39
3-3. Conversion Factors used for transmissivity estimation.....43
4-3. Summary of Analysis Methods.....54
5-3. Summary of Analysis Methods.....65
6-3. Summary of Analysis Methods.....76
7-3. Summary of Analysis Methods.....87
8-3. Summary of Analysis Methods.....99
9-3. Summary of Analysis Methods.....109
10-3. Summary of Analysis Methods.....124
11-3. Summary of Analysis Methods.....134
12-3. Summary of Analysis Methods.....144
13-3. Summary of Analysis Methods.....157
14-3. Summary of Analysis Methods.....168
15-3. Summary of Analysis Methods.....178
16-3. Summary of Analysis Methods.....190
17-3. Summary of Analysis Methods.....203
18-3. Summary of Analysis Methods.....212
19-3. Summary of Analysis Methods.....223
20-3. Summary of Analysis Methods.....235
21-3. Summary of Analysis Methods.....248

A Preliminary Assessment of Hydrogeologic Suitability for Aquifer Storage and Recovery (ASR) in Oregon

CHAPTER 1
INTRODUCTION

Background

Groundwater can be intentionally replenished using a variety of techniques. Aquifer Storage and Recovery (ASR) refers specifically to the practice of withdrawing surface water during times of high flow, treating it to drinking water standards and injecting it through a well into an aquifer with sufficient storage capacity. During subsequent dry season periods of high demand, this stored water is pumped out (recovered) at the same well and added to the distribution system (see Figure 1-1).

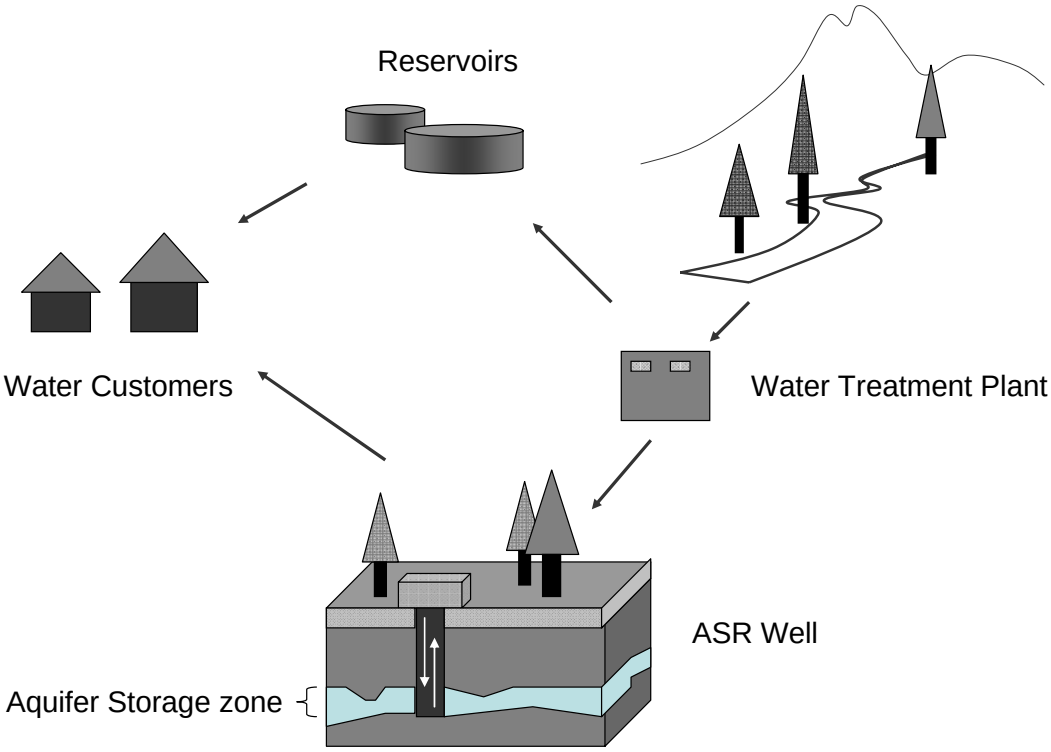


Figure 1-1. ASR system illustration. A municipal ASR system, where winter stream flow is stored underground for withdrawal through the same well the following summer.

Generally, ASR is useful to store water in deep or confined aquifers (water bearing layers of rock that are bounded above and below by low permeability layers).

The term Artificial Recharge (AR) refers to the technique of spreading water into shallow spreading basins on the ground surface, and allowing it to infiltrate into the underlying aquifer (see Figure 1-2). AR is usually conducted in unconsolidated or highly fractured aquifers that are close to the surface.

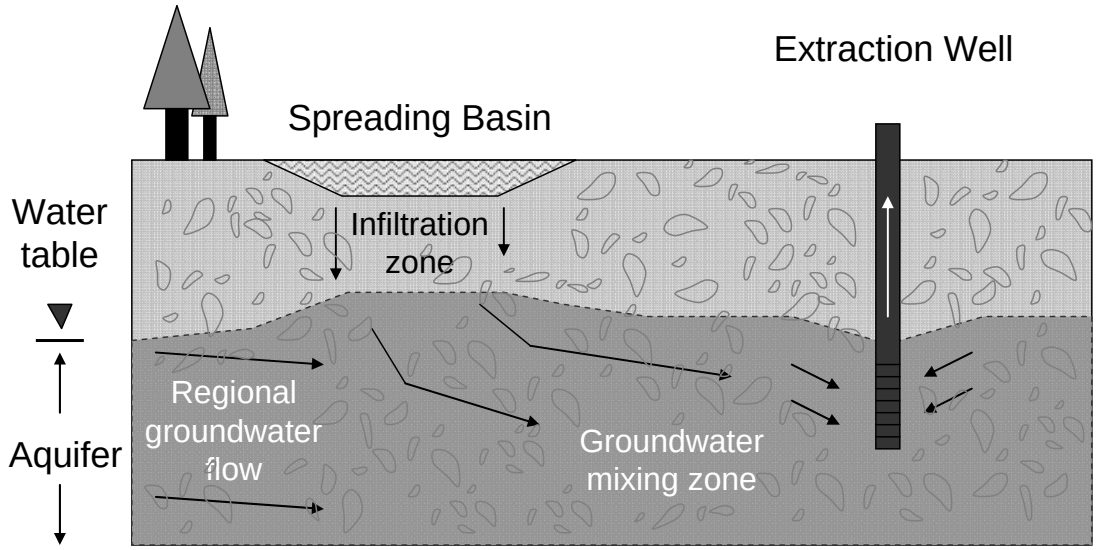


Figure 1-2. AR system illustration. An AR project, where water infiltrates through shallow spreading basins. This water can be withdrawn down-gradient through a well for irrigation or other uses.

In Oregon, the climate is well suited to ASR and AR because the state receives nearly two-thirds of its precipitation during the winter months, with a pronounced dry summer season on both sides of the Cascade's rain shadow. During the dry season water use peaks due to increased irrigation and municipal use, while surface water supply is at its lowest. Many communities have surface water rights in the high flow months that they are not fully utilizing. ASR and AR can capture some of this flow and store it to supplement dry season water supplies.

Oregon's population is expected to increase by 41% by the year 2030, which further intensifies the pressure on limited water supplies (Western Governor's Association, 2007). This may intensify the pressure on water supplies, especially when

combined with climate change influences on precipitation patterns. In anticipation of long term water management challenges, the Oregon Water Resources Department (OWRD) conducted this state-wide assessment of hydrogeologic suitability for ASR and AR to assist communities that are evaluating water storage options. These assessments are based on the range of reported aquifer parameters, and indicate an aquifer's general suitability for ASR or AR. Site-specific evaluation is essential to identify any groundwater boundaries or local variations in aquifer parameters that may influence ASR or AR.

ASR in Oregon

Oregon currently has twelve authorized ASR test sites which store surface water between November and June. Municipal operations are located in Beaverton, Tualatin, Tigard, Salem, Clackamas, Baker City, Pendleton, Portland and Dallas. Two agricultural projects near Echo, in the Umatilla basin, are also testing ASR. Nine of these sites store water in Columbia River Basalt aquifers, one in the Siletz River Volcanics, and two in buried alluvial deposits.

While ASR projects are required to obtain an ASR limited license to test operations, they can use water under the authority of existing water rights for later diversion to the originally authorized use. Also, ASR requires well injection as the means to store, while AR projects may use well injection or infiltration. Injection water must be treated to drinking water standards, so ASR requires both filtration and disinfection infrastructure before injection, unless treated water can be purchased from a municipal supply system.

AR in Oregon

There are approximately five authorized AR sites in Oregon, with purposes including supplemental irrigation, domestic water supply, water level decline mitigation, and wetland replenishment. Projects include the County Line Water Improvement District in Morrow/Umatilla Counties, Buell-Red Prairie Domestic Water Association in Polk County, and the Hudson Bay Irrigation District, working with Walla Walla

Watershed Council in Umatilla County. Additionally, an agricultural ASR site near Echo, in the Umatilla Basin, uses AR to filter surface water before it is injected at the ASR well.

In Oregon, AR is generally less expensive to implement that ASR, because water quality requirements are less restrictive for AR. Water for AR must meet the "non-degradation" standards of Oregon Department of Environmental Quality (ODEQ). This means that the recharge water must either maintain the aquifer water at its original quality or better, but it does not have to meet drinking water requirements. Surface water often meets these standards, but periodic water quality monitoring is necessary.

AR projects require a new permit to divert water for the purpose of aquifer recharge and a secondary groundwater permit to extract this water. AR and secondary permit holders need not be the same entity.

Objective and Scope of this study

The primary objective of this study is to assess the physical hydrogeologic systems in Oregon for ASR suitability. The state-wide survey provides a general assessment that can point the way for future, site-specific investigation. The main focus is on municipal applications of ASR, but secondarily, agricultural use is assessed. Finally, AR suitability is addressed qualitatively, especially in rural areas. According to the National Research Council (2007), regional aquifer storage suitability studies are an important step towards utilizing this technology to our full advantage.

The scope of this study is limited to those aquifers that are presently accessed by water wells. This data limitation confines the investigation to formations within about 1,000 ft (305 m) below the surface because most water wells in Oregon do not exceed this depth. Future development of deeper formations may reveal new ASR opportunities, and sites found unsuitable by this study may have deep aquifers that are more feasible for ASR.

This assessment of ASR and AR suitability in Oregon is an example of secondary research (DEFRA, 2006), because it is a synthesis of existing data (Figure 1-3). DEFRA argues that assembling and interpreting existing data is as important as gathering new

evidence, particularly when it is in response to urgent policy issues. The product of synthesizing aquifer data from other studies is a new understanding of Oregon aquifer systems' suitability for ASR. This directly addresses water allocation policy issues in the state, where in many places water is fully allocated or over-allocated. ASR is a tool that can help communities cope with these water allocation limitations.

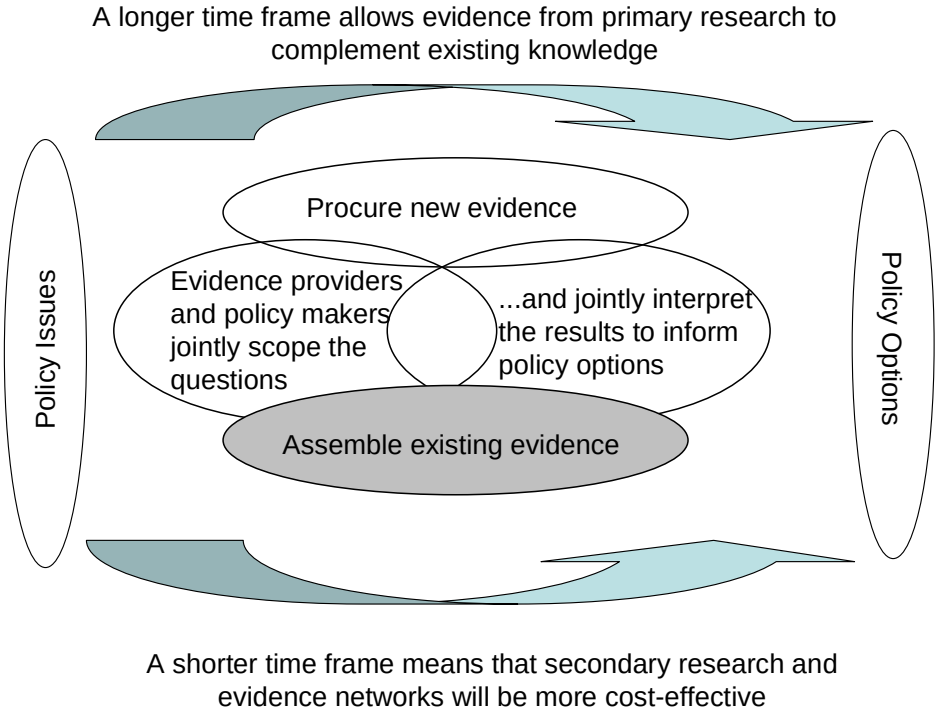


Figure 1-3. Primary vs. secondary research. This study is an example of secondary research, which is a cost effective and efficient method to gain new understandings of the physical world by the synthesis of existing data (DEFRA, 2006). It is an important method used to address policy-maker's needs for expedient and useful investigations.

How to use this thesis

Chapters 1 through 3 introduce ASR Case Study information for context, and also present the methods applied by this study. These sections are important to understanding the analysis which follows. The basin chapters (Chapters 4 through 21), defined as the eighteen OWRD administrative basins (Figure 1-4), are each intended to stand alone. The reader can pick an area of interest and explore that basin chapter without reading the entire work sequentially. First, the hydrogeology of each basin is outlined with regards to

ASR and AR suitability. This assessment of the geology can be applied by the reader to either municipal or agricultural ASR or AR. Second, specific large capacity wells are assessed, with even geographic distribution across the basin when possible. Regardless of whether the selected well is used for municipal or agricultural supply, the physical suitability of the aquifer applies. AR suitability is acknowledged briefly and qualitatively for each location, because it can be another important underground water storage technique. The summary chapter presents an overview of general trends of ASR and AR suitability across the state and implications of this work.

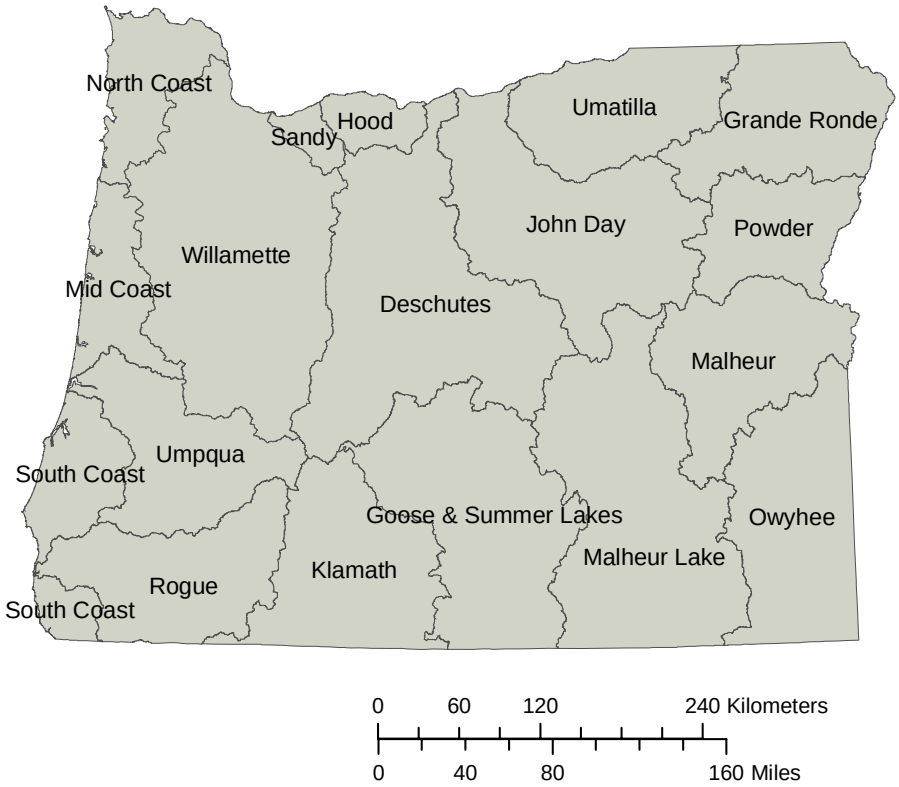


Figure 1-4. Oregon hydrologic basins. Assessment of ASR suitability was organized by Oregon Water Resources Department (OWRD) administrative basins (Data Source: Oregon Geospatial Data Clearinghouse, accessed 2006). There is a chapter for each basin, which discusses geologic suitability generally and then examines specific assessment points.

CHAPTER 2
ASR CASE STUDIES: LESSONS LEARNED

Background

ASR has been practiced in Oregon and around the world for several decades. This wealth of experience can inform future projects by providing examples of problems solved, the ranges of feasible parameters, and troublesome factors that can be insurmountable. Oregon experience includes 10 sites that store water in basalt with distinct interflow zones, and two projects that use another aquifer type. Examples from outside the state can provide valuable guidance to future Oregon projects that do not use basalt aquifers.

Oregon ASR Case Studies

There are presently 12 ASR sites (Table 2-1) in Oregon operating under limited licenses, which means they have applied for and been issued a license from the state to conduct ASR testing for a period of five years. After five years, the licensee can opt to renew for further testing, apply for a permit, or to cancel the license altogether. Currently, all the sites in Oregon are still in the testing phase, although Portland has cancelled their license. ASR sites are clustered in the central and northern Willamette Valley, north central and northeastern Oregon (Figure 2-1). Rather than discuss each site separately, the following sections discuss important considerations for ASR, and discusses the experience of various Oregon ASR projects.

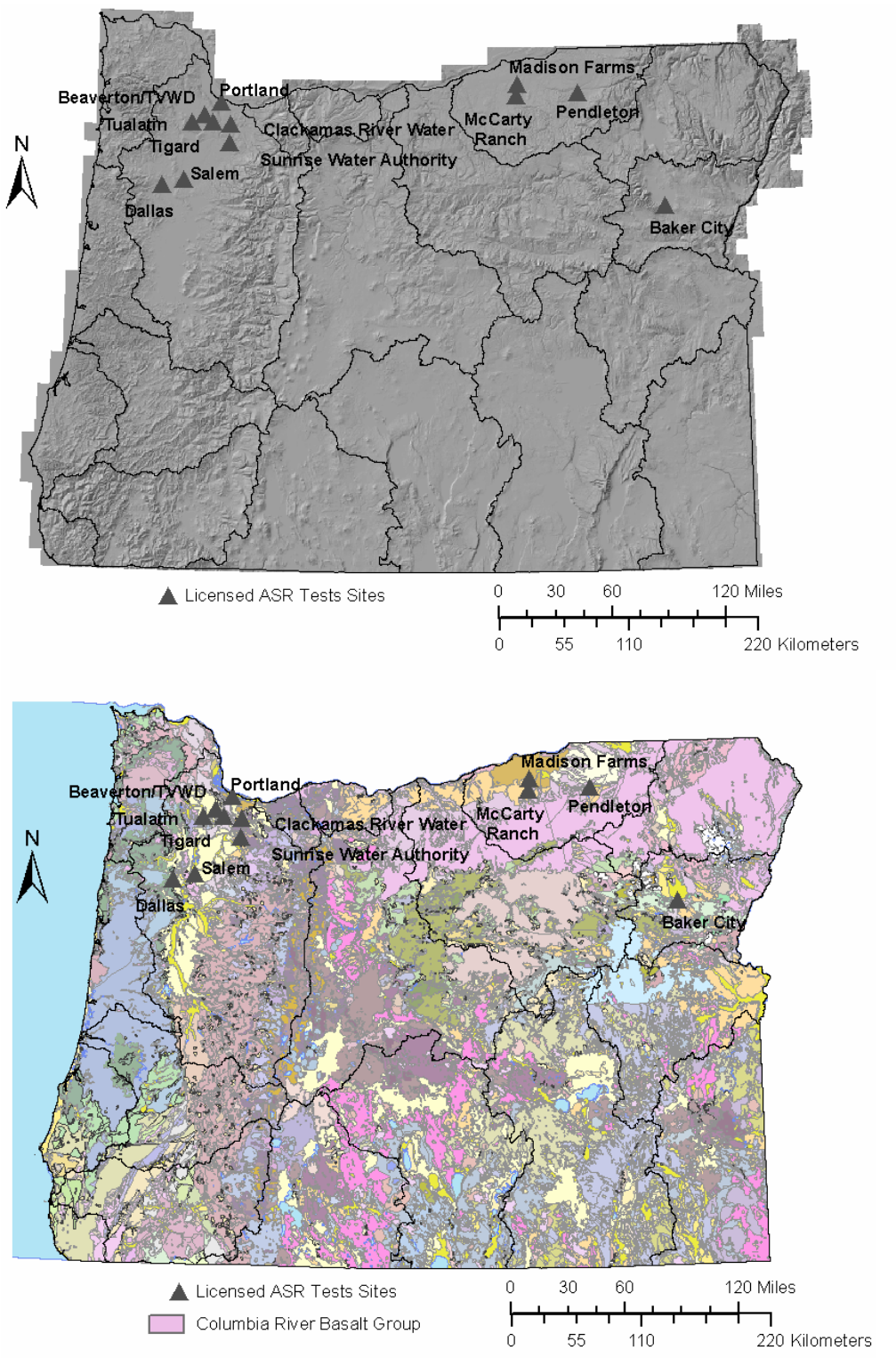


Figure 2-1. Existing ASR sites in Oregon. Licensed ASR test sites in Oregon have strong correlation with Columbia River Basalt (Data sources: Oregon Geospatial Data Clearinghouse, 2006; Walker and MacLeod, 1991; Wright, 2006).

Table 2-1. Summary of licensed Oregon ASR sites.

Location	Use	Aq-uifer Lith-ology	T (ft^2/d)	Geologic Struct-ure	Source	Water Qual-ity Issues	Clogg-ing Issues
Salem	Municipal	Basalt	14,500		North Santiam River	Source Water Turb-idity	Yes: Sed-iment
Beaverton & Tualatin Valley Water District	Municipal	Basalt	65,550 6,800	Faults	Bull Run, Tualatin Rivers	N/A	N/A
Clackamas	Municipal	Basalt	1,750		Clackamas River	Radon	N/A
Portland	Municipal	Alluv-ium	1,080		Bull Run River	Turb-idity	Yes: iron
Tigard	Municipal	Basalt	900	Faults	Bull Run River	N/A	N/A
Pendleton	Municipal	Basalt	35,300		Umatilla River	N/A	Yes: air
Baker City	Municipal	Basalt	980	Faults	7 Springs	N/A	N/A
Tualatin	Municipal	Basalt	3,540	Faults	Bull Run River	N/A	N/A
Dallas	Municipal	Basalt	1,300		Rickreal Creek	Saline ground-water	N/A
Sunrise Water Authority	Municipal	Alluv-ium	1,400		Clackamas River	N/A	N/A
Madison Farms	Irrigation	Basalt	10,700	Folds and faults	Alluvial Collector Well	Nitrate	N/A
McCarty Ranch	Irrigation	Basalt	10,700	Folds and faults	Alluvial Collector Well	Nitrate	N/A

Aquifer Lithology

Madison Farms, McCarty Ranch, Beaverton, Tualatin Valley Water District (TVWD), Tualatin, Salem, Tigard, Clackamas, Baker City and Pendleton ASR projects utilize or plan to use Columbia River Basalt interflow zones as the target storage aquifer. Investigations into future ASR sites in Mt. Angel are also considering basalt aquifers for storage (Malia Kupillas, personal communication, 2007).

The Columbia River Basalt was emplaced in a series of flows (17.5 to 6 Ma; Beeson and Moran, 1979). The centers of the flows tend to be massive with very little pore space through which water can flow. Fractures provide the main groundwater flow paths in these flow centers. In between flows, the basalt tops are often brecciated, meaning angular pieces of the basalt are broken and accumulate in a permeable layer. The permeability of interflow zones and brecciated flow tops can be quite high, and they usually constitute a confined or semi-confined aquifer because the permeable layer is bounded on its top and bottom by less permeable, more massive basalt flows (Figure 2-2). Columbia River basalt is unique hydrogeologically because it contains interflow zones, where water moves quickly through the aquifer under the influence of pumping or hydraulic head gradient. However, because these aquifers are confined, they are often slow to recharge, which means pumping at high rates can lead to groundwater declines over time. In the context of ASR, this is an advantage, because water can be injected at high rates into the storage created by over-pumping in the aquifer.

Position in Basalt Flow	Lithology	Hydrogeology	Hydraulic Conductivity
Center	See below		See below
Base	Vesicular, platy		Moderate to high
Interbed	Silt, clay		Very low
Top	Vesicular, brecciated		High
Center	Basalt, vesicularity decreases with depth, vertically jointed		Horizontal: low to moderate Vertical: lower than horizontal conductivity
Base	Vesicular, platy		Base, interbed and top: moderate to high
Interbed	Sand, Gravel		
Top	Vesicular, brecciated		
Center	See above	General direction of groundwater flow	See above

Figure 2-2: Columbia River Basalt schematic (modified from Lindholm, 1996). Interbeds and broken basalt flow tops and bases are the most permeable water-bearing layers and are used for most ASR in Oregon.

Basalt aquifers used for ASR are usually deep formations, which secures the stored water from purposeful or inadvertent mining by other wells. Basalt aquifers are also generally not highly reactive aquifers; although they can contain waters with elevated manganese and iron. ASR tests in Oregon have not found serious water quality problems when injected water is recovered from Columbia River Basalt storage.

The City of Dallas, Oregon began testing ASR in basalt units of the Siletz River Volcanics in late 2005. This formation is one in a series of volcanics deposited throughout what is now the Oregon Coast Range. The Siletz River Volcanics were emplaced approximately 56 million years before the present (Armentrout and Suek, 1985). Because the volcanics were extruded underwater, they contain pillow basalts which are often highly permeable. Dallas's ASR has not yet experienced problems

related to the hydraulic properties of this formation, although there have been water quality hurdles, which are discussed in a later section of this chapter.

Portland completed ASR tests between 2002 and 2004 at the Columbia South Shore Well Field. This project targeted the Troutdale Formation, which is a sand and gravel aquifer extending along the Columbia River from east of Portland to the Pacific Ocean. The small grain size of the aquifer and the mineral assemblage suggest a higher potential for chemical reactions to occur than in basalt aquifers. Tests found that after injection, storage and recovery the well experienced a decrease in specific capacity (Golder Associates, 2003).

Sunrise Water Authority has also been licensed to test ASR in a deep alluvial aquifer of the Troutdale Sand and Gravel Formation (OWRD, 2007). Feasibility studies completed in 2006 (Groundwater Solutions Inc., 2006) found the aquifer could store up to 600 million gallons (2.3×10^6 m^3) of injected water. Although the project was licensed to begin testing in February of 2007, at present the results have not been reported, so effects of the alluvial aquifer lithology on ASR are presently unknown.

Transmissivity

There are several related (but not equivalent) quantitative terms that describe the ease with which fluids move through geologic formations. The permeability of an aquifer is a measure of how easily fluids can move through the connected pore spaces in rock and has units of length squared (e.g., cm^2). Hydraulic conductivity relates the ease with which fluid at a particular density and viscosity can move through a rock; it is expressed in units of distance per time (e.g., ft/d). Transmissivity is hydraulic conductivity multiplied by the formation's thickness, so it accounts for the amount of aquifer available for fluid transmission. Transmissivity has units of volume per time per unit thickness (e.g., ft^3/d/ft or more simply, ft^2/d).

Transmissivity is an important aquifer parameter for ASR. This is because it quantifies both the ease with which water can move through the geologic formation, and also the thickness of the formation. For example, if a formation transmits water at a lower rate than may be desirable, its large thickness may compensate for a low flow rate

by providing more storage volume. Conversely, an aquifer that transmits water at a high rate could be thin and still useful. One rule of thumb is that values greater than 10,000 ft^2/d (929 m^2/d) are quite suitable for ASR if other factors are appropriate (Jeff Barry, personal communication, 2006). Brown (2005) found that a transmissivity ranging from 5,000 to 25,000 ft^2/d (315 to 430 m^2/day) is most suitable for ASR. It should also be noted that the size of the project will also influence which transmissivity is suitable; a project that needs to store a small volume of water may be able to use an aquifer with lower transmissivity than a project that needs to store a larger volume.

Among the 12 Oregon ASR sites, the lowest transmissivity is found in Tigard, with 870 ft^2/d (80 m^2/d); the highest transmissivity is found in Beaverton with 65,600 ft^2/d (6,100 m^2/d); the average is 19,900 ft^2/d (1,850 m^2/d). This wide range illustrates not only the significant variability in Columbia River Basalt's transmissivity, but also the adaptability of ASR to different aquifer environments.

Geologic Structures' Influence on ASR

Geologic structures can act as groundwater boundaries or conduits. Faults can be flowing fracture zones that leak to the surface or connect storage zones at different depths when influenced by the increased pressure of ASR injection. They can also be sealed by fault gouge clays and rendered impermeable, decreasing aquifer storage capacity.

Tualatin Valley Water District (TVWD) completed a series of ASR tests reported in 1997 (CH2M Hill, 1997) which utilized faulted Columbia River Basalt aquifers. Extensive faulting with offset greater than 1,000 ft (305 m) truncates the storage zone, and provided escape paths to the surface. This structural effect was discovered when a spring developed during injection about 2,700 ft (820 m) from the ASR well. The spring's flow decreased after injection was halted. The project had planned to store up to 100 million gallons (378,500 m^3), but testing revealed its storage was limited to 10 or 20 million gallons (37,850 to 15,700 m^3) due to these previously unknown aquifer boundaries and the leaky confined nature of the storage zone. In this case, aquifer compartmentalization by faults significantly decreased the aquifer's storage capacity (Groundwater Solutions, Inc., 2003b).

ASR tests in Baker City, Tigard, and Echo Junction (Groundwater Solutions, Inc, 2003a; Golder Associates, Inc., 2001; CH2M Hill, 1993) also noted fault truncation of basalt aquifers, but testing found ASR was not limited by these structures. Echo Junction, in the Umatilla Basin, also displays significant folds in the basalts. Testing at the ASR wells has not revealed local effects of folds on storage capacity.

Water Quality Issues

Source water quality

As a rule, ASR in Oregon can only be conducted if injection water meets drinking water quality standards. This means that the easiest way to conduct ASR is at a water treatment plant, or to use water that is produced for municipal use at such a plant. Generally, ASR source water is the same that is used for municipal supplies, so water quality issues are known and addressed within the existing systems. Therefore, source water quality has not been a large hurdle for cities in Oregon implementing ASR, because the infrastructure was in place before ASR began.

On the other hand, agricultural ASR in Oregon has experienced significant source water quality issues because these projects do not have water treatment plants on-site. Both Madison Farms and McCarty Ranch, located near Echo Junction of the Umatilla Basin, use water from shallow alluvial collector wells as their source for injection water. This means irrigation water infiltrates into the soil, incorporates some of the nitrates from fertilizers, and then makes its way to the collector well. The infiltration process removes particulate matter, in effect filtering the water. This source water has nitrate levels that at times exceed the allotted 5 mg/L allowed by the original ASR limited license. In this case, the drinking water quality limit is 10 mg/L, and ASR limited licensing in Oregon requires that constituents in injection water not exceed 50% of drinking water standards. As a compromise, these two sites are authorized to inject water containing up to 7 mg/L of nitrate. Both projects have installed systems that measure recharge water quality and have the ability to shut down injection when nitrates exceed 7 mg/L (OWRD, 2004a, 2004b).

Even when injection water meets drinking water standards, there can still be geochemical issues stemming from the differences between source water and native groundwater. Source water for ASR is usually surface water, which has higher dissolved oxygen levels than native groundwater. Dissolved oxygen levels can interfere with ASR in several ways. Introducing oxygenated water into the anaerobic subsurface can cause geochemical reactions with the aquifer matrix. Air can also become entrained, meaning the air bubbles adhere to the aquifer matrix and reduce its permeability, which has been observed and so far not successfully remediated at Pendleton's Stillman ASR well (Pendleton Public Works Department, 2006). According to Pyne (1995, 2005), air entrainment can be avoided by installing a down-hole injection pipe that prevents water from "cascading" into the well, a process that oxygenates water. However, in Pendleton's case this approach has not remedied the problem.

Turbidity in source water has been addressed by water treatment plants at municipal ASR sites in Oregon, including Portland and Baker City. During storm events, water from Bull Run River (Portland's source water) or the springs that supply Baker City can become quite turbid, and the project managers opt to shut down operations until the slug of suspended sediment passes the intake pipes (Groundwater Solutions, Inc., 2003).

Native groundwater quality

Native groundwater can contain heavy metals, salts, nitrate or other constituents in levels above drinking water standards. These dissolved components can pose health threats, or they can be aesthetic concerns for water consumers. In order to use such an aquifer for ASR, it must be possible to maintain a "bubble" of high quality injected water near the well for recovery. The term "recovery efficiency" refers to the percentage of injected water that can be recovered and still meet drinking water quality standards. Sites often evaluate the success of storage in substandard water quality aquifers by their recovery efficiency. The cost/benefit analysis has to consider whether the cost of ASR is balanced by the benefit of the recovered portion of the water. When recovery efficiency dips too low, ASR in non-potable aquifers may not be economically viable. On the other

hand, extensive experience with this technique in Florida, demonstrates that despite the losses to mixing and diffusion during storage, these projects can be beneficial.

According to Kimbler et al. (1975), success of saline storage sites is dependent on five hydrogeologic factors: diffusion rate, groundwater gradient, separation of injected and native waters by density differences, low angle of aquifer dip and aquifer storage zone thickness. Subsequent work (Wood et al., 1990; Haggerty and Gorelick, 1995; Zinn et al., 2004) has found that aquifer heterogeneity can also impact solute transport and the resulting recovered water quality. For example, as high quality water is injected into an aquifer, it may move lower quality native ground water out of zones of high hydraulic conductivity through advection, while the native water will move more slowly by advection through low conductivity zones. This means that when stored water is recovered, some of the lower quality water will remain within the injected bubble, and degrade its overall quality through processes of both advection and diffusion.

An example of brackish native groundwater can be found in Dallas, Oregon, where ASR testing began in 2005. This project is unique to Oregon because it is the first to store drinking water in an aquifer containing non-potable native groundwater. The receiving aquifer is Siletz River volcanics, and native groundwater contains levels of chloride greater than secondary drinking water standards. This presents mixing challenges, which decrease the volume of potable water that can be recovered at the ASR well. At this site, project managers have found that they can minimize the mixing that results from ASR operations by limiting injection and recovery rates. In this case, the rate has been held around 168 gpm (916 m^3/d), which is well below the rate most projects use; injection rates at other Oregon projects range from 400 to 2,750 gpm (2,180 to 14,988 m^3/d). Recovery efficiency at Dallas ranges from 23 to 50%, meaning 23 to 50% of the water injected can be recovered at the same well. The city has found it can extend the usefulness of ASR water by recovering stored water until it reaches 2,000 mg/L of chloride. This water is mixed with other sources of water in the municipal system to dilute the chloride to acceptable levels (Golder Associates, Inc., 2007). Water mixing is often employed by municipalities to dilute undesirable constituents, either for safety or to accommodate the public's expectations of consistent water flavor.

Recovered water quality

Water recovered after storage can include undesirable constituents dissolved from the aquifer matrix or acquired through mixing and diffusion with the native groundwater. This is another reason ASR is most feasible at water treatment plants. Recovered water can then be treated as needed before it enters the distribution system.

ASR testing by Clackamas River Water found radon in recovered water at concentrations greater than 300 piC/L (Groundwater Solutions, Inc., 2006b), which is the suggested drinking water limit in Oregon (Oregon Health Division, 1998). In this case, radon is naturally occurring in the groundwater environment, and the gas dissolves into injected water during its storage period. In their Annual Report for Clackamas River Water's ASR, Groundwater Solutions, Inc. (2006b) proposed that the recovered water be aerated to release the radon acquired during storage, indicating this issue may not be a serious threat to the project. According to the U.S. Environmental Protection Agency, radon in drinking water represents a minor portion of total radon found in indoor environments, and poses a threat mostly when it is released into the air such as during a shower or washing clothing (Oregon Health Division, 1998).

Tualatin Valley Water District (TVWD) experienced customer complaints when ASR water increased the hardness of the municipal supply (CH2M Hill, 2000b), but this was an aesthetic concern more than a health risk. It was remedied by mixing ASR water with other supplies to minimize the effect.

Portland found slightly elevated levels of sulfate in recovered water, in amounts less than 10 mg/L. This was attributed to interaction between the injected water, which had dissolved oxygen at higher concentrations than native groundwater, and pyrite in the aquifer matrix. However, there were no exceedences of primary drinking water quality standards during recovery operations (Golder Associates, Inc., 2003).

Clogging Issues

One of the most common problems during ASR is decreased permeability of the well or aquifer during and after injection. Partial clogging of well screens, gravel pack around the well or of the aquifer matrix itself can be caused by injection of sediment

suspended in the water, air trapping in pores, mineral precipitation triggered by injection water, temperature differences between injected and native ground waters, or biological activity (Pyne, 2005). Clogging is often reversible by back flushing the well, meaning that the well can be pumped at a high rate to pull the clogging materials back out of the well, or chemical treatment can be employed to remediate or prevent the condition.

According to Foxworthy (1970), Salem experienced some clogging issues in the early stages of ASR. Permeability was decreased by sediment suspended in the injected water clogging the well and aquifer. The problem was remedied by back-flushing the well to remove the injected particles and subsequently, source water was filtered before injection. Later tests (Golder Associates, 1994) found no further clogging issues.

Portland's ASR site at the Columbia South Shore well field also experienced some clogging. Geochemical interactions between the Troutdale Sandstone and the oxygenated injection water caused some precipitation of iron minerals that reduced specific capacity of the well (CH2M Hill, 2000a). Water treatment of the source water was necessary to prevent further mineral precipitation. However, the project was discontinued because the city can currently meet its water supply needs with other existing systems, so this issue may not have been addressed. It should be noted that this site had a very shallow water table (about 5 ft below the surface) combined with low transmissivity; there did not appear to be sufficient storage capacity in this aquifer for large-scale ASR.

ASR tests conducted by the U.S. Geological Survey at The Dalles, Oregon found temperature differences between injection and native groundwater decreased the specific capacity of the well. The source water was colder than groundwater, and therefore more viscous, which had the effect of decreasing the rate at which water could move through the aquifer (Foxworthy, 1967). This site is not currently conducting ASR, but an adjustment in the source water temperature would probably prevent this decrease in flow rate.

Public Concerns

ASR is a relatively new technology, and its impact on land and water users can be a concern. Water in Oregon is managed as a public resource, so one user's impact on others is considered. During the licensing process, a public notice is released and input is considered before issuance of a limited license by the state. In the 12 licensing processes experienced in Oregon so far, there have been relatively few expressed public concerns. Another source of public input is during ASR tests, when occasionally there are noticeable effects on other users in the area. Examples include water level rise in nearby wells, new springs forming on the surface during injection (rare), and the impact of using source water either on fish or other water supply to other users.

Baker City received more input than any other ASR application to date. The project is unique because the city collects water from seven different springs and creeks, and transports this water to town through several miles of pipeline. There was great concern from neighbors and other users that spring water withdrawn by the city would impact their resources, and also that the city would waste water through leaks in the pipeline and back flushing operations at the ASR well (Scanlon Engineering, 2003). In this case, the city received a permit which required some actions to limit waste and the impact on existing users (OWRD, 2004c).

Sunrise Water Authority, located southeast of Portland, also received public input concerning the withdrawal of river water from fish habitat. These concerns were evaluated and not deemed a significant barrier to ASR (OWRD, 2007).

Recent tests in Tigard revealed water level rise in a nearby undocumented well, meaning one that was not recorded by the state, so its existence was not incorporated into the ASR plan for Tigard. During injection, landowners reported water levels rising to the surface at the undocumented well. The ASR project created an artesian well at this location, meaning that the well owners needed to install new plumbing equipment to control the outflow of water. The city of Tigard is currently working with the landowner to adapt or cap the well as needed (Donn Miller, personal communication, 2007).

ASR outside of Oregon

In addition to Oregon sites, published case studies for 38 other ASR sites were compiled for this study, to ascertain common parameters and potentially systematic problems. Because Oregon ASR has focused on basalt aquifers, it is necessary to look elsewhere for information about other types of systems. Data compiled for this study about ASR sites outside of Oregon include sites from the U.S. and around the world that have published test results (Figure 2-3, Appendix A).

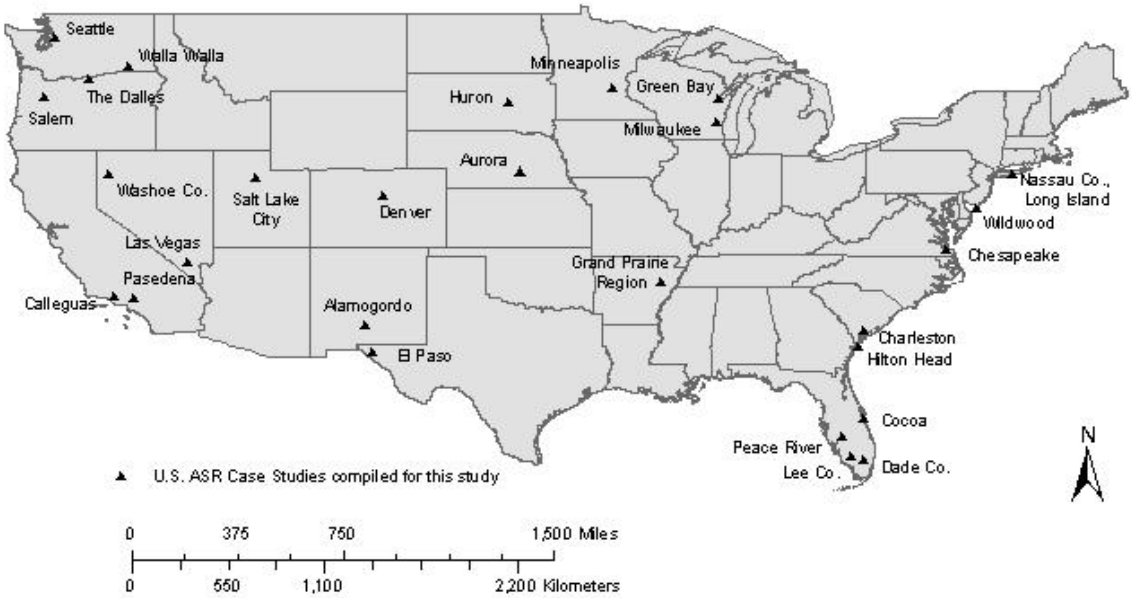


Figure 2-3. ASR case studies in the U.S. ASR locations compiled from outside the U.S. include the United Kingdom, Kuwait, Australia, Namibia, Brazil, Puerto Rico, The Netherlands, and Canada (Map Data source: U.S. Geological Survey, 1999).

Aquifer Lithology

Outside of Oregon, aquifers of various lithologies have been employed for ASR projects. It is useful to examine these sites to understand the range of possible storage zone characteristics, and the potential problems unique to certain lithologies.

Limestone aquifers have been utilized in Charleston, South Carolina; throughout the United Kingdom; Adelaide, Australia; several counties in Florida; Kuwait; and Arecibo, Puerto Rico (Quinones-Aponte, 1989; Pyne, 2005; Fitzpatrick, 1986; Merritt, 1997; Campbell et al., 1997; Mukhopadhyay, 1998; Gale et al., 2002; Gerges et al.,

2002). Limestone aquifers at these ASR sites contain brackish groundwater. This presents native groundwater quality issues, but hydraulically the karst formations in Florida provide extremely transmissive groundwater environments which have proved suitable for ASR in some locations. Lee County, FL found injection into the limestone aquifer decreased the specific capacity of the well, most likely due to dissolution and subsequent re-precipitation of calcium minerals. The problem was remedied by injecting low pH water into the aquifer to dissolve the clogging precipitates (Fitzpatrick, 1986). There is little limestone in Oregon, excepting small exposures in the Blue Mountains of northeast and southwest Oregon.

Sandstone has been used for ASR in Denver, Colorado; Green Bay and Milwaukee, Wisconsin; the United Kingdom and South Goulburn Island, Australia (CH2M Hill, 1999; Gale et al., 2002; Pavelic et al., 2002; Brown, 2005). These units are confined to semi-confined, which is advantageous for ASR because injected water is less likely to find a pathway to discharge at the surface. The common problem in sandstone ASR projects seems to be geochemical: reactions between injection water and the aquifer matrix either clog the aquifer or degrade water quality during storage. The ASR project in Green Bay, Wisconsin's sandstone aquifer found the recovery of heavy metals from pyrite in the aquifer rendered the site infeasible (CH2M Hill, 1999). Milwaukee noted no major problems stemming from storing surface water in a sandstone aquifer (Miller, 2001). Pavelic et al. (2002) found the sandstones at South Goulburn Island reacted with injected water to form iron oxyhydroxide deposits, which decreased permeability. Periodic back flushing of the well during the storage period was sufficient to maintain adequate permeability. Tertiary sandstone aquifers are found throughout the state of Oregon, with the largest exposures in Malheur River, Goose and Summer Lakes, Umatilla, Hood, and John Day Basins, in addition to coastal outcrops. Based on the experience elsewhere, it appears ASR may be feasible in these formations, but geochemical reactions will have to be carefully monitored.

Sand and gravel aquifers, both confined and unconfined have been targeted for ASR in Long Island, New York; Seattle, Washington; Salt Lake City, Utah; Washoe County, Nevada; Huron, South Dakota; Las Vegas, Nevada; Calleguas, California;

Lancaster, California; Myrtle Beach, South Carolina; Wildwood, New Jersey; Aurora, Nebraska; Pasadena, California; The Netherlands; El Paso, Texas; Grande Prairie, Arkansas and Mannheim, Ontario (Sneigocki, 1964; Lichtler et al., 1980; Schneider et al., 1987; Pyne, 1995; Castro, 1995; Palmer et al., 1997; Wooton et al., 1997; Baquai, 2002; Saaltink et al., 2003; Brown, 2005; Sheng, 2005). Sand and gravel aquifers tend to have moderate to high permeability, depending on the deposits' grain size and degree of sorting.

Several sites have successfully utilized sand and gravel aquifers for ASR. Tests in Alamogordo, New Mexico utilized an unconfined basin-fill aquifer that did not encounter serious difficulties, but rather enabled the municipality to fully utilize their water allocation by storing unused portions during low demand periods (Brown, 2005). A project in the Grand Prairie Region, Arkansas conducted 18 years of testing and found ASR was successful in recharging the over-drafted sand and gravel aquifer in conjunction with surface spreading AR operations (Sneigocki, 1964; Sneigocki et al., 1965).

There are also examples of problems encountered during ASR due to the sand and gravel aquifer type. Washoe County, Nevada attempted an ASR project to replenish an over-drafted sand and gravel aquifer. Unfortunately, the surficial aquifer and soil had fractured during subsidence caused by groundwater declines, and injected water leaked through these fractures before adequate storage was obtained (Brown, 2005). Tests in Huron, South Dakota found despite the confined nature of the aquifer, naturally high water levels limited the storage capacity. Many of the alluvial aquifers in Oregon have high water tables that may experience a similar limitation, but areas that are experiencing groundwater decline have not yet reported subsidence.

Fractured rock aquifers are the least common aquifer type for artificial recharge projects. They have been used in the Federal District of Brazil and Windhoek, Namibia (Cadamuro et al., 2002; Murray and Tredoux, 2002). Cadamuro et al. (2002) found that ASR was feasible in the fractured quartzites of the Federal District of Brazil, with no adverse effects to date. The project in Windhoek stores desalinated water in a fractured quartzite and schist aquifer, with no reported negative impact. These experiences may

shed light on areas in the southwest of Oregon, where bedrock aquifers tend to be highly fractured, low permeability metamorphic units.

Basalt aquifers have been used in Oregon as discussed in the previous section, and also in Walla Walla, Washington (Price, 1961). Price (1961) concluded from ASR tests in the Columbia River Basalt that despite possible structural boundaries, the aquifer was entirely suitable for ASR.

Transmissivity

Transmissivity at ASR projects varies widely. The average transmissivity for all the studies complied by this study is 14,800 ft^2/d with standard deviation of 18,740 ft^2/d (1,380 m^2/d, standard deviation of 1,700 m^2/d). While Brown et al. (2005) find the most suitable range of transmissivity for ASR is 5,000 to 25,000 ft^2/d (315 to 430 m^2/d) the results of this study indicate that while this range is ideal, there are examples that fall outside this range, given other appropriate parameters.

The lowest transmissivity found by this study is 220 ft^2/d (20 m^2/d), in Charleston, South Carolina's limestone and sand aquifer. However, recovery efficiency, or percentage of injected water recovered ranged from 94 to 110%; indicating that despite the low permeability this project was considered successful (Campbell et al., 1997). Charleston is followed by the fractured quartzite units in Windhoek, Namibia with transmissivity of 650 ft^2/d (60 m^2/d; Murray and Tredoux, 2002), and the sandstone aquifer at South Goulburn Island, Australia with 750 ft^2/d (70 m^2/d; Pavelic et al., 2002).

Denver, Colorado's Highland Ranch ASR site experienced problems caused by the low transmissivity (1,000 ft^2/d or 90 m^2/d) in the sandstone aquifer. Clogging due to geochemical reactions further reduced permeability and the pressure of injection fractured the aquifer, creating secondary problems associated with the new fractures (Brown, 2005).

The highest transmissivity recorded by this study is in a Cretaceous Chalk aquifer in the United Kingdom 67,300 ft^2/d (6,250 m^2/d) (Gale et al., 2002). This chalk aquifer contained non-potable groundwater, and the recovered water had to be treated to improve water quality. The high transmissivity may have contributed to the mixing and dispersion

rates during ASR. Beaverton, Oregon basalt is a close second at 65,600 ft^2/d (6,100 m^2/d) (CH2M Hill, 1997), with no reported adverse effects. This is followed by an alluvial sedimentary aquifer in Manheim, Ontario at 59,200 ft^2/d (5,500 m^2/d) (Wooton et al., 1997).

Geologic Structures' Influence on ASR

As discussed in the Oregon ASR case study section, geologic structures can control the size of projects, especially by fault truncation of aquifer storage zones. Unanticipated hydraulic connection between aquifers can also be problematic. Injected water may escape from the storage zone and can potentially create undesirable springs at the surface by following fractures as preferential flow paths.

Windhoek, Namibia's ASR project found that during injection into the fractured quartzites, the flow path was controlled by thrust faults. Apparently, the faults created the most permeable zones in the aquifer. The project intends to replenish an over drafted aquifer which extends under the city and the nearby Aaus Mountain range. The thrust faults parallel the aquifer units, and therefore project managers use these as conduits for injected water (Murray and Tredoux, 2002).

Washoe County, Nevada (Brown, 2005) ASR was rendered impossible when injected water escaped the storage zone through fractures. Land subsidence caused by previous aquifer over drafting created soil fractures that created an escape path for injected water to reach the surface.

Water Quality Issues

Source water quality

Quality of source water can have a profound effect on ASR projects, by affecting the well and aquifer hydraulics or increasing water treatment expenses. Most projects are located at water treatment plants, because it is the most efficient way to address water quality during injection and recovery periods.

Seattle, Washington experienced high levels of algae in the source water, which is drawn from Lake Youngs Reservoir. Algae decreased the permeability at the well during

injection. The project has been relegated to an emergency supply for the city after conservation and efficiency measures decreased the overall demand. ASR is not currently necessary to meet dry season needs for this reason, but the site is maintained for use during drought or natural disasters that may affect above ground storage facilities (Brown, 2005; Pyne, 2005).

Tests at Grand Prairie, Arkansas found the recharge water temperature was lower than native groundwater temperature. This decreased the aquifer hydraulic conductivity, because colder water is more viscous (Sneigocki, 1964, Sneigocki et al., 1965).

Wildwood, New Jersey has been operating 4 ASR wells since 1968. Over time, the permeability of the well and aquifer has been gradually decreasing due to iron in the source water. However, the project continues to be useful as a salinity barrier in the coastal area (Pyne, 2005).

Native groundwater quality

As discussed in the previous section, heavy metals in native groundwater have rendered some ASR sites unsuitable, while in other cases it has been remedied. Salinity issues have also been successfully addressed in many projects. Brown (2005) reported 29 ASR sites worldwide that are storing fresh water in brackish aquifers. This study has examined some of those brackish sites, because Oregon does have brackish aquifers that are beginning to be used for ASR, as found in Dallas, Oregon.

In Lee County, Florida, freshwater stored in a brackish aquifer has been successfully recovered (Fitzpatrick, 1986). Mukhopadhyay et al. (1998) reported similar success in a Kuwait project that injects desalinated seawater into a brackish aquifer. Charleston, South Carolina has been successfully injecting and recovering fresh water into a brackish limestone aquifer since 1993 (Campbell et al., 1997).

Palmer et al. (1997) found that ASR north of Pasadena, California in an alluvial aquifer was limited by nitrate levels in the groundwater. However, after testing it was concluded that ASR actually improved groundwater quality by diluting nitrates to below drinking water standards through in-situ mixing in the aquifer.

Langerak, The Netherlands injects water into a sand aquifer where the native groundwater is saturated with respect to calcium. Initial tests found that injection water dissolved calcite from the aquifer, re-precipitated it and decreased aquifer permeability. This was remedied by saturating injection water with respect to calcium to prevent further dissolution (Saaltink et al., 2003).

Tests by the British Geological Survey storing water in Cretaceous chalk aquifers found that native brackish groundwater degraded injection water to the extent that recovered water had to be treated (Gale et al., 2002). Hydraulically the ASR site was feasible but water quality issues due to the native groundwater were a significant hurdle.

Recovered water quality

Stuyfzand et al. (2002) found high levels of dissolved iron, manganese and ammonia at a test site in the Southern Netherlands, which had dissolved from pyritiferous sands in recovered water. These reactions prevented the continuation of ASR. In Green Bay, Wisconsin, ASR operations were rendered unsustainable due to oxidation of heavy metals from pyrite in the aquifer (CH2M Hill, 1999).

ASR testing in Arecibo, Puerto Rico, in a fractured quartzite aquifer found that recovered water was not potable due to chemical reactions that occurred during storage. However, the project determined that injection served as a salinity intrusion barrier. Despite hydraulic suitability, poor recovered water quality prevented ASR being used for drinking water.

Pyne (2005) found ASR at Chesapeake, Virginia mobilized manganese from the sand aquifer. Tests concluded that maintaining pH less than 8 in the injection water reduced the manganese content of recovered water. Some water treatment was also required after recovery to meet safe drinking water standards.

Clogging Issues

One undesirable side effect of ASR can be the clogging of aquifer pores by sediment, air, mineral precipitation triggered by injection water, or biological activity.

Walla Walla, Washington (Price, 1961) reported clogging and subsequent reduced specific capacity of wells in basalt aquifers due to sediment in injection water clogging aquifer pores. This decrease in permeability was reversed by back flushing the well, and subsequent injections included a filtration process to prevent introducing sediment into the well. More recent tests have not reported this problem.

Air entrainment, a process where air bubbles in injection water attach to aquifer particles, effectively reducing the porosity, was reported in Manheim, Ontario (Wooton et al., 1997) and Walla Walla, Washington (Price, 1961). Both authors reported that adding injection mechanisms that prevent water from cascading down the well greatly reduced air entrainment and subsequent aquifer clogging.

Mineral dissolution and subsequent precipitation is another common clogging mechanism that can decrease aquifer and well screen permeability. Geochemical reactions can be driven by introducing oxidized water into an anaerobic aquifer environment, by changing the pH of the groundwater, or by introducing water with different mineral concentrations than the native groundwater. In South Goulburn Island, Australia, Pavelic et al. (2002) reported clogging by oxyhydroxide formation. Periodic backflushing remedied the problem, and is a necessary ongoing part of the ASR operation. In Chesapeake, Virginia, Pyne (1995) recorded manganese mobilization caused by injection water with pH greater than 8.0. Decreasing the pH of injection water halted Mn precipitation and aquifer clogging.

Temperature differences between injected and native water can also trigger mineral precipitation or changes in viscosity that ultimately decrease a well's specific capacity. In Callegas, California Pyne (1995) reported a reduction in transmissivity after injection due to an 11 °F (3 °C) temperature difference between injected and native groundwater. In the Grande Prairie Region, Arkansas, low temperature injection water decreased specific capacity at the well (Sneigocki, 1964, Sneigocki et al., 1965).

Bacteria and algae can propagate in well casings or anaerobically in the aquifer to decrease permeability. In Nassau County, New York, biological activity clogged the aquifer and led to abandonment of the ASR project (Aronsen et al., 1983). Further investigation reported by Schneider et al.(1987) discovered that AR through surface

spreading basins was more successful in recharging the sand aquifer, with less clogging and lower operation costs.

CHAPTER 3
ASR SITE SCREENING METHODS

Introduction

The state-wide scope of this study required a combination of assessment tools to produce meaningful results. Site assessment methods employed by this study include both quantitative and qualitative methods. The two main tools employed were a site rating system adapted from Brown et al. (2005) and volumetric analysis developed by this study. Secondary tools include a site evaluation decision tree system developed by this study and the comparison to existing ASR case studies.

Brown's Site Rating System

Brown et al. (2005) created a site screening tool that incorporates several ASR feasibility factors into a numerical rating system. This system was designed for the Florida Everglades restoration project, where large scale ASR well fields are planned to replenish wetlands. Although this system was designed specifically for southern Florida conditions, it has more universal applications. It has been adapted for this study to fit smaller scale ASR projects likely to occur in Oregon for water supply purposes. Table 3-1 illustrates the original system as Brown designed it for Florida, and the modifications that have made it applicable to Oregon ASR.

Pass/Fail Screening Criteria

The first stage of rating a site looks at critical factors that could render a site unsuitable for ASR. Brown's version has three criteria, the version adapted for Oregon has two.

Distance to Source Water

The distance to source water must be less than 3 mi (4.8 km) for a potential site to pass the first criteria. This addresses the cost involved in moving water large distances. It should be noted that there may be cases in the future where investment in pipelines or canals may be deemed worthwhile.

Table 3-1. Brown's site rating system.

Brown et al. (2005) **Developed for Florida Everglades**	**This Study** **Adapted for Oregon Conditions**
PASS/FAIL SCREENING 1. Distance from source water to well < 3 miles 2. Minimum project size = 5 acres 3. Land Use is NOT urban, subdivisions, Lakes wetlands, coastal habitat, landfills	PASS/FAIL SCREENING 1. The same as Brown 2. Not applicable to Oregon 3. Land Use is NOT Lakes, wetlands, landfill, protected habitat
SECONDARY SITE EVALUATION **Ecological Suitability** 0 = very likely habitat of protected species 1 = somewhat likely 2 = not likely	SECONDARY SITE EVALUATION The same as Brown
Well Density 0 = more than 5 wells per square mile 1 = 1 to 5 wells 2 = no wells	The same as Brown
Source Water Quality 0 = meets no drinking water standards 1 = meets some standards 2 = meets all standards	The same as Brown
Ground Water Quality 0 = meets no drinking water standards 1 = meets some standards 2 = meets all standards	The same as Brown
Road Density 0 = low density 1 = medium density 2 = high density	Not applicable to Oregon
Proximity to Power Lines 0 = not adjacent to lines 1 = near small KVA city lines 2 = near major transmission lines	Not applicable to Oregon
Transmissivity 0 = T < 5,000 ft^2/d or T > 25,000 ft^2/d (No 1) 2 = 5,000 ft^2/d < T < 25,000 ft^2/d	The same as Brown
Distance to Source Water (No 0) 1 = all others 2 = Source is near Lake Okeechobee Not included in published system for the Everglades, but outlined in Brown (2005), and supported by Aspect Consulting, LLC (2005) in Washington State. Not included in Brown et al. (2005), but outlined in Brown (2005).	**Distance to Source Water** 0 = distance > 3 miles 1 = 1 mile < distance to source < 3 miles 2 = distance to source < 1 mile **Hydraulic Gradient** 0 = Gradient > 0.01 1 = 0.01 to 0.001 2 = Gradient < 0.001 **Aquifer Thickness** 0 = Aquifer < 25 feet thick (No 1) 2 = Aquifer > 25 feet thick

Minimum acreage

The system for the Florida everglades requires a minimum of 5 acres (0.2 km^2) to install an ASR well field. However, projects in Oregon that are of interest to this study are smaller scale water storage operations. There are existing sites in Oregon that occupy only a city lot (Donn Miller, personal communication, 2007); therefore this criterion was eliminated for Oregon's study.

Land Use

The third pass/fail criteria in Brown's system examines land use constraints; eliminations are based on land uses including urban, suburban land, wetlands, lakes, reservoirs, streams, protected wildlife habitat, and landfills. Urban and suburban land is not disqualified from this study.

Secondary Site Evaluation Process

Once a site has passed the first level of screening, secondary evaluation criteria are applied. Each criterion has a numerical rating system, as illustrated in Table 3-1, and the details of each are discussed below. This study has expressed the results as a percentage of ideal ASR site characteristics. It is important to note that some suitability factors can be improved with investment in infrastructure. The rating system evaluates the situation according to current conditions; a low score indicates the need for more investment than a high score, especially if the root of the low score is from source water quality, distance to source water or well density. Low scores in these areas can be improved by investment in infrastructure. Other factors that might cause a low score, such as transmissivity, hydraulic gradient and aquifer thickness cannot be easily remedied.

Ecological Suitability

This criterion examines the likelihood that an ASR project might adversely affect a protected species or habitat. In Oregon this often includes fish habitat, which can be affected by stream withdrawal; the timing of changes in flow volume and temperature are

critical to many species' survival. This factor is easiest to evaluate in areas that have already experienced fish declines, but it is safe to assume that most streams in Oregon have some fish that are vulnerable to flow changes.

Well Density

Well Density is an indication of the likelihood that an ASR project could affect nearby wells' water levels. It also suggests how secure the stored water is from "piracy", or withdrawal by wells not associated with the storage and recovery project. Well density was estimated by this study from OWRD well log data by counting the number of wells in the same township, range and section as the well of interest; only those with similar open interval depths and therefore located in approximately the same aquifer were counted. If well density is high in the aquifer of interest, feasibility may increase by considering deeper, less densely developed aquifers.

Source Water Quality

The assessment of the potential for chemical interaction between groundwater, injected water and the aquifer matrix is beyond the scope this study. However, this criterion examines the source water quality in general terms of the degree to which it meets or does not meet drinking water quality standards. Since source water has to be treated to drinking water quality before injection in Oregon, this gives some indication of how much a stake holder may have to invest in water treatment before operating an ASR project. If source water does not meet drinking water standards, and it will not unless the source is a treatment plant, investment is required to build or expand water treatment facilities before ASR can begin.

Ground Water Quality

Ground water quality is also assessed in terms of the degree to which it meets drinking water quality standards. If native ground water quality is poor, this cannot be remedied. However, many ASR projects utilize brackish aquifers by maintaining a "bubble" of high quality injected water around the well. According to Pyne (1995,

2005), ASR has been successfully employed in aquifers of poor ground water quality, but some stored water is lost due to mixing of injected water with native water.

Transmissivity

The permeability of the aquifer is of utmost importance to the success of an ASR system. Transmissivity is proportional to permeability, also accounting for the fluid properties of viscosity and density, and the aquifer thickness. Transmissivity has units of volume per time per width, for example $ft^3/d/ft$ or more simply, ft^2/d. According to Brown et al.(2005), the ideal transmissivity range is 5,000 ft^2/d to 25,000 ft^2/d (465 to 2,323 m^2/d). Brown provides an upper limit to transmissivity because in cases where the receiving aquifer contains low quality water, high transmissivity may allow the high quality injection water to escape the well's radius of influence during the storage period. While values above and below this range may be feasible is some situations, this range offers the best chance for ASR success.

Distance to Source Water

The shortest distance between source water and an injection well is the least expensive project to install. An ASR project is most feasible when the source water is less than 3 mi (4.8 km) from the injection wells, but even this distance may be prohibitively expensive for some stakeholders (Brown et al., 2005).

Hydraulic Gradient

Brown (2005) found the ideal hydraulic gradient for ASR is less than 0.001. An ASR modeling study by Aspect Consulting, LLC (2005), examined basalt aquifers in eastern Washington with a hydraulic gradient of 0.0013, with a 90-day injection period, a 60-day storage period, and a 60-day recovery period. The study found 89 percent of stored water was recovered at the same well. The same situation modeled with a 0.015 hydraulic gradient resulted in zero percent recovery. This supports Brown's criteria, and therefore is included in this study.

Aquifer Thickness

The ideal aquifer thickness for ASR is greater than 25 ft (7.6 m). This is because a thin aquifer forces injected water to spread out horizontally, and water may produce a large diameter "injection bubble". This increases the likelihood that stored water will escape the influence of the injection well, and also may move the water into the range of neighboring wells. Aquifer thickness is defined as the open interval of the well in this study. It may still be feasible to use a thin aquifer for ASR, but it would require careful study to ensure that the stored water is recoverable.

Aquifer thickness helps bound the lower end of transmissivities. For example, if an aquifer transmits water at a lower rate than may be desirable, its large thickness may compensate for slow rate of flow by providing more storage volume. Conversely, an aquifer that transmits water at a high rate could be thin and still useful.

It is important to note that some criteria in Brown's system overlap, for example transmissivity quantitatively includes aquifer thickness, and yet aquifer thickness is considered as a separate criterion. This provides a useful balance, because an aquifer with a high transmissivity may also be a thin aquifer, which could result in injection water traveling outside the well's influence. The high transmissivity may be suitable to accepting water, but the thin (< 25 ft or 7.6 m) aquifer may be less suitable for ASR. Well density and aquifer thickness are a similar example. While a thin aquifer may increase the chance of water escaping into neighboring wells due to a large diameter storage bubble, if well density is low, then this may counteract the risk of losing water to other wells. The two factors are evaluated separately to accommodate this relationship.

Brown's system was applied to ASR case study data to provide background information for comparison to new site assessments. The fact that existing sites have from 43% to 88% of ideal parameters indicates that there is a wide range of feasible sites. Potential ASR sites in Oregon are compared to these results in later chapters.

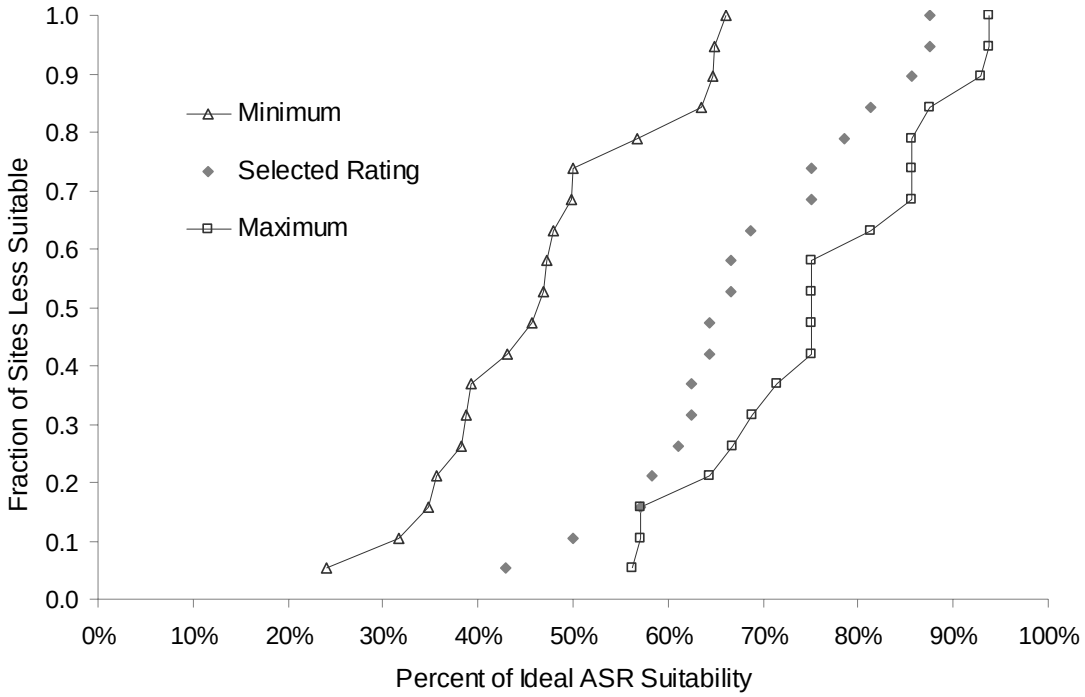


Figure 3-1. Case studies' results from Brown's site rating system. Existing ASR sites have from 43 to 88% of ideal parameters. Uncertainty ranges from +/- 5 to 20%.

Uncertainty in Brown's site rating system

Uncertainty ranges from +/- 5 to 20% (Figure 3-1). This was evaluated by selecting the minimum and maximum reasonable rating for each parameter. Each evaluation criterion has uncertainty attached to its value, and some ratings are more qualitative than quantitative. Qualitative ratings are produced for land use, ecological suitability, and water quality. For example, the current land use is known if the site in question is a water treatment plant. However, if it is not, then the immediate area around a well chosen for analysis is assumed not to be a lake, wetland, or landfill, since none of these uses lend themselves to a feasible water well site. Ecological suitability is estimated from the known species in the river that would serve as the source water, the exact river reach where water is withdrawn was not examined for the presence of threatened species. Water quality is not based on lab test results, but rather the fact that if there is a water treatment plant, then the source water is assumed to meet all drinking water standards. If there is not a treatment plant it probably meets some drinking water

standards. A site is rated as meeting no drinking water standards if the source water was known to be contaminated or if the groundwater is saline or non-potable for another reason. There is some uncertainty in these ratings, but the system is set up in such a way that it assesses the site generally in these terms.

Other criteria are rated based on quantitative data points. Aquifer thickness is estimated from well log data which report the open intervals in the well, and the intrinsic assumption is that the well is fully penetrating the aquifer. This is reported by the driller at the time of well installation. Transmissivity is either estimated from the specific capacity reported in well logs or drawn from published reports when possible. Uncertainty is variable, and well logs are chosen with a preference for those that had conducted pump tests longer than one hour in duration, but this condition is not always met.

Distance to source water was estimated on a GIS, and uncertainty stems from locating the well without field verification. The number of analyses for this study prohibited field locating wells. It is assumed that the well location relative to source water could be acceptably estimated from township, range section information about the well.

Hydraulic gradient is estimated from published studies that have mapped hydraulic heads. In some cases, gradient was reported in published studies specific to certain wells. Uncertainty may stem from seasonal or longer term variations in water levels that are affected by hydraulic gradients.

ASR Metric Analysis

Another assessment tool developed by this study is an ASR metric. It provides another estimate of ASR feasibility before implementing detailed site specific tests. The metric incorporates data attained from well logs, water rights and availability databases and published hydrogeologic studies.

Theory

This ASR metric relates injection rates to potential groundwater storage rates. Volumetrically, a municipality or agricultural interest would need to store a minimum amount of water for it to be economically viable, and that volume would be injected over a given time. The aquifer has an intrinsic maximum storage rate, related to transmissivity and head space in the aquifer. As long as the volume of aquifer storage is larger than the volume of water to be stored, this could be a feasible ASR site.

An ASR metric describing this relationship between groundwater storage rates and injection rates can be derived from the Theis (1935) and Cooper-Jacob (1946) non-equilibrium equations. From Theis we know that in a confined, homogeneous, infinite aquifer of uniform thickness, the drawdown at a pumping well can be quantified as follows.

$$\Delta h = \frac{Q}{4\pi T}\int_{u}^{\infty} \frac{e^{-u}}{u} du = \frac{Q}{4\pi T} W(u) \tag{1}$$

where

$$W(u) = -0.5772 - \ln u + u - \frac{u^2}{2*2!} + \frac{u^3}{3*3!} - \frac{u^4}{4*4!} + \ldots \tag{2}$$

and

$$u = \frac{r^2 S}{4Tt} \tag{3}$$

where Δh = head change in the well, Q = constant well discharge as volume per time, T = transmissivity, r = radius of the well, t = time since pumping began, $W(u)$ = Well function, and S = storativity. Cooper and Jacob (1946) observed that at late time, or large values of t, u is very small. The third and higher order terms of the infinite series of the Theis equation becomes negligible. This leads to the Cooper-Jacob equation

$$\Delta h = \frac{Q}{4\pi T}\left(-0.5772 - \ln \frac{r^2 S}{4Tt}\right) \tag{4}$$

Converting to base ten logarithms it becomes

$$\Delta h = \frac{2.3Q}{4\pi T} \log \frac{2.25Tt}{r^2 S} = \frac{2.3Q}{4\pi T} F \tag{5}$$

This equation estimates whether an ASR project will or will not exceed the aquifer capacity to store water:

$$\text{ASR metric} = \frac{\max \Delta h}{\Delta h} \tag{6}$$

Where the denominator is the head change at the ASR well resulting from injection and the numerator is the maximum feasible head change in the well. From equation (5), Δh can be bracketed by the maximum and minimum reasonable parameters for ASR projects.

	Maximum Value from Case Study Data	Minimum Value from Case Study Data
Transmissivity (T) in ft^2/d	70,000	700
	Minimum Possible Value	Maximum Possible Value
Storativity (S)	0.0001	0.30
Well radius squared in ft $(r_w)^2$	$(0.25)^2$	$(2)^2$
	Maximum Possible Result for F	Minimum Possible Result for F
t = 120 days	15.3	5.2

Table 3-2. Determination of F factor in the ASR metric.

The range for *F* is determined by the fact that the largest value for *T* and the smallest values for *r* and *S* will result in the largest value of *F*. The converse is also true; the minimum *T* and the maximum *S* and *r* produce the minimum value for *F*. The value of *F*, for all practical purposes, spans a narrow range (Table 3-2). This range could be made smaller by excluding *T* from the unknowns, but we have chosen to make the metric as simple as possible. The most conservative value for *F* will minimize the ASR metric so as to exclude sites that are marginally feasible. Consequently, we chose twice the maximum *F*, 30.6, as an engineering safety factor. Equation (6) then becomes

$$\text{ASR Metric} = \frac{\max \Delta h}{\left(\frac{2.3Q}{4\pi T}\right)(30.6)} = \frac{T \max \Delta h}{5.6Q} \tag{7}$$

Although the ASR metric is rooted in the Theis equation for estimating drawdown for confined aquifers, it can also be applied to unconfined aquifers, using a drawdown conversion equation:

$$s = b - \left(b^2 - 2bs'\right)^{\frac{1}{2}} \tag{8}$$

where s is drawdown in an unconfined aquifer, b is the aquifer thickness, and s' is the drawdown calculated using the Theis solution as if it were a confined aquifer. This method is valid when the drawdown is much less than the aquifer thickness, the aquifer is homogeneous, infinite and flow is horizontal (Neuman, 1972, 1974, 1975).

In an unconfined aquifer, *h* cannot be brought above land surface. In a confined or semi-confined aquifer, it is possible to inject water until the potentiometric surface is above the land surface. However, this can cause artesian flow in neighboring wells, and create springs and seeps near the ASR well.

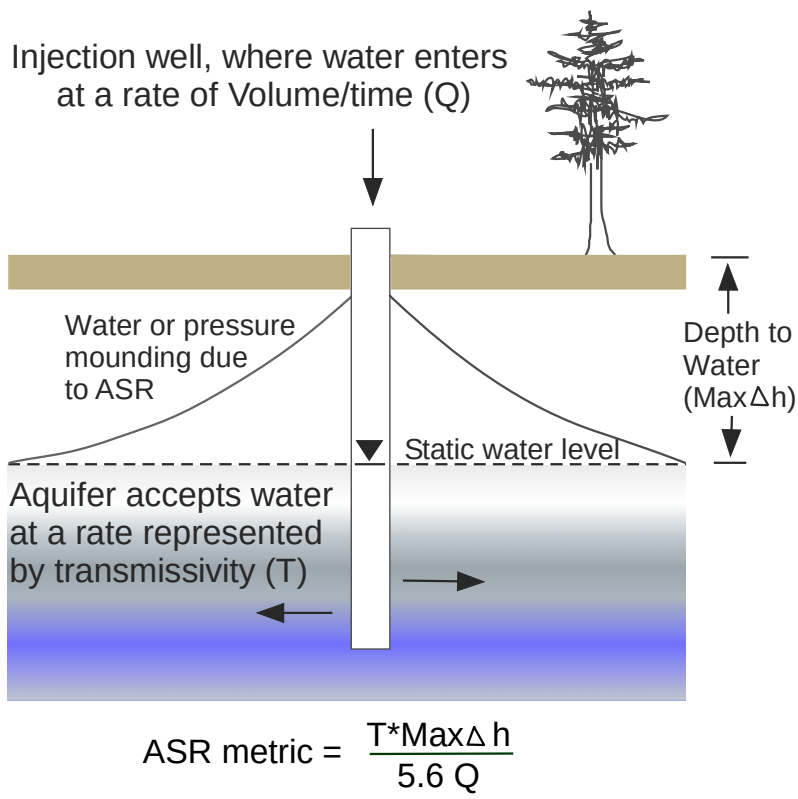


Figure 3-2. ASR metric methodology illustration. The metric compares the rate at which water is available to the rate at which water can be accepted by the aquifer.

Alternatively, the ASR metric can be more exactly calculated by removing transmissivity from the F factor. The ASR metric then appears as follows:

$$\text{Revised ASR Metric} = \frac{T \max \Delta h}{2.3Q(\log T + 2.35)} \tag{9}$$

Analyses for this study use the original ASR metric, because it is more conservative than the revised version. At a specific site, the revised version will be useful for future work.

The volume to be stored is theoretical in this study; it was approximated as ½ a municipalities' water treatment plant capacity for 120 days, or if that data were unavailable, as ½ a municipality's surface water rights for 120 days. The assumption is that during four months in the winter, a municipality might not be using ½ of the surface water they had rights to use, but could store that water for later withdrawal.

The metric provides an indication of whether the aquifer has sufficient storage for the available surface water. A result of "1" indicates that the volume to be injected is equal to the storage volume available in the aquifer. However, this result means the aquifer has marginally sufficient storage because raising the groundwater level to the surface would have the potential to create undesired effects such as water seeping into basements or releasing in newly formed springs. A result indicating ASR is volumetrically feasible is greater than "1", indicating the volume to be stored is less than the maximum available storage space in the aquifer. A result less than 1 indicates insufficient aquifer storage. In this case, the stakeholder will have to store less water or risk artesian conditions and seismicity.

It is important to note the limitations of this method. It is intended to consider only the physical potential for ASR; social needs, financial constraints, land use limitations, water quality and other important factors are not addressed. It also does not incorporate the influence of aquifer boundaries, which can significantly limit aquifer storage. The use of specific capacity to estimate transmissivity is another source of error. Low specific capacity may only indicate low well efficiency, rather than insufficient aquifer storage. Therefore, this site screening metric indicates an aquifer's minimum capacity for ASR.

This metric has been tested with ASR case study data, to verify its relevance. Published reports of successful ASR projects supplied the transmissivity, head space, injection volume and time. Most of these studies produced results greater than 1 (Figure 3-3). Portland has the least successful project according to the metric, with a result less than 1, and it has been abandoned by the city, although not for reported technical difficulties (Donn Miller, personal communication, 2007). However, Portland's site had a shallow depth to water (less than 10 ft) and a large volume to store, indicating the site was not compatible with the scale of the proposed project.

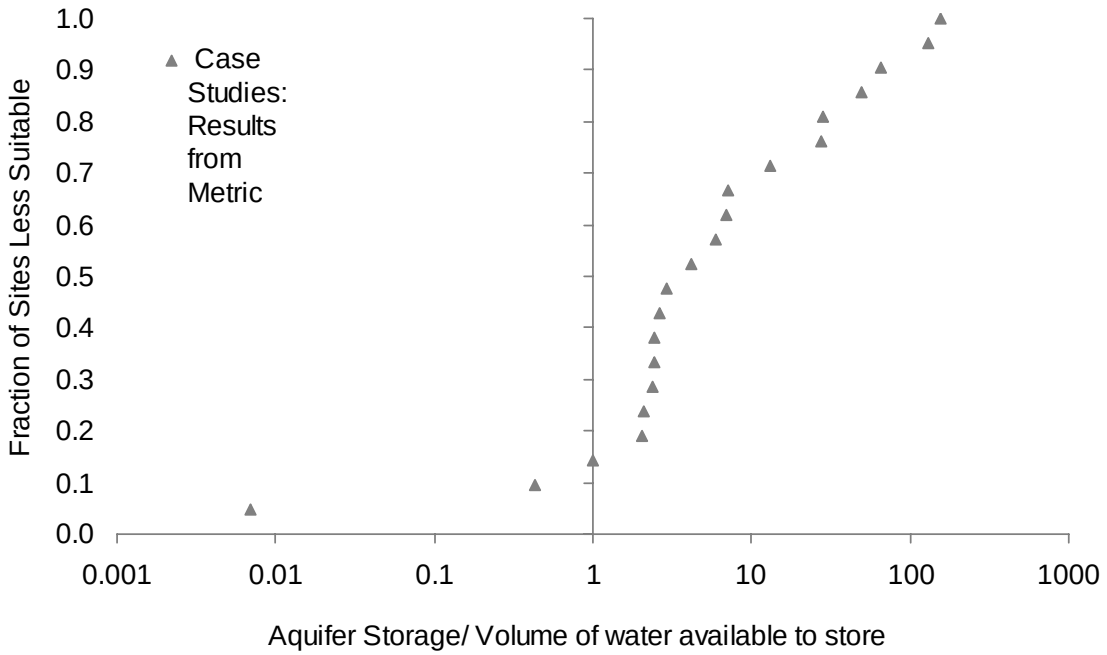


Figure 3-3. Case studies' results from ASR Metric analysis. All case studies except Portland and Tigard have results greater than 1, indicating aquifer storage is sufficient.

Estimating Transmissivity

The ASR metric incorporates transmissivity and head space in the well to describe the storage potential of the aquifer at a particular well. However, transmissivity data is difficult to acquire in many places because it requires pump test data, preferably pump tests with durations longer than 24 hours. On the site specific scale it is entirely possible to conduct these tests, but on a state wide scale it is not feasible. Therefore, it is

necessary to employ an estimation method for transmissivity. Several estimation methods have been developed, and after testing several, the method Razack and Huntley (1991) was selected. Transmissivity can be estimated from specific capacity using the following equation for heterogeneous aquifers:

$$T = A\left(\frac{Q}{s}\right)^{0.67} \tag{8}$$

Where A is a constant that depends on the units of T (Table 3-3), Q is the well yield and s is the drawdown recorded during a pump test at the time of well installation.

T	Q/s				
	m^2/s	m^2/d	ft^2/s	ft^2/d	gpm/ft
m^2/s	0.36	$1.8(10^{-4})$	0.073	$3.6(10^{-5})$	0.0012
m^2/d	31000	15.3	6300	3.12	106
ft^2/s	3.87	0.0019	0.79	$3.9(10^{-4})$	0.013
ft^2/d	$3.4(10^{5})$	165	68100	33.6	1140

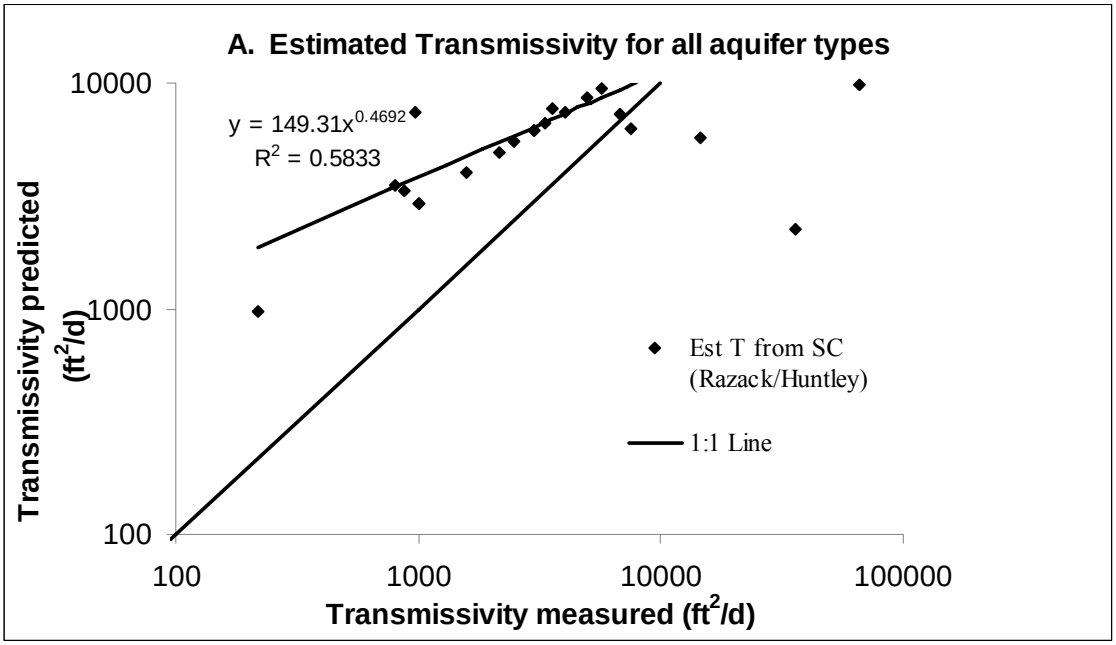
Table 3-3. Conversion factors used for transmissivity estimation. They are used in equation (8) (Razack and Huntley, 1991).

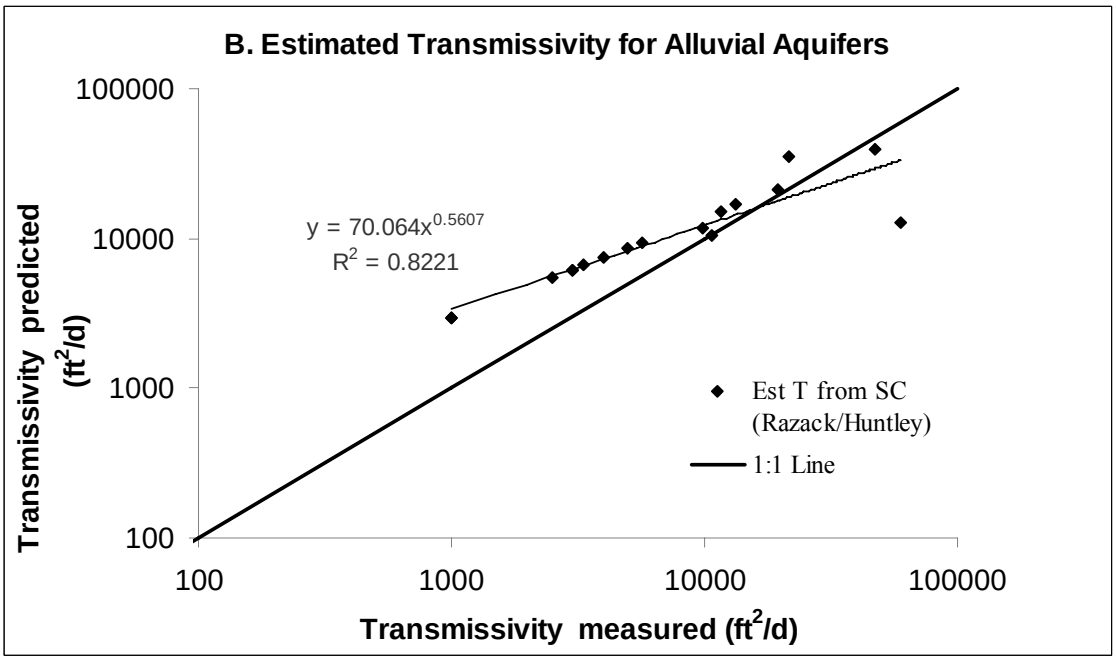
There is uncertainty in any estimation of transmissivity (T). Error stems from well inefficiency, which is due to well construction and the inability of a well to conduct water at the same rate as the aquifer material. There are also several approximations incorporated into the data points, including the assumption that the well's open interval equals the aquifer thickness. However, the specific capacity of a well is still a fair indicator of aquifer properties, as we see in the following investigation of error analysis.

Analysis of Transmissivity Error Generated from Specific Capacity

To test the uncertainty associated with transmissivity estimation methods, ASR case study data with known specific capacity for the well and transmissivity that had been calculated independently from pump test analyses were compared to transmissivity derived with the Razack and Huntley (1991) model. When applied to data from all types of aquifers, the correlation coefficient was 0.58 as illustrated in Figure 3-3. This same model applied to only data from alluvial aquifers, the correlation coefficient increased to 0.82.; when applied to non-alluvial aquifers, there was very little correlation. These

model tests indicate that alluvial aquifer wells' specific capacity is a good predictor of transmissivity, while specific capacity from wells in aquifers with more irregular flow patterns, such as Columbia River Basalt, is not a good predictor of transmissivity.





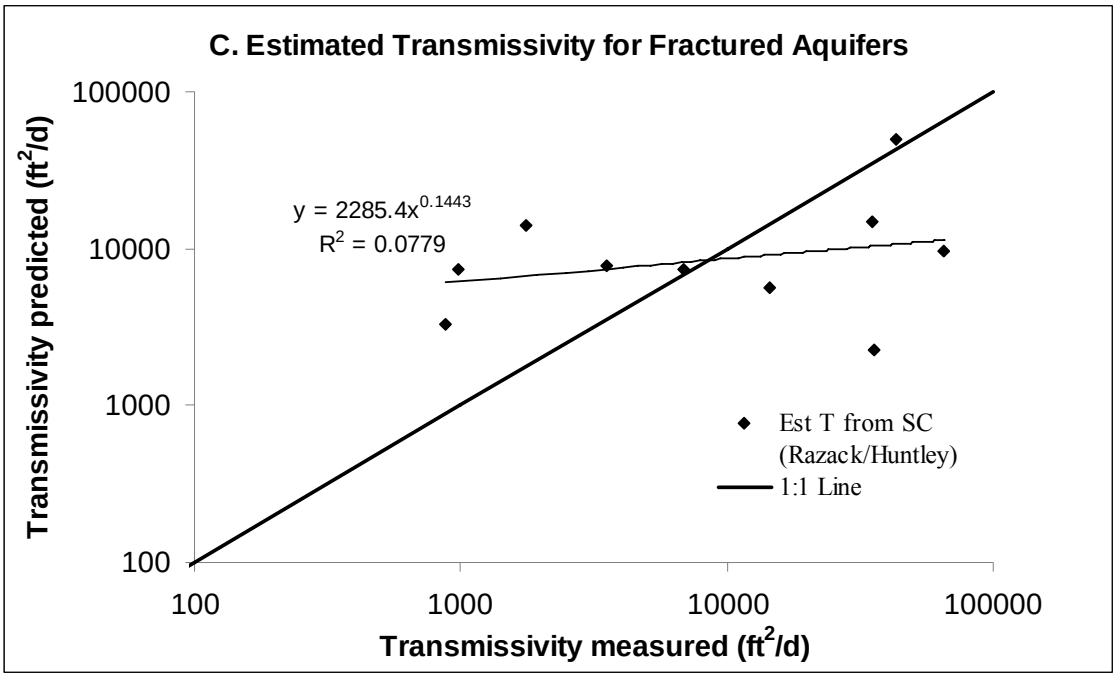


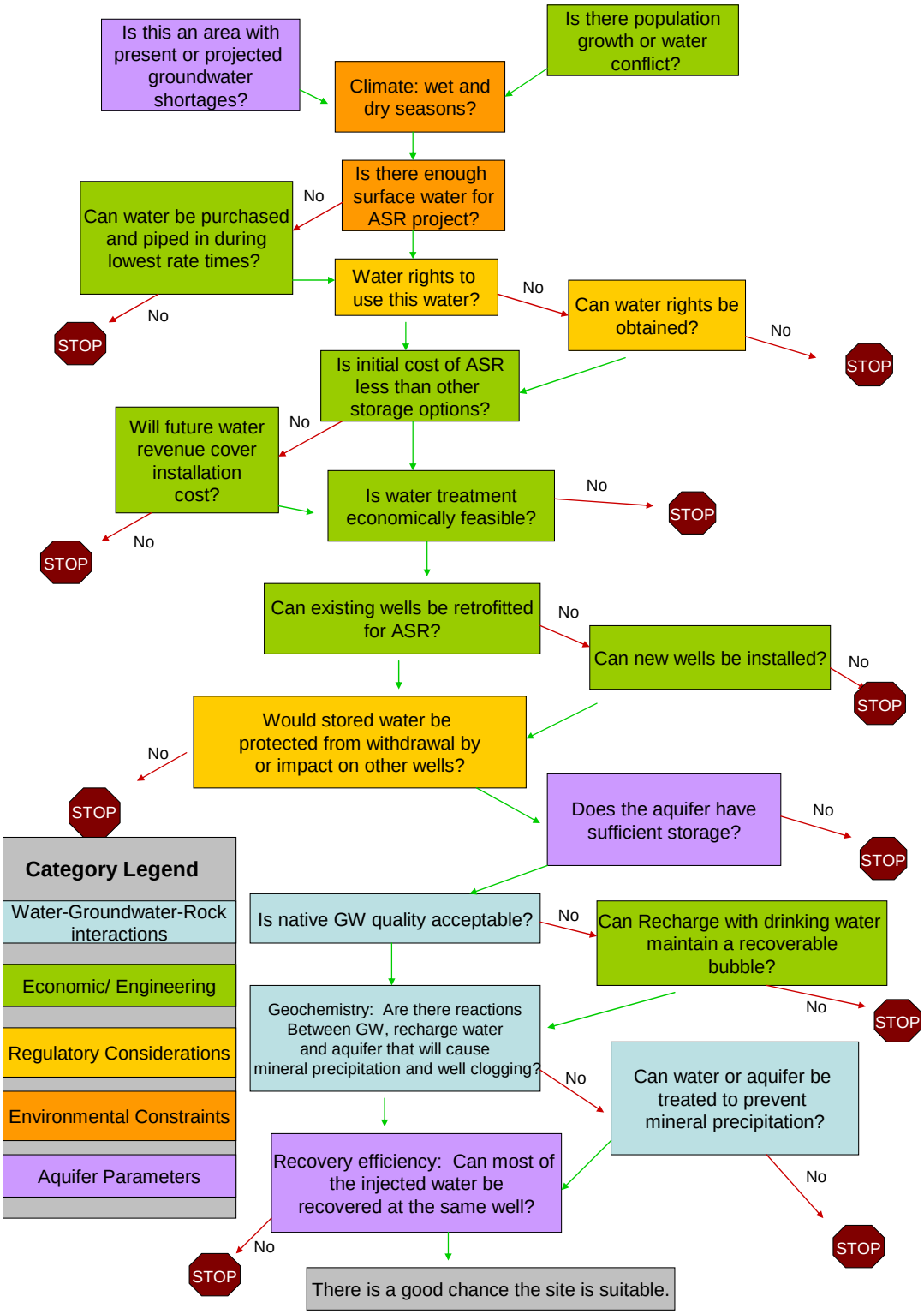
Figure 3-4. Error associated with transmissivity estimation. A. Data from ASR sites with a variety of aquifer types, including alluvial and fractured rock aquifers, show a correlation coefficient of 0.58 for estimation of transmissivity from specific capacity. B. Alluvial aquifer data is better fit, with a correlation coefficient of 0.82. C. Specific capacity of wells in fractured rock aquifers are a poor indicator of transmissivity, with a correlation coefficient of 0.078.

For this study, the high uncertainty in predicting transmissivity from specific capacity in basalt aquifers indicates estimates are only a first-order approximation. Whenever possible, reported transmissivity values were incorporated in place of estimated values. The fact that transmissivity cannot always be predicted further illustrates the necessity of site specific studies to determine when ASR is feasible.

ASR Site Screening Decision Tree

Another site assessment tool developed by this study is an ASR decision tree (Figure 3-5). It considers economic, engineering, geochemical, regulatory and aquifer parameters.

Figure 3-5: ASR Site Assessment Decision Tree:
Is this a suitable ASR site?



CHAPTER 4
DESCHUTES BASIN

Basin Hydrology

The Deschutes Basin covers approximately 10,495 mi^2 (27,182 km^2) and is drained by the Deschutes River and its major tributaries: the Crooked River from the east, Metolius River from the west, and Little Deschutes River from the south-southwest. Watershed divides delineating the basin are found to the west at the crest of the High Cascades, to the south along the Walker fault zone, to the east at the crest of the Ochoco Mountains and to the north at the Columbia River.

Precipitation varies widely both spatially and temporally. Average annual precipitation ranges from approximately 4.5 in (114 mm) in January to less than 1 in (25.4 mm) in August (Gannett and Lite, 2004). In the High Cascades of the western Deschutes Basin, average annual precipitation exceeds 200 in (5080 mm), largely as snow, while at lower elevations precipitation averages less than 10 in (254 mm) (Taylor, 1993). This indicates that the majority of groundwater recharge for the basin occurs in the Cascades, and groundwater flows toward the center of the basin to discharge into the Deschutes and Lower Crooked Rivers throughout the year (Gannett and Lite, 2004).

Physical Setting

The Deschutes Basin includes landscapes ranging from alpine peaks to high desert plateaus (Figure 4-1). The eastern area, bordered by the Ochoco Mountains,

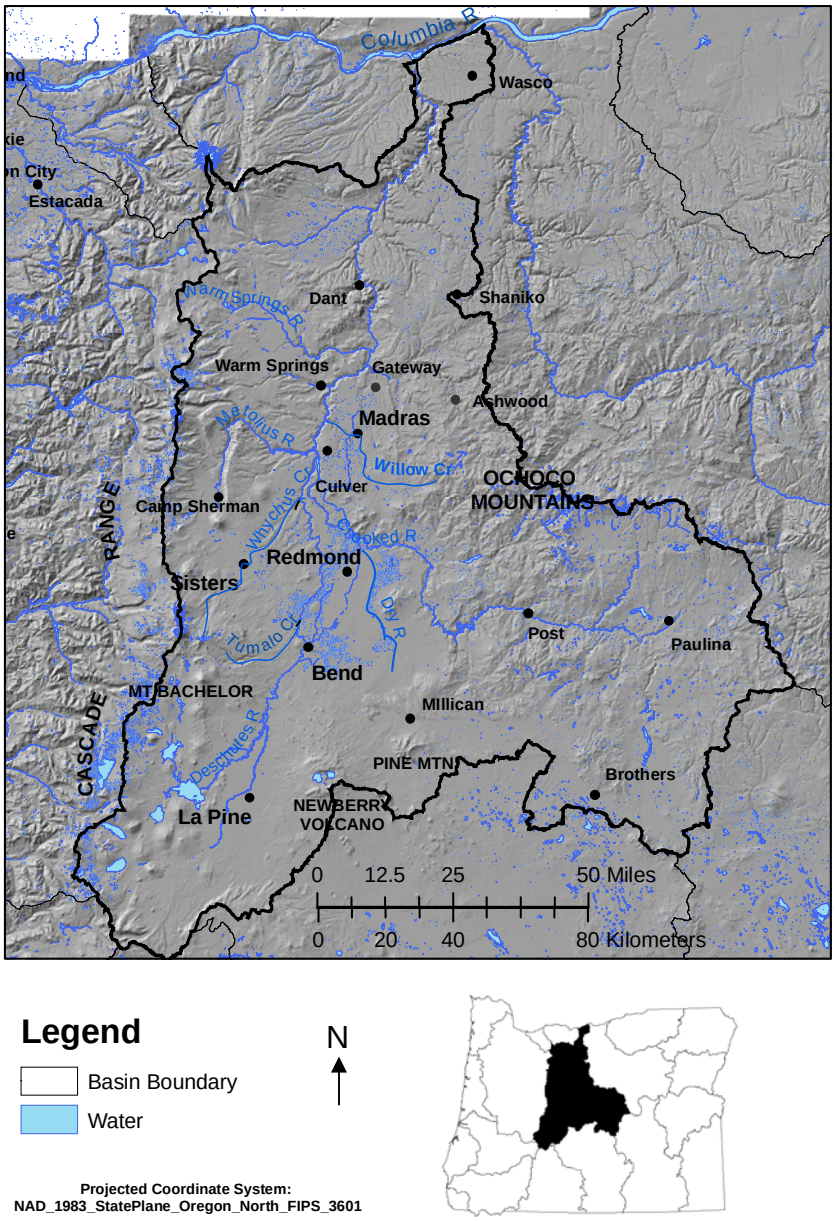


Figure 4-1. Deschutes Basin location map. This map illustrates the topographic features, rivers and towns in the Deschutes Basin that are examined in this study. (Data sources: Wright, 2006; Oregon Geospatial Data Clearinghouse, 2006).

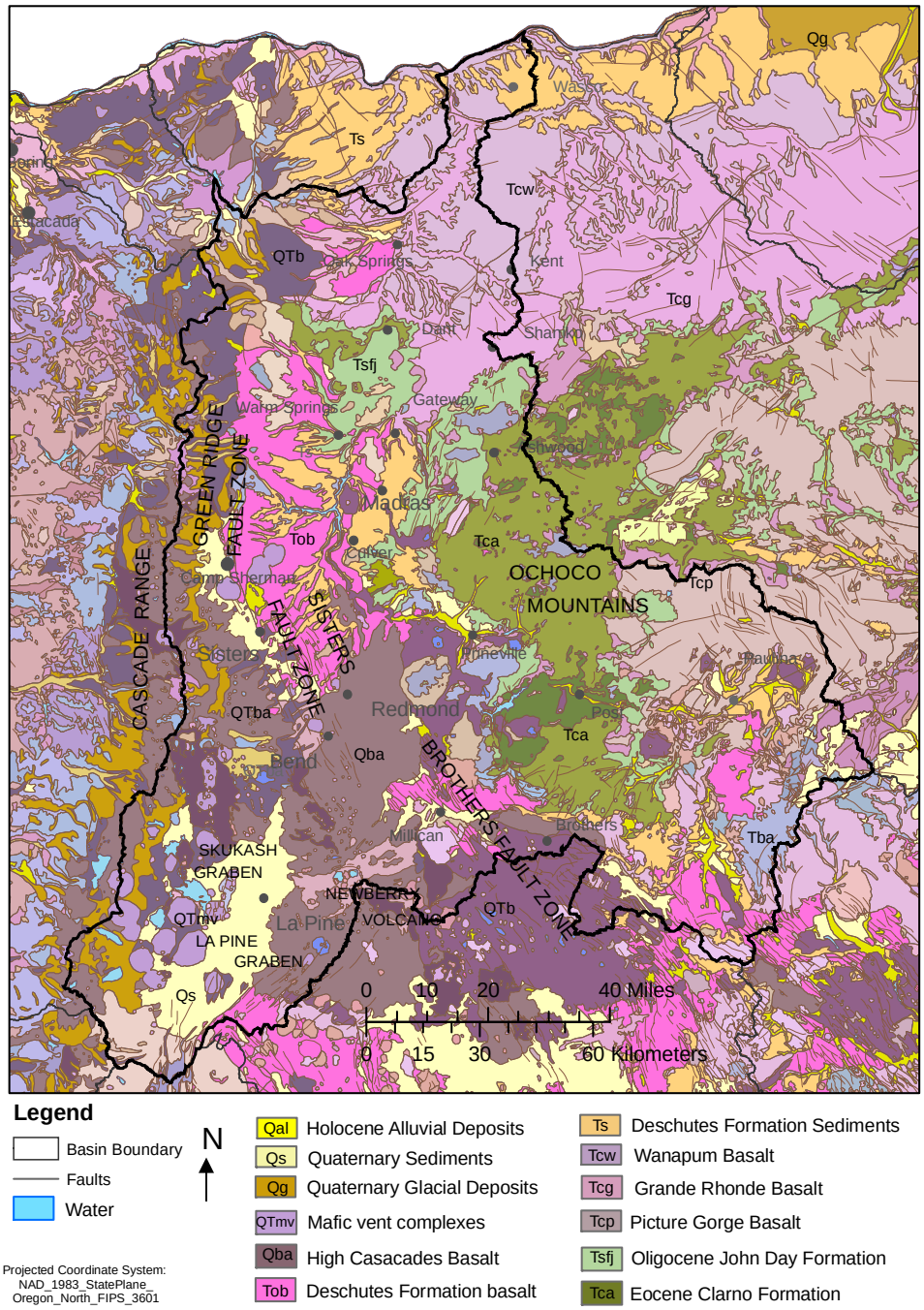


Figure 4-2. Deschutes Basin geology map. Geologic formations of importance to future ASR in the Deschutes Basin include basalts and alluvium as potential injection target zones (Data source: Walker and McLeod, 1991).

constitutes the oldest part of the basin, composed of exotic terranes accreted during the Mesozoic to form the Blue Mountains (Vallier and Brooks, 1986). Surface and groundwater are recharged at this high point and flow west off the Ochoco Mountains, over and through Cenozoic andesite, rhyolite and Miocene basalts toward the Deschutes River. The basin also includes part of the High Lava plains, characterized by Quaternary basalt cinder cones and shield volcanoes. The western edge of the Deschutes Basin is in the Cascade Range, a subduction zone volcanic arc trending north to south through the state. The northern end of the basin, as it flows into the Columbia River, covers the western portion of the Deschutes-Umatilla Plateau's massive Columbia River Basalt Group.

Hydrogeologic Units

Geologic units exposed in the Deschutes Basin are Tertiary to Quaternary in age. Major geologic units (Figure 4-2) are discussed in detail in the following section.

Clarno Formation

The Eocene Clarno Formation (Tca) extends from Brothers north to Ashwood and east into the adjacent John Day basin. North of Paulina it is overlain by Picture Gorge Basalt. The Clarno Formation is composed of a series of mudflows, ash flows and andesitic flows, and has a maximum thickness of 1,000 ft (305 m). Abundant fossils of tropical plants and land mammals can be found in this formation (Orr and Orr, 2000). Gonthier (1985) reported well specific capacity to average less than 1 gpm/ft (18 m^2/d); aquifer hydraulic conductivity to be 0.01 to 1 ft/d (0.003 to 0.3 m/d) and transmissivity to be less than 1,000 ft^2/d (93 m^2/d). These low values make it generally unsuitable for ASR or AR projects, although there may be local exceptions.

John Day Formation

The John Day Formation (Tsfj) is composed of early Oligocene volcanic ash interbedded with sedimentary strata and basalt flows. It extends from below the Cascades, under the central Deschutes basin, and outcrops on the west edge of the basin

at Pine Mountain and in the foothills of the Ochoco mountains. Thickness reaches a maximum at 4,000 ft (1,219 m) at the eastern edge of the Deschutes Basin (Robinson et al., 1984). Hydraulic conductivity ranges from 0.01 to 1 ft/day (0.003 to 0.3 m/day); specific capacity averages less than 1 gpm/ft (18 m^2/d) (Gonthier, 1985). This low permeability formation makes up much of the hydrologic basement of the Deschutes Basin (Lite and Gannett, 2002).

Columbia River Basalt

Miocene Columbia River Basalt flows underlie parts of the eastern half of the Deschutes Basin as the Prineville Basalt (Tcp, 15.77 Ma), with a maximum thickness of 700 ft (213 m) near Bowman Dam (Ken Lite, personal communication, 2006); Picture Gorge Basalt interbedded with Grande Ronde Basalt (Tcg, 15.6-16.8 Ma); and Wanapum Basalt (Tcw, 14.5- 15.2 Ma) (Beeson and Moran, 1979). Massive flows are separated by permeable interflow zones which are important groundwater sources near Madras and Gateway (Lite and Gannett, 2002), with hydraulic conductivity varying from 1 to 10 ft/day (0.3 to 3 m/day). Wells have specific capacity from 4 to 10 gpm/ft (72 to 179 m^2/d) (Gonthier, 1985).

Deschutes Formation

The Miocene to Pliocene Deschutes Formation (Ts, Tob) is 1,000 to 2,000 ft (304 to 610 m) thick in the Deschutes Basin, and is the major aquifer (Lite and Gannett, 2002). It is composed of rhyolite, dacite, pyroclastic deposits, sedimentary deposits, basalt and andesite (Lite and Gannet, 2002). Tertiary basalt is exposed east of the Metolius River to Madras, and south to Bend. Between Bend and the Dry River it is overlain by Quaternary basalts originating from Newberry volcano. Sedimentary Deschutes Formation layers are exposed from Gateway to Culver and again west of the Deschutes River. Hydraulic conductivity is up to 2,300 ft/day (700 m/day) (Gonthier, 1985 and Lite, personal communication, 2006); storativity ranges from 0.0001 to 0.05; well specific capacity ranges from 13.2 gpm/ft (239 m^2/d) to 19.9 gpm/ft (357 m^2/d) (Gannett, 2001).

Cascade Range Volcanics

Miocene to Pleistocene andesitic lava flows and pyroclastic deposits of the High Cascades (QTba, Qba) border the western edge of the Deschutes Basin. Permeability is intragranular and fracture dominated. Volcanics are highly fractured and brecciated, which allows snow melt to infiltrate and recharge the basin's groundwater supply. Hydraulic conductivity ranges from 10 to 50 ft/d (3 to 15 m/d); well specific capacity ranges from 5 to 40 gpm/ft (90 to 717 m^2/d) (Gonthier, 1985). The high hydraulic conductivity of these volcanics has also been observed in canal leakage rates near Bend (Gannett, 2001).

Quaternary Sedimentary Deposits

Pleistocene and Holocene erosion of uplands, glacial deposits and alluvial activity created the Quaternary sediments (Qs, Qg) found in the La Pine subbasin and from Sisters southeast to Bend. Alluvial sedimentary deposits are also found in the subbasin around Millican and at the foot of the Blue Mountains. They are over 1,000 feet (305 m) thick near La Pine and average 100 feet (30.5 m) thick in other areas (Lite and Gannett, 2002). Sedimentary deposits form unconfined aquifers. Hydraulic conductivity ranges from 25 to 159 ft/d (7 to 48 m/d); wells have specific capacity ranging from 1.5 to 3 gpm/ft (27 to 54 m^2/d) (Gonthier, 1985).

Tectonic Structure Influencing Groundwater Flow

Major tectonic structures of the Deschutes Basin include faults and fault-bounded grabens. Although faults can potentially truncate aquifers by offsetting high permeability layers, it appears from previous studies that their main function in this basin has been to control sedimentary deposition (Lite and Gannett, 2002). Deposition in turn influences flow paths of groundwater by providing preferential flow paths.

The northwest trending Sisters fault zone appears southeast of Bend, continuing just east of Sisters and transitioning into the north-trending Green Ridge fault zone near Camp Sherman (Figure 4-2). Movement is primarily dip slip along the Sisters faults, and penetrates Tertiary basalt as well as Quaternary alluvium. This down-dropped structure

created depositional basins for streams descending from the Cascades carrying Pleistocene outwash. According to the work of Lite and Gannett (2002), the contrast in permeability between Pleistocene deposits and Miocene to Pliocene Deschutes Formation has formed shallow aquifers, especially in glacial outwash deposits near Sisters.

The Green Ridge fault zone displays down-dropped blocks to the east with displacement as far as 3,000 ft (914 m) (Conrey, 1985). Gannett (2001) found groundwater discharge west of the Green Ridge escarpment of 1,000 ft^3/s (28 m^3/s) that is likely due to this fault structure. Permeability differences between the truncated Deschutes Formation and Pliocene volcanics may contribute to this dramatic discharge of groundwater to surface water found at the headwaters of the Metolius River.

The Brothers fault zone trends northwest, for 130 mi (208 km) from southeastern Oregon through Millican. Normal faults caused by Cenozoic clockwise rotation of Oregon show displacement of less than 50 ft (15 m) to 300 ft (91 m) (Orr and Orr, 2000). According to Lite and Gannett (2002) groundwater is not affected by the Brothers fault zone.

The La Pine and Skukash grabens are northeast trending structures containing 1,800 to 2,400 ft (549 to 732 m) of sedimentary deposits. This depositional center of low permeability sediments overlie and are interbedded with high permeability lava originating from Newberry Volcano and the Cascades. Above the fine-grained sediments is an unconfined, fine to medium-grained sand layer, with occasional silt and gravel that serves as the main aquifer for the La Pine area (Lite and Gannett, 2002).

ASR Assessment

The purpose of this section is to provide a general assessment of specific locations for their potential to employ ASR as a part of water supply systems. Site specific investigation is essential to determine if a recharge project is technically, economically, and environmentally feasible. Positive results from this study indicate the site possesses many of the necessary components for successful aquifer recharge.

Table 4-1: Summary of Analysis Methods. ASR suitability assessment methods applied to Oregon sites. For more detail, see Chapter 3: Analysis Methods.

Method	Description	Result of Method
Volumetric Analysis	Mathematical comparison of aquifer storage capability to the volume of surface water available	If > 1, sufficient storage If = 1 marginal storage If < 1, insufficient storage
Brown's Site Rating System	Site is rated from 0 to 2 for each criteria such as distance to source water, water quality, groundwater flow rate, aquifer thickness	Produces % of ideal ASR parameters at a given site

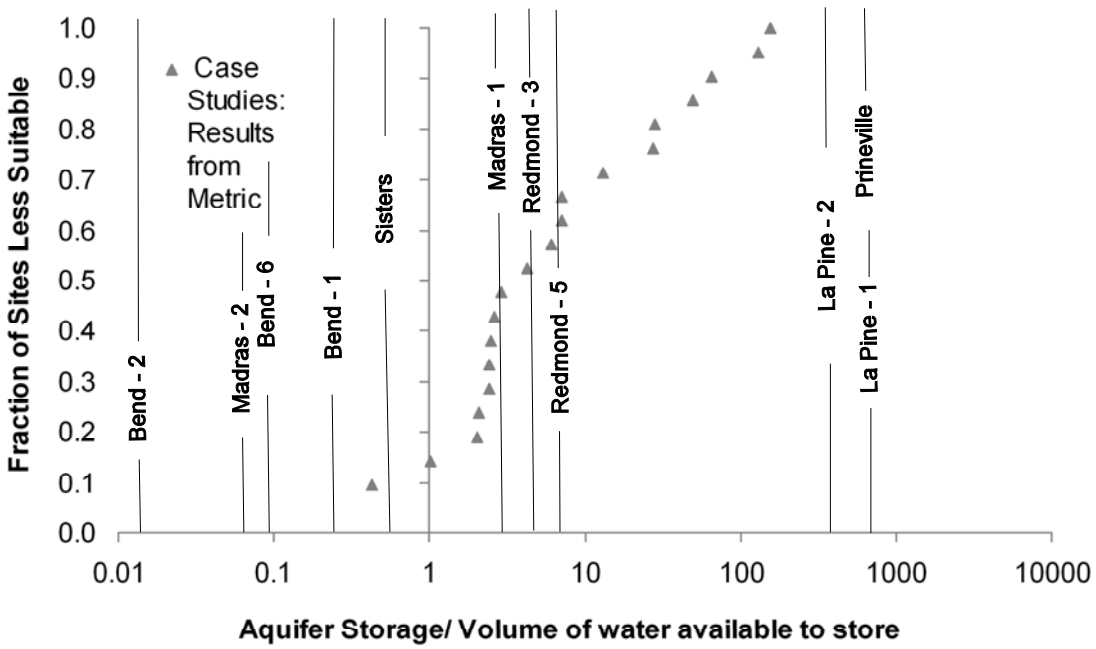


Figure 4-3: Deschutes Basin ASR metric results. Volumetric results for Bend-2, Madras-2, Bend-6 and Sisters indicate aquifer storage is not suitable for ASR. Other sites are volumetrically suitable. Data is listed in Appendix B.

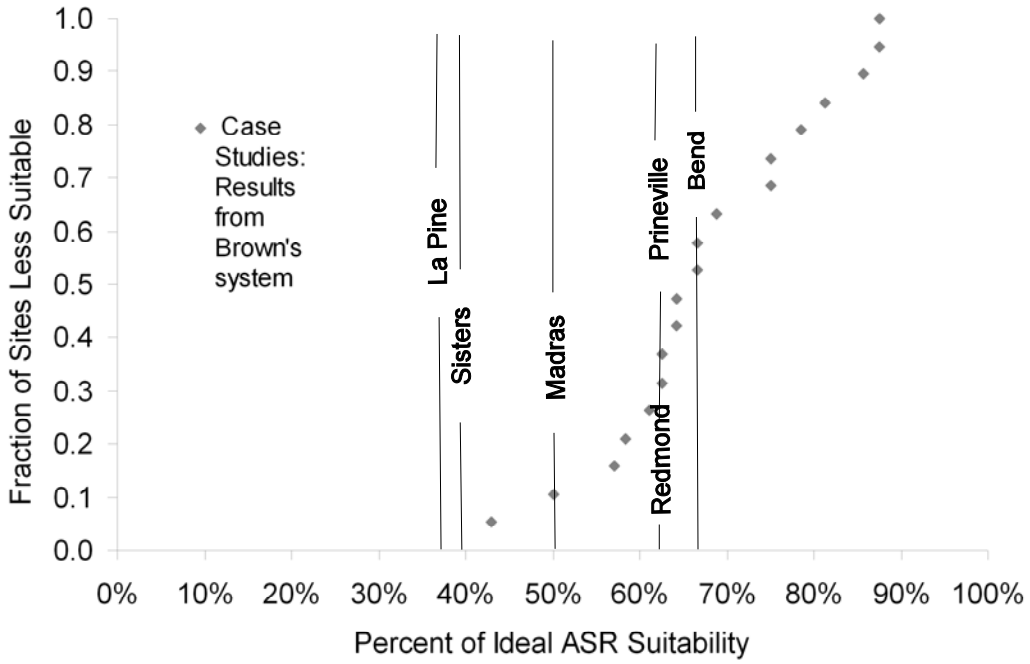


Figure 4-4: Deschutes Basin Brown's site rating system results. Deschutes Basin sites have from 36 % to 69% of ideal conditions for ASR. Results from 60% of case studies fall in the same range as the results for this basin. Data listed in Appendix C.

Madras

Madras is located in the high desert of Central Oregon, approximately 1 mi (1.6 km) from Willow Creek and 5 mi (8 km) from the Deschutes River. The town of Madras relies largely on groundwater for its public supply. The city purchases water from the Deschutes Valley Water District and uses local groundwater to augment the supply. According to the Water Resources Information System (OWRD WRIS, accessed 2006), surface water has been entirely allocated in the subbasin including Madras, so no new surface water rights can be acquired to expand the water supply.

Madras' groundwater levels are rising (1979 depth to water was reported 340 ft (104 m), while 1990 was 280 ft (84 m) (Gannett, 2001)). The city's population increased from 3,443 in 1990 to 5,146 in 2004 (U.S. Census, 2004).

Madras's municipal wells are screened from 360 to 470 ft (110 to 143 m) below the surface, drawing water from Deschutes Formation basalts (Tob), sands (Ts) and

Quaternary alluvial deposits of sand and gravel (Qs, Qal). A median value of transmissivity for Deschutes Formation basalts has been estimated as 800 ft^2/day (75 m^2/day), while Deschutes Formation sand has transmissivity of 2,100 ft^2/day (200 m^2/day), hydraulic conductivity is 110 to 160 ft/day (34 to 49 m/day), and storativity is 0.0015 (Gannett, 2001). These transmissivity values are below the ideal range of 5,000 to 25,000 ft^2/day (465 to 2,323 m^2/d) for ASR (Brown et al., 2005).

According to Gannett et al. (2001), the nearest known fault to Madras is about 5 mi (8 km) northeast of town, suggesting that the aquifers accessed for the municipal water supply are not truncated by faults within their radius of influence. There is very little tectonic structure cutting the Deschutes Formation outside of the Sisters Fault Zone, which is advantageous for ASR. However, Deschutes Formation basalts are largely unconfined to leaky confined, indicating a potential problem of injected water migrating out of the unit during ASR.

Volumetric analysis (Figure 4-3) indicates Madras-2 (basalt well) is not suitable for ASR, while Madras-1 (sand and gravel well) has sufficient storage. Brown's site rating system finds Madras has 50% of optimal ASR parameters. The site lost points for low transmissivity and an aquifer less than 25 ft (7.6 m) thick.

There is not potential for AR through surface spreading in the Madras area due to the hydraulic gradient of 0.02 to 0.04 (Gannett, 2001), indicating that infiltrated water may flow away too quickly to be recovered at the same location. However, it may be feasible to determine groundwater flow paths and withdraw water down-gradient from recharge ponds.

Redmond

Redmond is located approximately 3 mi east of the Deschutes River. The city has surface water rights to the Deschutes River year round, as well as groundwater rights. Population has increased from 7,163 in 1990 to 18,017 in 2004 (U.S. Census, 2004). Groundwater levels have shown some decline in municipal wells; depth to water in 1980 was 295 ft (90 m); in 2005 it was 312 ft (95 m) (Gannett, 2001). These factors probably

suggest both an increasing pressure on water supplies and long term climatic trends, as well as potential available storage capacity in the aquifer due to decline.

Municipal wells have open intervals varying from 200 to 800 ft (61 to 244 m) below the surface. They access the Deschutes Formation locally confined basalt (Tob), pyroclastic deposits, and sand and gravel layers (Ts). Well yields range from 1,100 to 1,300 gpm (6,000 to 7,100 m^3/d; OWRD well log data). Hydraulic conductivity for an ash and conglomerate layer has been measured at 60 ft/d (18 m/d), transmissivity 6,000 ft^2/d (560 m^2/d), storativity 0.1 and specific capacity 1,528 gpm/ft (27,391 m^2/d) (Gannett, 2001). Deschutes Formation sand and gravel aquifers have also been estimated to have a hydraulic conductivity 1,500 to 2,300 ft/d (457 to 700 m/d), transmissivity of 250,000 ft^2/d (23,225 m^2/d), storativity of 0.05 and well specific capacity of 7,130 gpm/ft (127,830 m^2/d) (Gannett, 2001).

Transmissivity values for Deschutes Formation sand and gravel aquifers suggest they are suitable for ASR; they are above the values found in many operational ASR sites. (Figure 4-3) Volumetric analysis indicates aquifer storage in the Deschutes Formation sand and gravel aquifer is sufficient for ASR. According to Brown's site rating system, Redmond has 63% of optimal ASR parameters. The site lost points for well density greater than 5 wells per square mile.

Redmond is operating infiltration basins as part of wastewater treatment, so this technology may translate to AR projects in Tertiary sediments and surface water chemistry found in the Deschutes Formation. The hydraulic gradient is 0.002 in the Redmond area (Gannett, 2001), which supports the recovery of water infiltrated into surficial aquifers.

Sisters

The City of Sisters is located near the confluence of Indian Ford Creek and Whychus Creek. Sisters has water rights to Pole Creek, which the city is currently leasing back to Whychus Creek. Sisters meets its municipal water needs with groundwater, and does not have a water treatment plant (Paul Bertagna, personal communication, 2006).

Municipal wells access Cascade Range basalt and andesite (Qba) and Quaternary alluvium (Qal), with well yields around 1,310 gpm (7,140 m^3/d; OWRD well log data). Transmissivity at Cascade Meadows in Cascade Range basalts was estimated by Gannett (2001) at 50,000 ft^2/d (2,645 m^2/d); transmissivity at Tollgate of glacial outwash and basalts is estimated at 10,000 ft^2/d (929 m^2/d). These values are either above or within the ideal range for ASR.

Brown's site rating system finds Sisters has 38% of optimal ASR parameters (Figure 4-4). The site scored poorly for low transmissivity, aquifer thickness less than 25 ft (7.6 m) and well density greater than 5 wells per square mile. Volumetric analysis indicates aquifer storage is insufficient for ASR (Figure 4-3). Overall, Sisters has a low potential for ASR.

Surficial alluvial aquifers may be suitable for infiltration basins for artificial recharge, however the local hydraulic gradient is relatively high at 0.05 (Gannett, 2001).

Bend

Bend is the largest city in the Deschutes Basin, located on the Deschutes River. It is growing rapidly with a population of 20,649 in 1990 increasing to 62,937 in 2004 (U.S. Census, 2004). Bend has water rights to 36 cfs from the Deschutes River flow at the mouth of Tumalo Creek, but uses groundwater for most municipal needs. Groundwater levels are primarily influenced by seasonal canal recharge and decadal climate trends, observed currently as about a 1 ft (0.3 m) decline per year (Ken Lite, personal communication, 2006). Groundwater recharge is largely from irrigation canal leakage; Gannett (2001) estimate 46% of canal flow is lost through percolation into the ground.

Municipal wells have open intervals from 140 to 800 ft (43 to 244 m) below the surface; water-bearing layers are interpreted as Deschutes Formation basalts (Tob) and sediments (Ts) with yields of 310 to 2,000 gpm (1,690 to 10,900 m^3/d; OWRD well log data). These basalts of the Deschutes Formation have an estimated hydraulic conductivity of 150 ft/d (46 m/d), transmissivity of 50,000 ft^2/d (4,645 m^3/d; Gannett, 2001). This is above the ideal range for ASR

Volumetric analysis indicates aquifer storage in the Deschutes Formation basalt is insufficient for ASR (Figure 4-3). Brown's site rating system finds Bend has 69% of optimal ASR parameters, with moderate scores on all parameters (Figure 4-4).

AR may be difficult in Bend, due to the hydraulic gradient ranging from 0.02 to 0.03 (Gannett, 2001). It may be possible to take advantage of high groundwater flow rates by capturing infiltrated water down-gradient of recharge ponds, but local investigation would be necessary.

La Pine

La Pine is located in a basin between the Cascades and Newberry Volcano, 2 mi (3.2 km) south of the Deschutes River. The population in 2000 was stable at 5,799 (U.S. Census, 2004).

Public supply wells have open intervals from 155 to 250 ft (47 to 76 m) below surface, accessing Newberry or Cascade Range basalt interflow zones. However, the aquifer is mostly sediments, ranging up to 1,000 ft thick in La Pine proper. Well yields are about 1,300 gpm (7,085 m^3/d; OWRD well log data). Transmissivity in upper, relatively coarse grained Quaternary sediments (Qs) is estimated at 4,000 ft^2/d (370 m^2/d) (Century West, 1982). This is slightly below the ideal range of 5,000 to 25,000 ft^2/d (465 to 2,323 m^2/d) for ASR.

Volumetric analysis indicates aquifer storage is suitable for ASR (Figure 4-3). According to Brown's site rating system, La Pine has 36% of optimal ASR parameters. The site lost points for low transmissivity and well density greater than 5 wells per square mile.

Significant faults in the La Pine Graben complex could affect storage capacity. In addition, the cost of piping source water from the nearest river to town may be prohibitive. La Pine is located in the center of an area of flat hydraulic gradient, ranging from 0.001 to 0.002; this indicates it could be candidate for AR through surface spreading. However, shallow groundwater system nitrate levels may prove this method infeasible (Doug Woodcock, personal communication, 2006), and high water tables also make AR unlikely to succeed.

CHAPTER 5
GOOSE AND SUMMER LAKES BASIN

Hydrologic Description

Situated in south-central Oregon, the Goose and Summer Lakes Basin covers approximately 7,960 mi^2 (20,620 km^2). This basin includes several closed subbasins where waters flow from up-thrown fault block highlands to central lowlands. Water leaves the basin only through broad, shallow evaporative lakes and plant transpiration. Major subbasins include Fort Rock Basin in the north, Summer, Abert, and Alkali Lake basins in the center; Goose Lake in the south; and Warner Lakes near the eastern border. Perennial streams are rare but include the Chewaucan, Silver, Buck, and Ana Rivers. North-south trending fault blocks to the east and west, and volcanic mountains to the north delineate the watershed boundaries of the basin. The Oregon-California border forms the southern political basin boundary.

The high desert climate of this basin is characterized by precipitation that varies between seasons and across the basin. Average annual precipitation ranges from approximately 9 in (230 mm) at Christmas Valley to 17 in (430 mm) at Lakeview (Oregon Climate Service, 2007). Groundwater recharge has been estimated at less than 0.1 ft per year, by percolation of winter precipitation into the fractured volcanic highlands and unconfined lowland sedimentary aquifers (Miller, 1986).

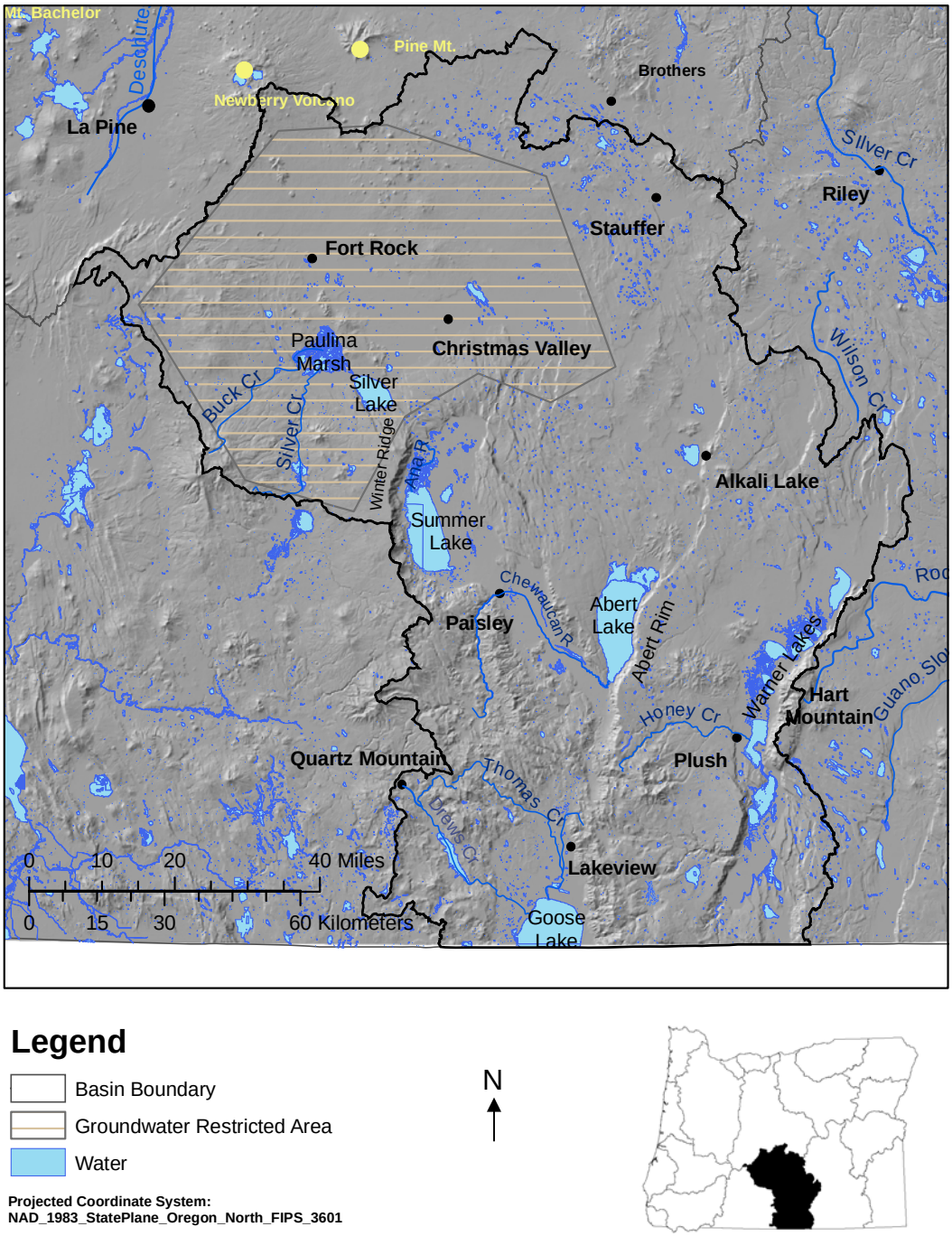


Figure 5-1. Goose and Summer Lakes Basin location map. Location of topographic features, rivers and towns in the Goose and Summer Lakes Basin that are examined in this study (Data sources: Wright, 2006; Oregon Geospatial Data Clearinghouse, 2006).

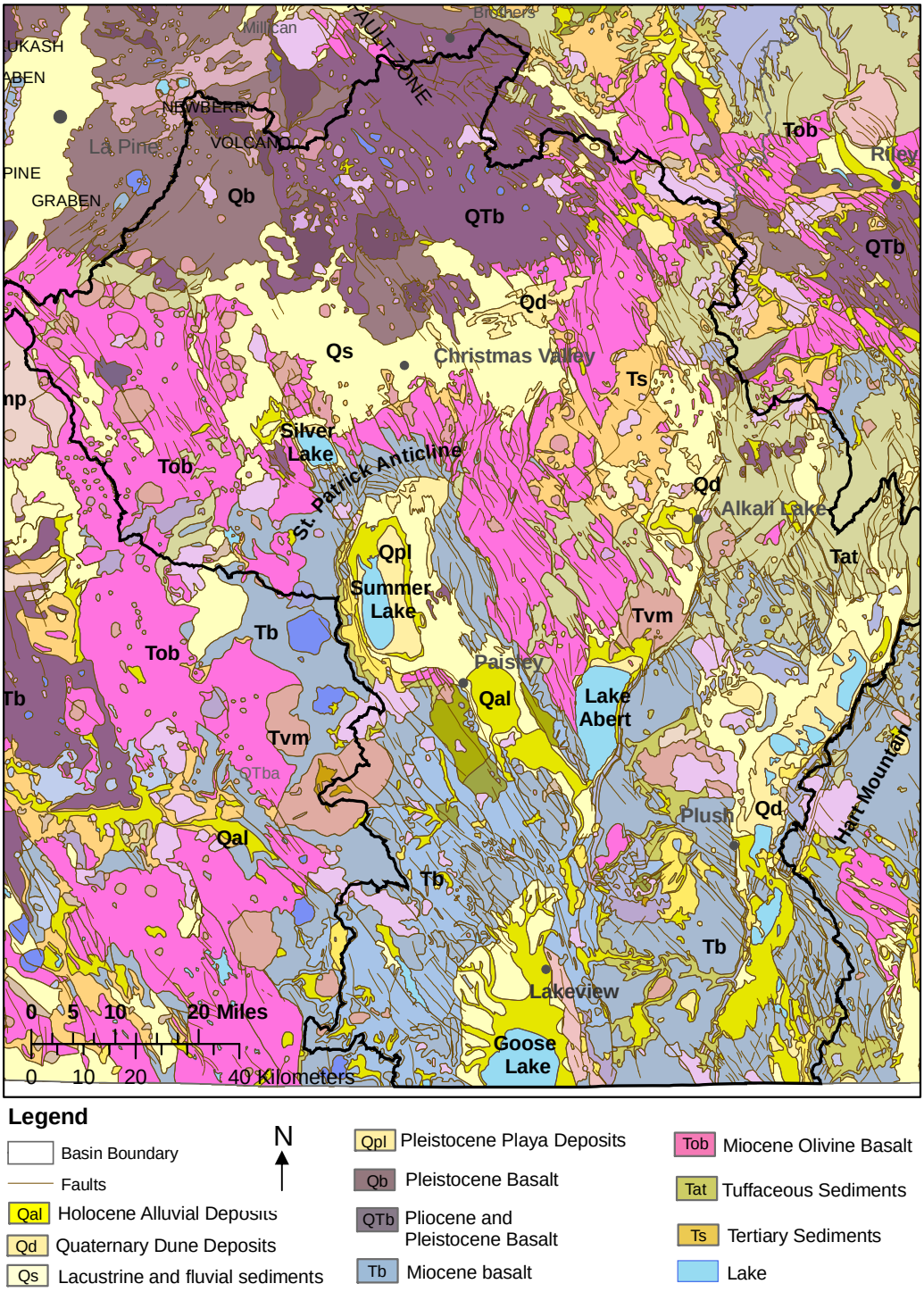


Figure 5-2. Goose and Summer Lakes Basin geology map. Geologic formation of importance to future ASR in the Goose and Summer Lakes Basin include basalts and basin fill sediments (Data source: Walker and McLeod, 1991).

Physical Setting

Goose and Summer Lakes Basin displays classic extensional Basin and Range topography (Figure 5-1). North-south trending normal faults have created up-thrown horsts and down-thrown grabens. Grabens contain sediments deposited by lakes and rivers. Lacustrine deposits cover areas much larger than the present lakes, indicating the lakes were formerly much larger than they are today. These sediments vary in grain size from very fine clays to permeable gravels at depth.

Groundwater Restricted Areas (Figure 5-1) are administrative regions designated by OWRD because they are experiencing long-term groundwater level declines. Further allocation within these areas is currently suspended, and some existing water rights have been limited to protect the resource.

Hydrogeologic Units

Major geologic units exposed in the basin are Tertiary to Quaternary in age. Listed from oldest to youngest they include Tertiary basalt and rhyolite, Tertiary tuffs, Tertiary and Quaternary alluvium and lacustrine sediments. Major geologic units (Figure 5-2) are discussed in detail in the following sections.

Tertiary and Quaternary Basalt and Rhyolite

Miocene to Pleistocene basalt and rhyolite (Tb, Tob, QTb, Qb) are exposed in the highland boundaries all around the basin. Groundwater flow is limited by extensional faulting in many areas (Gonthier, 1985). The basalts and rhyolites are developed by wells in Lakeview, near Alkali Lake, and in the Fort Rock basin. Based on the sampling of wells examined for this study, estimated transmissivity ranges over several orders of magnitude. Miller (1986) found the Tertiary basalt units to be highly productive aquifers, while the youngest Pleistocene basalts in the Fort Rock subbasin are above the water table and therefore not groundwater sources. These units have a correspondingly variable suitability for ASR.

Tertiary Tuff

Miocene to Pliocene pyroclastic and volcanically-derived sedimentary rocks (Tat), are exposed between Paisley and Alkali Lake, east and northeast of Alkali Lake to the basin boundary, and at smaller exposures in the northwest corner of the basin. The tuffs are generally clayey, fine-grained, and considered to be poor aquifers. Maximum total thickness is estimated at 400 ft (122 m), while individual flows average around a few feet thick (Hampton and Brown, 1964). In most places tuff lies above the water table and is therefore not a major aquifer. This unit is not likely to be developed for ASR.

Tertiary and Quaternary Sediments

Rivers and lakes have produced a variety of unconsolidated Pliocene to Holocene sediments (Qal, Qd, Qs, Qpl, Ts) which have accumulated in lake basins around Christmas Valley, Summer, Alkali, Abert, Warner and Goose Lakes. Pleistocene lake bed deposits of clay, sand and diatomaceous earth have a total thickness up to 200 ft (60 m). Beneath Pleistocene deposits, older sediments interbedded with basalts make up the Fort Rock Formation in the northwest corner of the basin, which has a maximum known thickness of 1,000 ft (304.8 m). Permeability ranges from low values in fine-grained tuffs to moderate values in diatomite and pumice (Hampton and Brown, 1964). Hydraulic conductivity in the sediments ranges from 25 to 150 ft/d (7.6 to 46 m/d); while transmissivity in the valley fill aquifer systems ranges from 1,000 to 15,000 ft^2/d (92.9 to 1,394 m^2/d; Gonthier, 1985). Wells in the basin utilizing these aquifer units tend to have low to moderate yields. ASR may be possible if injection and recovery does not impact other wells in the same aquifer.

Unconfined sedimentary aquifers may be useful for AR in areas with suitable transmissivity, source water quality and availability, especially in dune deposits northeast of Alkali Lake. However, uranium mill tailing contamination of the shallow aquifer northwest of Lakeview and a history of herbicide and pesticide disposal east of Alkali Lake indicate the need to examine groundwater quality and contaminant plume migration before aquifer recharge (U.S. Department of Energy, accessed 2007).

Tectonic Structure Influencing Groundwater Flow

Goose and Summer Lakes Basin is located in the northern Basin and Range province, and displays extensional, north-south trending normal faults. Faulting and folding influence basalt, andesite and tuffs (Figure 5-2). Displacement of Tertiary basalts is reported to be greater that 800 ft (244 m) in the northern end of the basin, while younger units show displacements of less than 100 ft (30.5 m; Miller, 1986). According to Gonthier (1985), faulting in the basalts limits groundwater flow by hydraulically disconnecting interflow zones, which are the main permeable sections of basalt flows in this area. ASR could be limited by faults where they compartmentalize basalt aquifers.

Normal faults in this basin also have shaped the surface water flow system by providing closed basin lowlands (or grabens) which collect the surface and groundwater runoff in lakes.

ASR Assessment

This purpose of this section is to provide a general assessment of specific locations for their potential to employ ASR as part of a water supply system. Site specific investigation is essential to determine if a recharge project is technically, economically, and environmentally feasible. Results from this study indicate that some sites possess many of the necessary components for successful ASR.

Table 5-1: Summary of Analysis Methods. For more detail, see Chapter 3: ASR Site Screening Methods.

Method	Description	Result of Method
Volumetric Analysis	Mathematical comparison of aquifer storage capability to the volume of surface water available	If > 1, sufficient storage If = 1 marginal storage If < 1, insufficient storage
Brown's Site Rating System	Site is rated from 0 to 2 for each criteria such as distance to source water, water quality, groundwater flow rate, aquifer thickness	Produces % of ideal ASR parameters at a given site

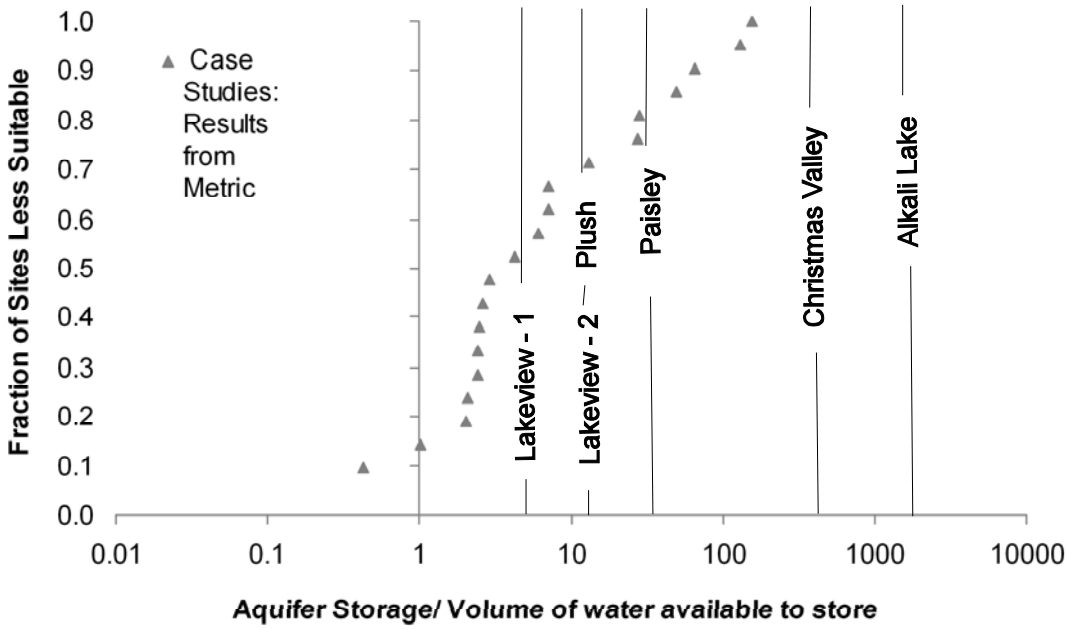


Figure 5-3: Goose and Summer Lakes Basin ASR metric results. Volumetric results for Christmas Valley, Paisley, Plush, Lakeview and Alkali Lake indicate aquifer storage is sufficient for ASR. Data is listed in Appendix B.

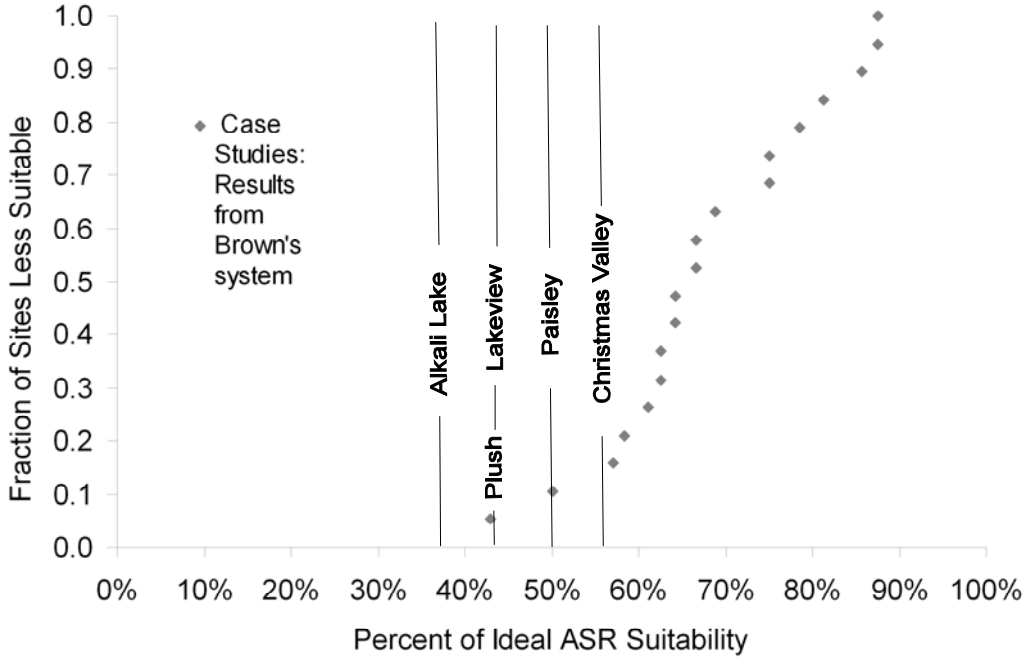


Figure 5-4: Goose and Summer Lakes Basin Brown's rating system results. Brown's ASR site rating system indicates Goose and Summer Lakes Basin sites have 36 % to 57% of ideal conditions. Results from 80% of case studies fall above the range of results for this basin. Data is listed in Appendix C.

Christmas Valley

Located in north-central Goose and Summer Lakes Basin, Christmas Valley is a small community that was developed in the 1960's. There are no perennial streams in the immediate vicinity. Water for domestic use is supplied by community wells owned by Christmas Valley Domestic Water Supply District (CVDWS). Population in the town was stable at 989 in 2006 (U.S. Census, 2006).

CVDWS's pumice and conglomerate Tertiary tuff (Tat, Qs) well (LAKE 1023) is screened from depths ranging from 630 to 660 ft (192 to 200 m) below the surface. The well yields 800 gpm (4,360 m^3/d). Transmissivity in the sediments is estimated by this study as 73,000 ft^2/d (7,000 m^2/d) from specific capacity data, which is above the ideal ASR range of 5,000 to 25,000 ft^2/d (465 to 2,323 m^2/d). It is similar to Beaverton's ASR site, with a reported transmissivity of 65,500 ft^2/d (6,092 m^2/d).

CVDWS currently has no surface water rights, and there are no major perennial streams in the vicinity (Oregon Geospatial Database, 2007). Groundwater declines of in the basin lowlands during the 1970's and 1980's in the Fort Rock Basin led to restrictions on new ground water use (Figure 5-1). It was determined by Miller (1986) that groundwater withdrawals were approximately equal to recharge, indicating that further groundwater appropriations should be limited. Groundwater declines create storage potential for ASR.

This site fails Brown's site rating system because source water is greater than 3 mi (4.8 km) away. The site also lost points for high transmissivity. Volumetric analysis indicates aquifer storage is sufficient to inject 1 cfs (2,447 m^3/d) for 120 days in pumice and conglomerate aquifers (Figure 5-3). Access to source water for injection is the largest barrier to ASR or AR at this location.

Paisley

Paisley is located on the Chewaucan River, near the western basin boundary. The town currently has no surface water rights, but 1 cfs (2,447 m^3/d) from the Chewaucan River is available (OWRD WARS, accessed 2007). This small community decreased from 350 to 242 residents between 1990 and 2004 (U.S. Census, 2004). While

population growth may not instigate water infrastructure changes, climate change or land use interests may warrant ASR interest in the future.

A municipal well (LAKE 4570) was selected to represent the local aquifer. The well has open intervals from 83 to 121 ft (25 to 37 m) below the surface, accessing the shallow Quaternary sand and gravel aquifer (Qal, Qs). Well yield is 120 gpm (654 m^3/d; OWRD well log data). Transmissivity is estimated at 3,000 ft^2/d (300 m^2/d) from specific capacity data. This value falls below the ideal range of 5,000 to 25,000 ft^2/d (465 to 2,323 m^2/d) for ASR, but is similar to Seattle's ASR site with transmissivity of 2,990 ft^2/d (278 m^2/d).

Volumetric analysis indicates the aquifer's available storage is sufficient to inject 1 cfs (2,447 m^3/d) for 120 days (Figure 5-3). This is calculated by approximating a theoretical surface water right of 1 cfs (2,447 m^3/d) from the Chewaucan River. Paisley has 50% of ideal conditions for ASR, according to Brown's site rating system. The site lost points for low transmissivity and the presence of a threatened fish species.

Plush

The town of Plush sits in the alluvium-filled lowlands of Warner Valley. It is situated about 1 mi (1.3 km) from the banks of Honey Creek. Plush currently has no surface or groundwater water rights, although there is water available in Honey Creek for storage (OWRD WARS, 2007).

A domestic well (LAKE 1852) has a low yield (15 gpm) and utilizes the shallow Quaternary gravel aquifer (Qs, Qal) at depths from 33 to 43 ft (10 to 13 m) below the surface (OWRD well log data, 2007). Transmissivity estimated from specific capacity is 1,900 ft^2/d (200 m^2/d). This is below the ideal range for ASR of 5,000 to 25,000 ft^2/d (465 to 2,323 m^2/d). However, this permeability is similar to Adelaide, Australia's ASR site which utilizes limestone with transmissivity of 1,900 ft^2/d (180 m^2/d). Head space in the well at the time of drilling was 23 ft (7 m) which does not allow for much water level rise during injection.

Volumetric analysis indicates aquifer storage is sufficient to inject 1 cfs (2,447 m^3/d) for 120 days (Figure 5-3). Brown's site rating system finds Plush has 43% of

optimal ASR parameters (Figure 5-5). The lost points for low transmissivity and the thickness of the aquifer is less than 25 ft (7.6 m). AR may be feasible in surficial gravel aquifers, depending on vertical permeability, water quality, and location of other wells that might access the stored water.

Lakeview

Located about 14 mi (22 km) north of the Oregon-California border, Lakeview is approximately 1.2 mi (2 km) from Thomas Creek. Alluvial and lake deposits underlie the lowlands north of present-day Goose Lake. The town has surface water rights to a maximum rate of 1.5 cfs (3,670 m^3/d) from several springs that are tributaries to Bullard, Camas and Burnt Creeks (OWRD WRIS, accessed 2007).

The Quaternary sand and gravel aquifer (Qs, Qal) supports Lakeview's municipal well (LAKE 2471). It accesses water-bearing layers at depths from 100 to 452 ft (31 to 138 m) below the surface, and yields 250 gpm (1,363 m^3/d; OWRD well log data, 2006). Another Lakeview municipal well (LAKE 2468), was drilled to the exceptional depth of 2,380 ft (725 m), with an open interval located in basalt from 2,072 to 2,380 ft (632 to 725m) below the surface. At the time of drilling it yielded 150 gpm (818 m^3/d). Transmissivities estimated from well specific capacities are 680 and 3,400 ft^2/d, respectively (64 and 310 m^2/d). Both sites have transmissivity below the ideal range of 5,000 to 25,000 ft^2/d (465 to 2,323 m^2/d). However, the sand and gravel aquifer has similar permeability to the Windhoek, Namibia site (650 ft^2/d or 60 m^2/d, Murray and Tredoux, 2002) and South Goulburn, Australia (750 ft^2/d or 70 m^2/d; Pavelic et al., 2002). The basalt well is similar to transmissivity found at the ASR site in Tualatin, Oregon (3,900 ft^2/d or 364 m^2/d; Groundwater Solutions Inc., 2003).

Volumetric analysis of both wells indicates aquifer storage is sufficient to inject 1 cfs (2,447 m^3/d) for 120 days at both wells. However, the sand and gravel well (LAKE 2471) has more storage than the basalt well (Figure 5-3). Lakeview has 43% of optimal ASR parameters in Brown's site rating system (Figure 5-4). The site lost points for poor groundwater quality, low transmissivity and the presence of threatened species. The

surficial gravel aquifers may be suitable for AR, depending on vertical permeability and water quality.

Lakeview uranium processing district, although not currently in operation, is located northwest of the town. Groundwater contaminant plumes have been detected in the shallow aquifer, and hydrothermal activity has rendered native groundwater high in undesirable minerals such as arsenic (U.S. Department of Energy, accessed 4/4/07). Careful water quality investigation is necessary to determine if local aquifers are suitable for drinking water storage.

CHAPTER 6
GRANDE RONDE BASIN

Basin Hydrology

The Grande Ronde Basin covers approximately 4,921 mi^2 (12, 745 km^2) and is drained by the Grande Ronde River and its major tributaries: the Minam and Wallowa Rivers from the south. The Imnaha River flows north to its confluence with the Snake River. Watershed divides delineating the basin are found to the south in the Wallowa Mountains, to the west at the Blue Mountain anticline, and to the east at the Snake River.

The climate is high desert. Average annual precipitation for the basin ranges from approximately 13 in (330 mm) at Union to 22 in (560 mm) at Elgin (Oregon Climate Service, 2007). Average monthly precipitation ranges from 1 to 3 inches (25 to 76 mm) from October through May, and from 0.5 to 1 inch (13 to 25 mm) from June through September. The majority of groundwater recharge for the basin occurs in the highlands of the Blue Mountains (Vaccarro, J.J., 1999).

Physical Setting

Valley plains surround the cities of La Grande and Joseph, which abruptly transition into mountainous uplands. The valleys are filled with alluvium, which has a maximum thickness of 2,000 ft (610 m) near La Grande (Hampton and Brown, 1964).

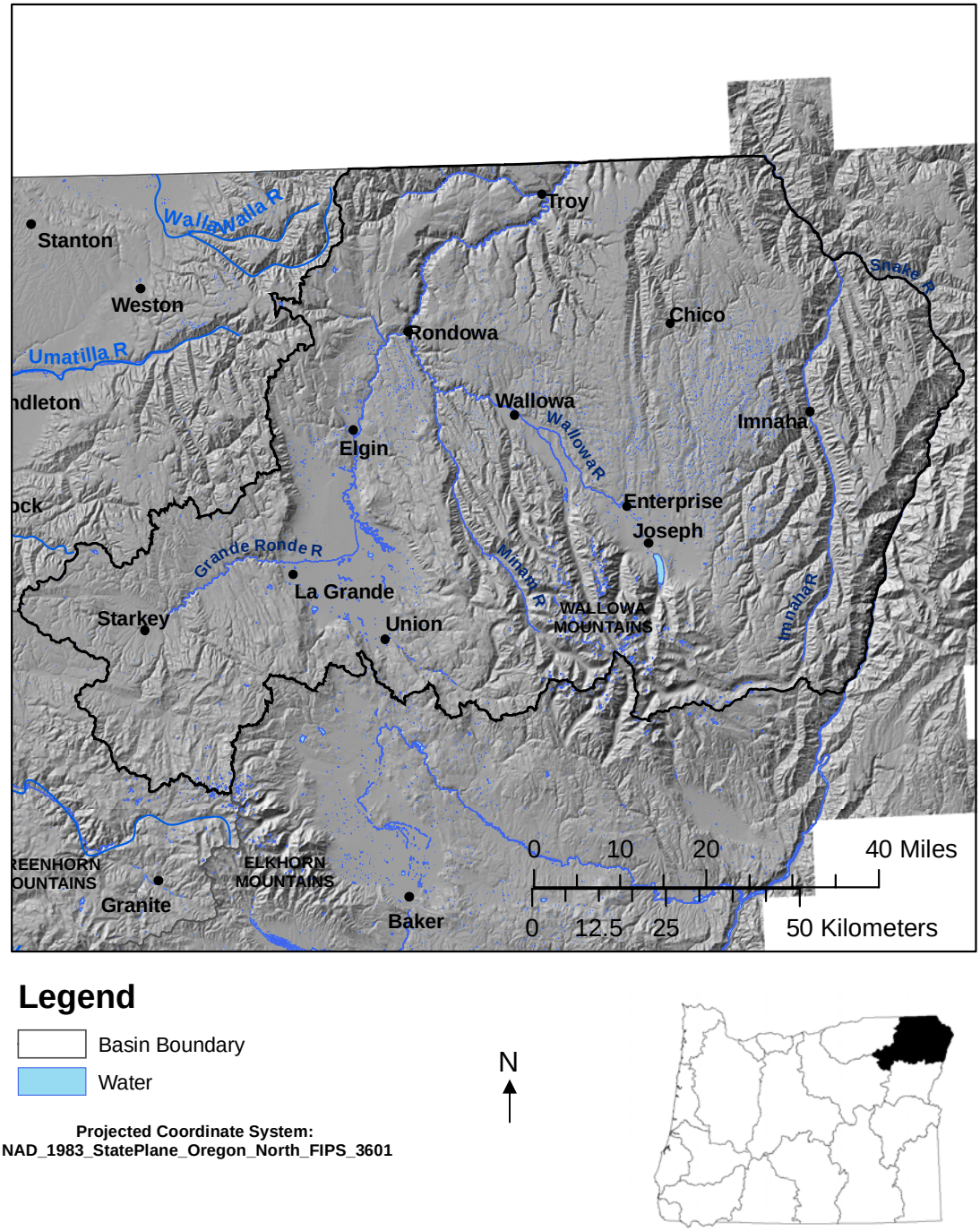


Figure 6-1. Grande Ronde Basin location map. Location of topographic features, rivers and towns in the Grande Ronde Basin that are examined in this study (Data sources: Oregon Geospatial Data Clearinghouse, 2006; Wright, 2006).

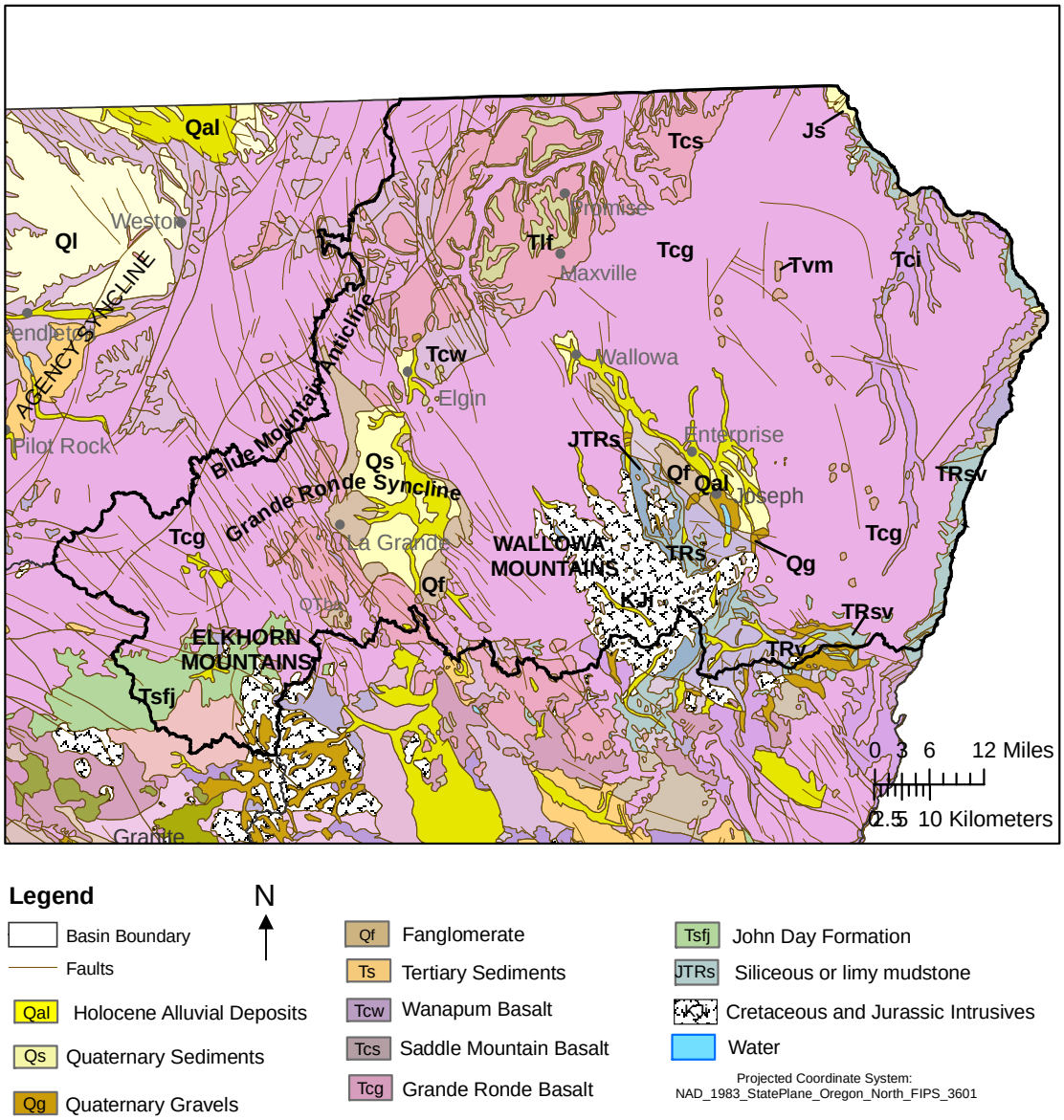


Figure 6-2. Grande Ronde Basin geology map. Geologic formations of importance to future ASR in the Grande Ronde Basin include Tertiary basalts and Quaternary alluvium (Data sources: Oregon Geospatial Data Clearinghouse, 2006; Walker and McLeod, 1991).

Hydrogeologic Units

Major geologic units in the basin include Triassic and Jurassic metamorphic and igneous basement rocks, the Miocene Columbia River Basalt group, and Quaternary alluvium. Pre-Tertiary rocks include the Triassic Wallowa terrane, an accreted volcanic

island archipelago which is exposed in the Wallowa Mountains and throughout Hell's Canyon along the basin's eastern border. Another large feature is the Wallowa batholith, a late Mesozoic pluton exposed in the Wallowa Mountains. Major geologic units' (Figure 6-2) suitability for ASR are discussed in detail in the following section.

Basement Rocks

Basement rocks include metamorphic (JTRs, TRsv, TRv) and intrusive igneous rocks (KJi) of the accreted Wallowa terrane (Vallier and Brooks, 1986). In the southwestern part of the basin, schist, greenstone and quartzite are exposed in the Grande Ronde River canyon. In the southeastern portion of the basin, marble, argillite and greenstone are exposed. Between La Grande and Joseph is the Wallowa batholith, a tonalitic pluton. Intrusives also include quartz diorite and granodiorite, found in the northeastern corner of the basin along the Snake River. According to Hampton and Brown (1964), these units have low permeability, and therefore are not generally suitable for ASR or AR.

Columbia River Basalt

Miocene Columbia River Basalt flows overlie areas of welded tuff as Grande Ronde Basalt (Tcg, 15.6-16.8 Ma); Wanapum Basalt (Tcw, 14.5- 15.2 Ma); and Saddle Mountains Basalt (Tcs, 0.6-14.5 Ma) (Beeson and Moran, 1979). Massive flows are separated by permeable interflow zones, which are important groundwater sources throughout the basin. Total thickness of the basalt exceeds 3,000 ft (914 m) in the northern Grande Ronde basin (Hampton and Brown, 1964). This unit is exposed throughout the basin; it is overlain by alluvial sediments in the La Grande graben and locally along the Wallowa River from Joseph to Wallowa. Hydraulic conductivity varies from 1 to 10 ft/d (0.3 to 3 m/d); well specific capacity is 4 to 10 gpm/ft (72 to 179 m^2/d); transmissivity is estimated as 1,000 to 10,000 ft^2/d (304 to 3048 m^2/d) (Gonthier, 1985). Given appropriate local transmissivity and source water volume, this unit has potential for ASR use. Basalts in mountainous uplands tends to be cut by canyons, and therefore

groundwater in these units escapes to the surface easily (Hampton and Brown, 1964) . Some basalt will not be suitable for ASR for this reason.

Tertiary and Quaternary Alluvium

Pliocene through Holocene glacial events, lacustrine sedimentation and alluvial activity created the sedimentary deposits (Ts, Qf, Qg, Qs, Qal) found in the Grande Ronde and Wallowa River valleys. In the Grande Ronde Valley, hydraulic conductivity ranges from 10 to 100 ft/d (3 to 38 m/d); transmissivity ranges from less than 1,000 to 10,000 ft^2/d (93 to 930 m^2/d) (Gonthier, 1985). Unconfined sedimentary aquifers may be useful for AR in areas with suitable transmissivity and source water quality. ASR may also be possible if stored water can be protected from access by other wells.

Tectonic Structure Influencing Groundwater Flow

The Blue Mountain Anticline trends northeast from Heppner to Kamela (Figure 6-2). Basalt layers dip 5 to 8 degrees to the trough of the Grande Ronde syncline (Hampton and Brown, 1964), forming the western groundwater divide for the basin. The eastern limb transitions into the Grande Ronde syncline near La Grande. Groundwater from the Blue Mountains to the northwest and from the Elkhorn mountains to the south flows toward the city of La Grande.

Northwest trending normal faults cut Tertiary units across the basin, corresponding to the Olympic Wallowa Lineament. Faulting is concentrated in the western third of the basin. The city of La Grande is situated in an alluvium filled graben, with displacement approaching 4,000 ft (1,219 m; Hampton and Brown, 1964) at escarpments surrounding the La Grande basin.

ASR Assessment

The purpose of this section is to provide a general assessment of specific locations for their potential to employ ASR as a part of water supply systems. Site specific investigation is essential to determine if a recharge project is technically, economically,

and environmentally feasible. Positive results from this study indicate the site possesses many of the necessary components for successful aquifer recharge.

Table 6-1: Summary of Analysis Methods. For more detail, see Chapter 3: Analysis Methods.

Method	Description	Result of Method
Volumetric Analysis	Mathematical comparison of aquifer storage capability to the volume of surface water available	If > 1, sufficient storage If = 1 marginal storage If < 1, insufficient storage
Brown's Site Rating System	Site is rated from 0 to 2 for each criteria such as distance to source water, water quality, groundwater flow rate, aquifer thickness	Produces % of ideal ASR parameters at a given site

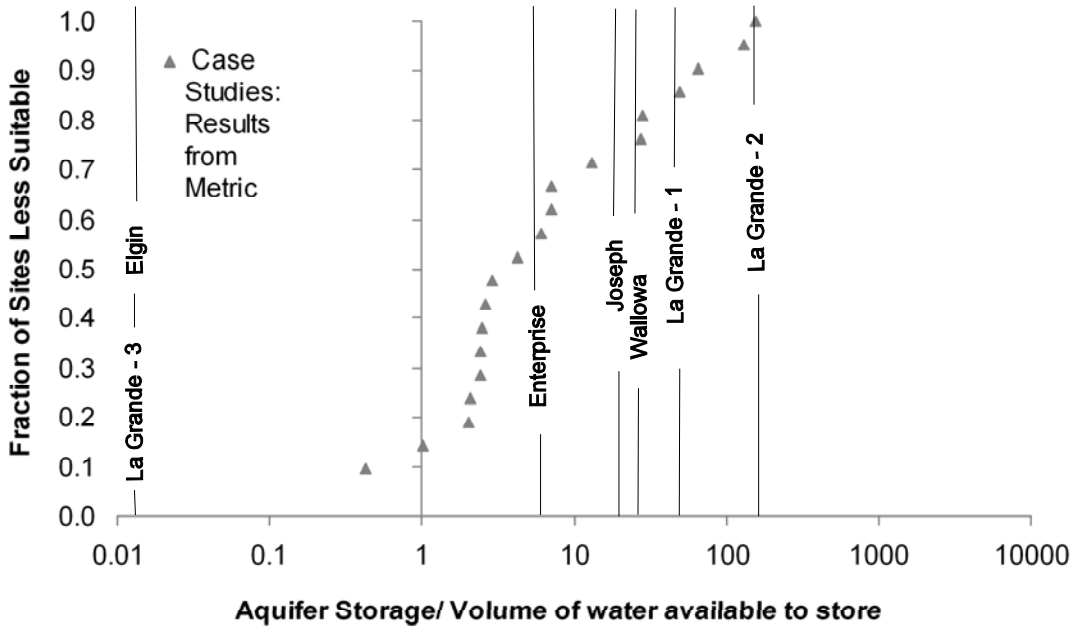


Figure 6-3: Grande Ronde Basin ASR metric results. Volumetric results for Enterprise, Joseph, Wallowa, La Grande-1 and La Grande-2 indicate aquifer storage is sufficient for ASR. Results for La Grande-3 and Elgin indicate the aquifer storage is unsuitable for ASR. Data listed in Appendix B.

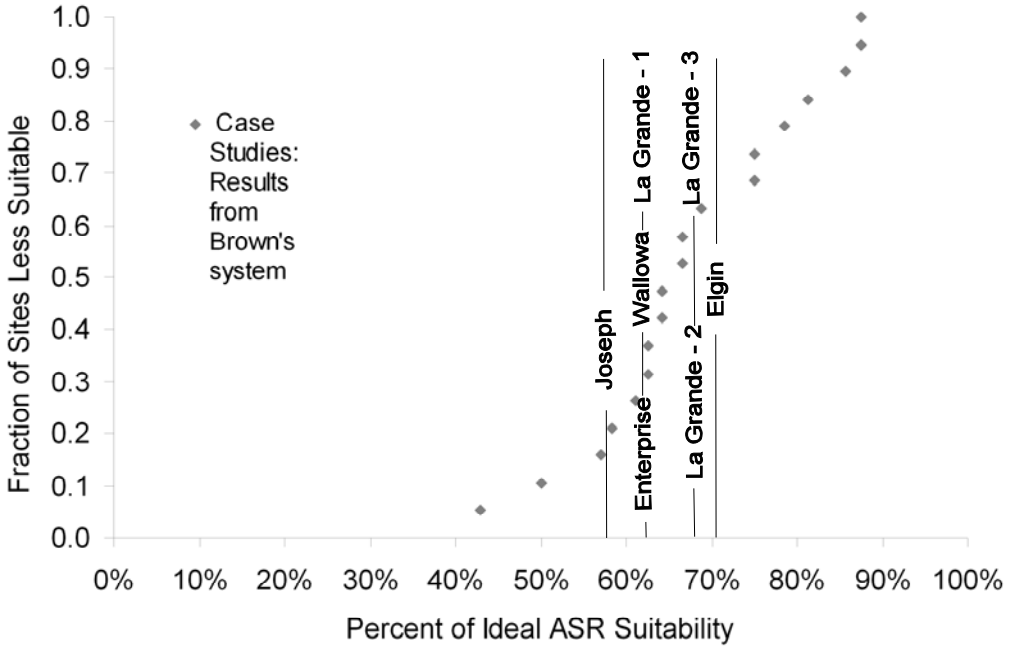


Figure 6-5: Grande Ronde Basin Brown's site rating system results. Brown's ASR site rating system indicates Grande Ronde Basin sites have from 57 % to 72% of ideal conditions. Results from 45% of case studies fall above the results for this basin. Data listed in Appendix C.

La Grande

La Grande is located 0.8 mi (1.4 km) from the Grande Ronde River. The City has water rights to 0.75 cfs (1,835 m^3/d) from the La Grande River Groundwater levels in a sedimentary aquifer in Alicel, about 1 mi. northeast of La Grande (State observation well 870) have not changed significantly in the past decade. Depth to water in both 1995 and 2005 was 100 ft (30.5 m), according to observation well records. Since two of the municipal wells for La Grande access alluvial deposits, the aquifer may be experiencing similar stability in water levels, given their proximity to the observation well. Site specific investigation is necessary to confirm this assumption. Population in the city of La Grande increased from 11,760 in 1990 to 12,440 in 2004 (U.S. Census, 2004).

La Grande's Quaternary sedimentary (Qs, Qal) municipal wells (La Grande-1, UNIO 778 and La Grande-2, UNIO 50520) are screened at depths ranging from approximately 115 to 520 ft (34 to 158 m). These wells have yields of 1,000 to 2,000

gpm (5,450 to 10,900 m^3/d), respectively. Transmissivity in the sediments is estimated by this study as 5,100 to 12,200 ft^2/d (470 to 1,130 m^2/d) from specific capacity data. A third municipal well (La Grande-3, UNIO 2028) accesses basalt aquifers from a depth of 1,107 to 2,430 ft (337 to 741 m). Specific capacity data was not recorded on the well log, therefore transmissivity could not be estimated. At the time of drilling, the basalt well yielded 2,600 gpm (14,170 m^3/d), which implies a productive aquifer.

According to Brown's site rating system, La Grande has 63 to 69% of ideal conditions for ASR (Figure 6-4). The site had moderate ratings for all the assessed parameters. Volumetric analysis indicates aquifer storage is sufficient for ASR (Figure 6-3). On the other hand, at the time of drilling the basalt well had no head space, which creates a negative value with this analysis tool, indicating this well is not suitable.

There is potential for AR through surface spreading in the La Grande basin. However, the fine-grained alluvium and lacustrine deposits may not have adequate vertical permeability, depending on the amount of clay present. Site specific testing is necessary.

Elgin

Elgin is located in the western Grande Ronde Basin, near the Grande Ronde River. The town sits in the northern end of the La Grande graben, on Quaternary alluvial basin fill. The city has surface water rights to a total of 134 cfs (347,898 m^3/d) from the Grande Ronde River, as well as groundwater supplies to meet its needs. Population has increased from 1,586 in 1990 to 1,642 in 2004 (U.S. Census, 2004), while groundwater levels have remained stable in a nearby observation well (UNIO 1717).

Elgin's municipal well (UNIO 1743) has open intervals from approximately 620 to 655 ft (189 to 200 m) below the surface, accessing Grande Ronde Basalt (Tcg) interflow zone aquifers. Well yield is 1,095 gpm (5,068 m^3/d; OWRD well log data). Transmissivity in the basalts is estimated at 6,200 ft^2/d (600 m^2/d) from specific capacity data, which is within the ideal range for ASR of 5,000 to 25,000 ft^2/d (465 to 2,323 m^2/d; Brown et al., 2005).

Volumetric analysis indicates the aquifer storage is insufficient to inject ½ the city's surface water rights for 120 days (Figure 6-3). The volumetric incompatibility may stem from a combination of a large available flow rate (134 cfs or 347,898 m^3/d), the moderate aquifer permeability indicated by specific capacity data, and the lack of head space in the well at the time of drilling. However, Elgin has 71% of optimal ASR parameters in Brown's site rating system (Figure 4-4). The lack of head space may make this site unsuitable for ASR, despite other favorable conditions.

Wallowa

Located on the Wallowa River, the town of Wallowa sits on Columbia River Basalt overlain by Quaternary alluvial deposits. The city has water rights to 10.1 cfs (24,715 m^3/d) from Bear Creek, a tributary to Wallowa River. Population increased from 748 to 824 residents between 1995 and 2004 (U.S. Census, 2004).

A municipal well (WALL 146) accesses Columbia River Basalt (Tcg, Tcw) interflow zones, and yields 1,700 gpm (9,265 m^3/d; OWRD well log data, 2006). Transmissivity estimated from specific capacity is 7,900 ft^2/d (700 m^2/d). This is within the target range for ASR.

Volumetric analysis of this site indicates aquifer storage is sufficient to inject ½ of the city's surface water rights for 120 days (Figure 4-3). Brown's site rating system finds Wallowa has 63% of optimal ASR parameters, with high scores for transmissivity, aquifer thickness and proximity to source water (Figure 4-4). AR may be feasible in surficial gravel aquifers. Surface spreading would avoid the expense of installing a water treatment plant for an ASR project, if conditions meet AR needs.

Enterprise

Enterprise is located on the Wallowa River. Groundwater levels are stable at nearby State Observation well 884. Depth to water in both 1995 and 2005 was 12 ft, and population decreased from 1,905 residents in 1990 to 1,800 in 2004 (U.S. Census, 2004). The town has water rights to a 14.75 cfs (36,093 m^3/d) from Spring Branch Creek.

A municipal well (WALL 50195) has open intervals from 421 to 1,315 ft (128 to 400 m). Water-bearing layers are Grande Ronde Basalt (Tcg) with a yield of 1,023 gpm (5,575 m^3/d; OWRD well log data). Transmissivity estimated from specific capacity is 6,200 ft^2/d (600 m^2/day). This is within the target range for ASR.

Volumetric analysis indicates the basalt municipal well is suitable for ASR (Figure 6-3). According to Brown's site rating system, Enterprise has 63% of optimal ASR parameters. The site scored high for transmissivity, proximity to source water and aquifer thickness greater than 25 ft. AR may be possible in overlying alluvial deposits, if conditions are appropriate.

CHAPTER 7
HOOD BASIN

Basin Hydrology

The Hood Basin covers approximately 1,027 mi^2 (2,659 km^2). It is drained by the Hood River, Fifteenmile Creek and Mill Creek. Watershed divides delineating the basin are found to the west at the peak of Mt. Hood, in the hills east of Fifteenmile Creek and to the north at the Columbia River.

The basin transitions from alpine and dense evergreen forest conditions at the crest of the High Cascades to wet, mild conditions near sea level at the west end of the Columbia River Gorge and drier conditions upriver to the east. In the High Cascades of the western Hood Basin, average annual precipitation exceeds 45 in (1125 mm), largely as snow. Precipitation averages 30 in (750 mm) in Hood River, decreasing to about 14 in (350 mm) in The Dalles (Oregon Climate Service, 2007). Surface and groundwater is recharged in the High Cascades and flow toward the Hood and Columbia Rivers.

Physical Setting

Hood Basin topography ranges from alpine peaks to alluvial valleys (Figure 7-1). The western edge incorporates the High Cascades at 11,225 ft (3421 m) decreasing to 90 ft (27 m) above sea level at Hood River. The High Cascades are formed of Miocene through Holocene basalt, andesite and tuff (Priest, 1990). East of the Cascades lies the Hood River subbasin, characterized by Miocene Columbia River Basalt overlain by Cascade andesite and basalt; these are in turn overlain by Quaternary alluvial and glacial sand, gravel and mudflow deposits. The basement rock is composed of the Eagle Creek Formation in the Hood River Valley. East of the city of Mt. Hood, sandstone, shale, conglomerate and tuff of the Dalles Formation overlie Columbia River Basalts.

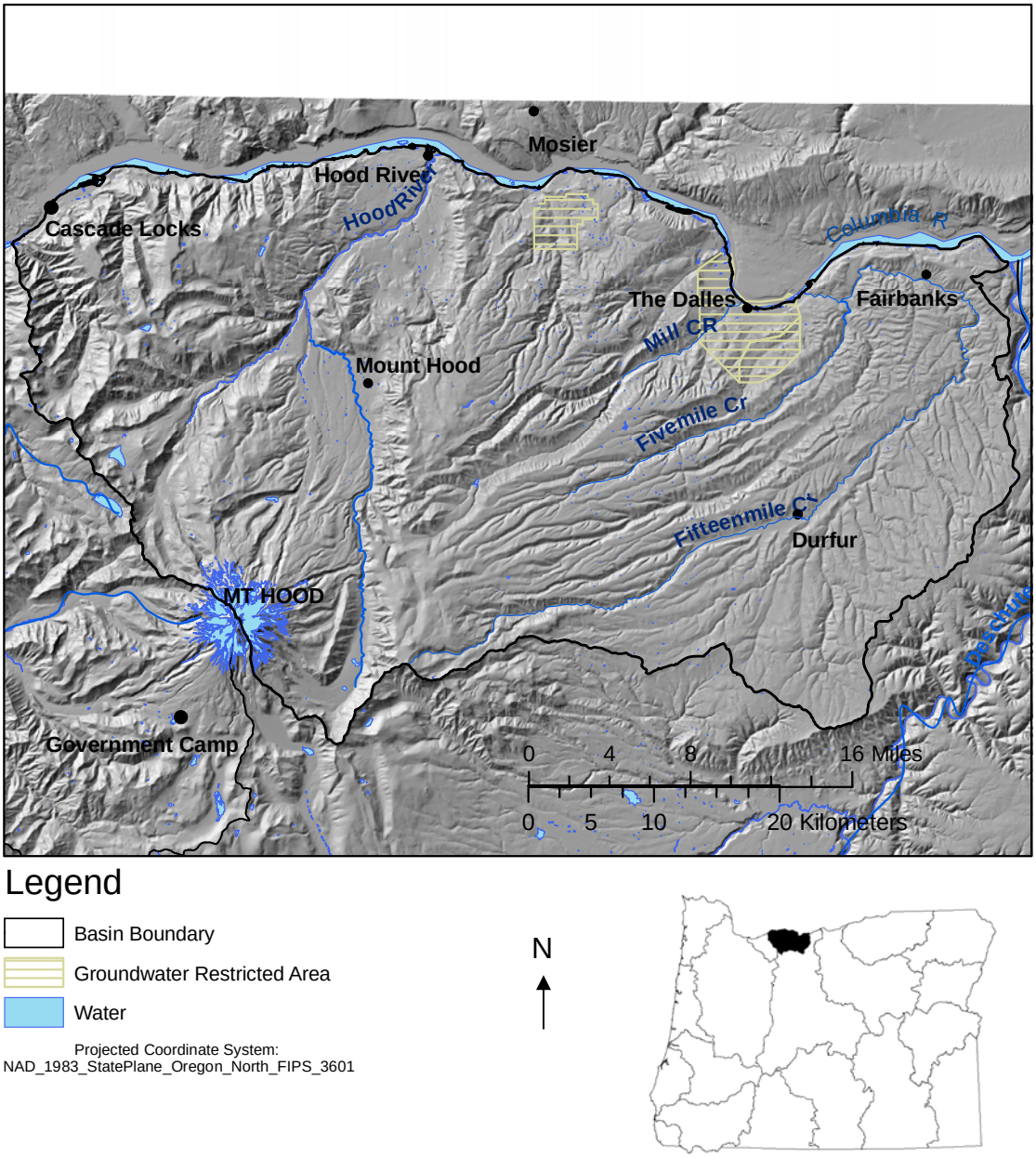


Figure 7-1. Hood Basin location map. Location of topographic features, rivers and towns in the Hood Basin that are examined in this study (Data sources: Oregon Geospatial Data Clearinghouse, 2006; Wright, 2006).

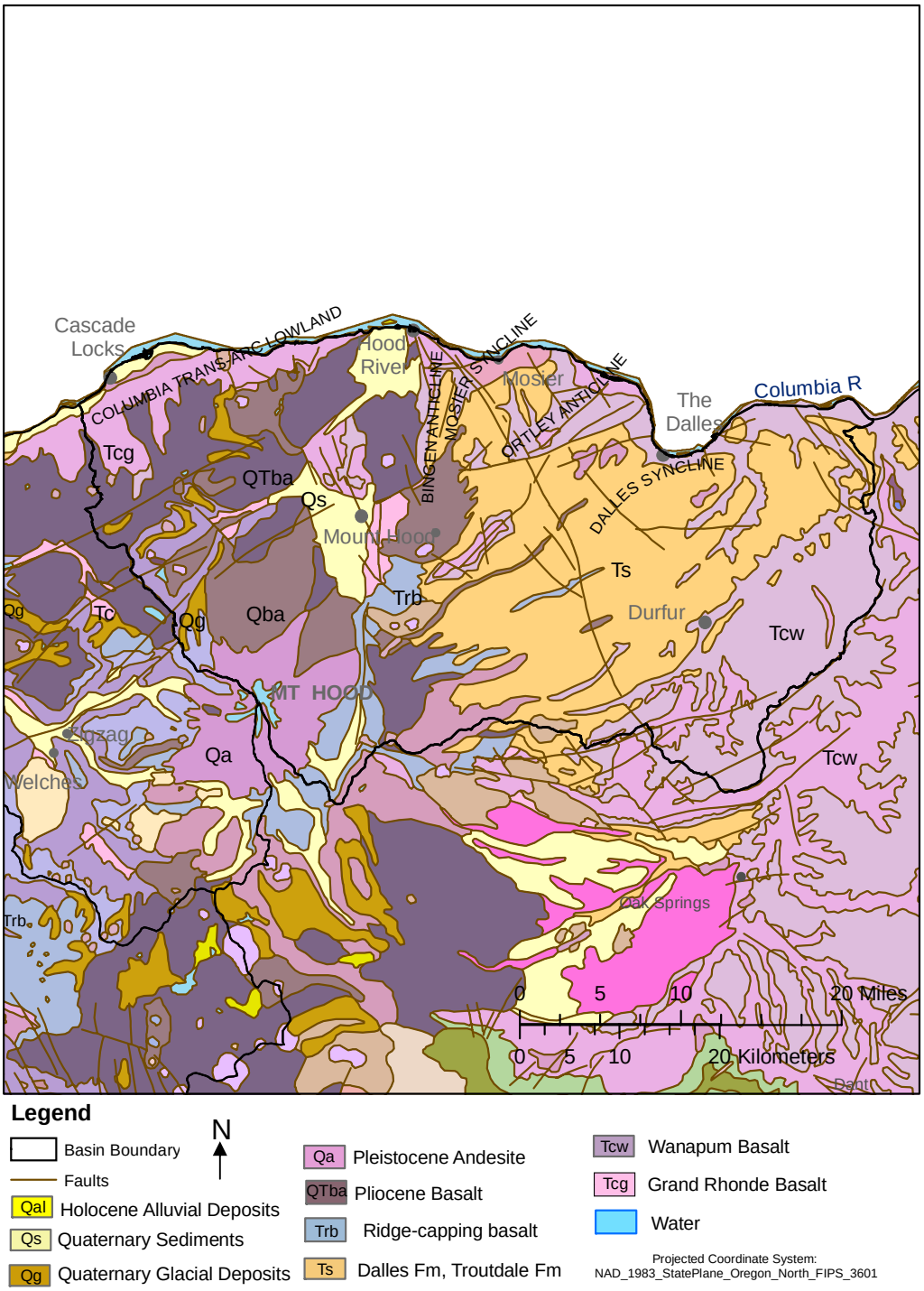


Figure 7-2. Hood Basin geology map. Geologic formations of importance to future ASR in the Hood Basin include Quaternary and Tertiary Basalts (Data Sources: Oregon Geospatial Data Clearinghouse, 2006; Walker and McLeod, 1991).

Groundwater Restricted Areas (Figure 7-1) refer to administrative areas defined by Oregon Water Resources Department, where groundwater declines have prompted an action to limit further groundwater allocation. Any location that has experienced long-term groundwater decline has intrinsic storage capacity for ASR or AR.

Hydrogeologic Units

Geologic units (Figure 7-2) are discussed in detail in the following section.

Eagle Creek Formation

The Eagle Creek Formation represents the basement low permeability boundary to regional groundwater flow in the Hood River subbasin. It is characterized by poorly sorted volcanic sediments, conglomerates, tuffs, with some andesitic flow layers. It ranges from 0 to 4,200 ft (1,280 m) in thickness (Allen, 1960). According to Sceva (1966), a 200 ft (61 m) deep well at a U.S. Forest Service Ranger Station accessing this formation yielded 4 gpm (22 m^3/d), with 170 ft (52 m) of drawdown. This indicates low transmissivity which makes the Eagle Creek Formation unsuitable for ASR or AR projects.

Columbia River Basalt Group

The Miocene Columbia River Basalt group (Tcg, Tcw) consists of several basalt flows. These include the Pomona, which is a member of the Saddle Mountains Basalt, and Priest Rapids and Frenchmen Springs basalts which are members of the Wanapum Basalt (Lite and Grondin, 1988). The group exceeds 2,000 ft (610 m) in total thickness in the Hood Basin (Grady, 1983). Individual flows are characterized by a thin, highly fractured zone at its base. Middle flow sections tend to be massive with vertical cooling joints which are irregularly spaced. The upper zone is generally broken, rubbly, vesicular, brecciated or weathered basalt (Grady, 1983). In some places, pillow basalts occur where the flow entered water. Broken zones at the top and bottom of flow layers can be highly permeable, and represent the main aquifers in the basin. Texture, water-bearing properties and unit thickness vary throughout the basin. The Columbia River

Basalt group is exposed along the Columbia River Gorge, along anticlines throughout the basin and along the southeastern edge of the basin.

Average specific capacity of wells in the Hood Basin Columbia River Basalt is 88 gpm/ft (1,575 m^2/d), although in The Dalles Groundwater Reservoir specific capacity is reported to be as high as 550 gpm/ft (9,860 m^2/d; Grady, 1983). Transmissivity is reported to range from 11,500 to 24,000 ft^2/d (1,068 to 2,230 m^2/d) in the Pomona basalt and from 9,100 to 29,900 ft^2/d (845 to 2,778 m^2/d) in the Priest Rapids basalt at Mosier (Lite and Grondin, 1988). The U.S. Geological Survey conducted ASR tests in basalt at The Dalles in 1965, with favorable results (Foxworthy, 1967).

Dalles Formation

The Pliocene Dalles Formation (Ts) consists of volcanic mudflow deposits, sandstone and tuff. It is exposed throughout most of the eastern half of Hood Basin (Figure 7-2). Maximum total thickness is approximately 1,800 ft (549 m), saturated thickness is less than 300 ft (91 m) (Grady, 1983). Well yields are low to moderate, producing 0.5 to 55 gpm (2.7 to 300 m^3/d). The formation is generally poorly-sorted, although there are permeable lenses of well-sorted sandstone in the deeper layers of the unit (Grady, 1983). Moderate permeability indicates that while this aquifer is an important domestic groundwater source (Foxworthy, 1967), it is not likely to be a primary target for ASR or AR.

High Cascade Lavas

Pliocene, Pleistocene and Holocene volcanic activity deposited andesite, basalt, tuff and breccia (Trb, QTba, Qa). They are exposed in the Cascade Mountains from the peak of Mt. Hood north to the Columbia River near Hood River, and east to the headwaters of Fifteenmile Creek. Thickness varies with topography, ranging from 100 to 3000 ft (30 to 914 m) (Leonard and Collins, 1983). Water-bearing layers occur mainly between lava flows or in broken, irregular zones. Wells accessing these layers produce 0.5 to 88 gpm (484 m^3/d; Grady, 1983). Due to the rugged, steep terrain is this area, the High Cascade lavas are not likely candidates for ASR or AR.

Quaternary Deposits

Pleistocene and Holocene deposits (Qg, Qs, Qal) consisting of clay to boulder sized particles overlie the Dalles Formation and the Columbia River Basalt in the Hood Basin as valley fill. These include the poorly-sorted glaciofluvial deposits that resulted from the Missoula floods of 13,000 years ago, as well as alluvial deposits. The highest yielding deposits are alluvial sand and gravel deposits found along the Hood and Columbia Rivers. Thickness ranges up to about 200 ft (61 m) (Sceva, 1966). Permeability is low to high, depending on grain size and the degree of sorting. This aquifer's variable permeability indicates it may be suitable for surface spreading AR operations in some areas, while other areas will not be feasible. ASR projects are unlikely in this formation due to its variable character.

Tectonic Structure Influencing Groundwater Flow

Major tectonic structures of the Hood Basin include dip-slip faults, strike-slip faults and compressional folds resulting in anticlines and synclines that form local groundwater divides and subbasins. The Rocky Prairie thrust fault referred to by Lite and Grondin (1988) impedes groundwater flow from the Columbia Hills anticline toward the Mosier syncline. This is evidenced by the 430 ft (131 m) difference in artesian pressures observed above and below the thrust fault. Other faults known to affect groundwater flow are found in Hood River and The Dalles (Oregon Water Resources Department, 1965). According to Newcomb (1969), northwest trending faults throughout the basin affect groundwater flow locally, and will require site specific study to determine impact on potential ASR projects.

ASR Assessment

The purpose of this section is to provide a general assessment of specific locations for their potential to employ ASR as a part of water supply systems. Site specific investigation is essential to determine if a recharge project is technically, economically, and environmentally feasible, but positive results from this study indicate the site possesses many of the necessary components for successful aquifer recharge.

Table 7-1: Summary of Analysis Methods. For more detail, see Chapter 3: Analysis methods.

Method	Description	Result of Method
Volumetric Analysis	Mathematical comparison of aquifer storage capability to the volume of surface water available	If > 1, sufficient storage If = 1 marginal storage If < 1, insufficient storage
Brown's Site Rating System	Site is rated from 0 to 2 for each criteria such as distance to source water, water quality, groundwater flow rate, aquifer thickness	Produces % of ideal ASR parameters at a given site

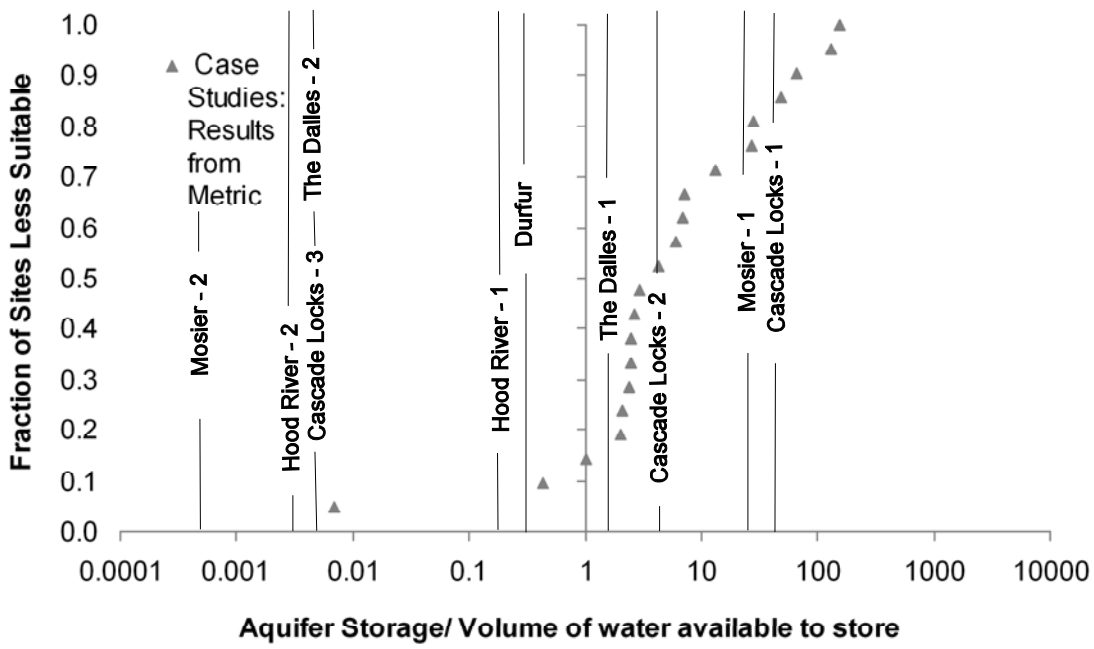


Figure 7-3: Hood Basin ASR metric results. Volumetric results for Mosier-2, Hood River-2, Cascade Locks-3, The Dalles-2, Hood River-1 and Durfur indicate the aquifer storage capacity not suitable for ASR. The Dalles-1, Cascade Locks-2, Mosier-1 and Cascade Locks-1 have sufficient aquifer storage. Data listed in Appendix B.

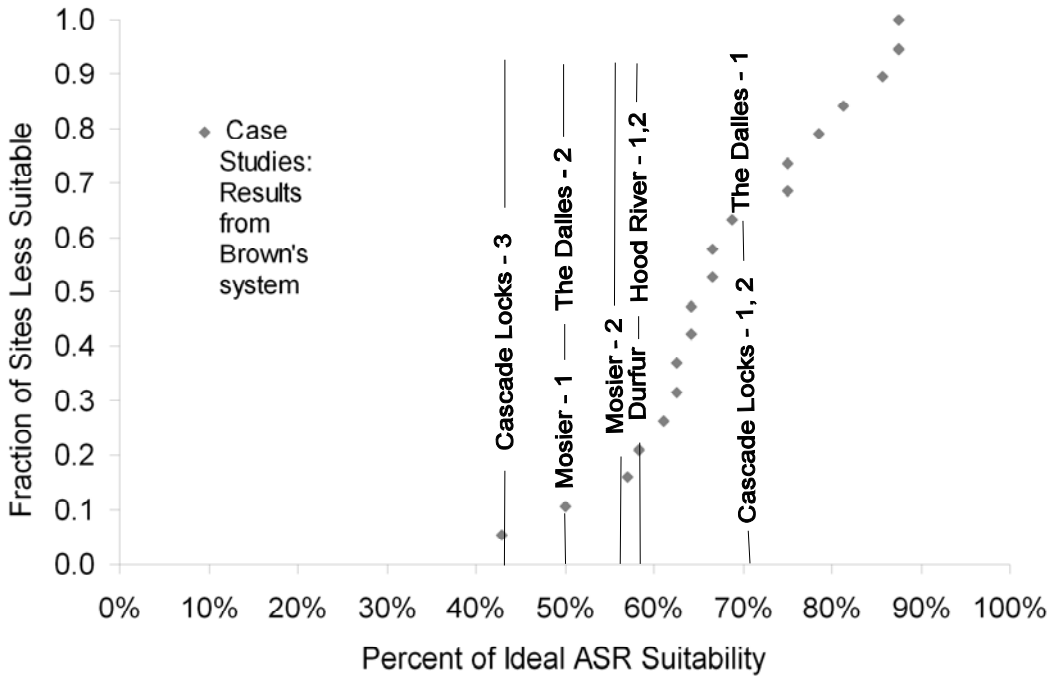


Figure 7-4: Hood Basin Brown's rating system results. Brown's ASR site rating system indicates Hood Basin sites have 40 % to 71% of ideal conditions. Results for 30% of case studies are greater than the range of results for this basin. Data listed in Appendix C.

Cascade Locks

Cascade Locks is located in the northwestern corner of the basin. The City of Cascade Locks currently uses groundwater rights for municipal water supply (OWRD WRIS, 2006). While groundwater levels in Cascade Locks are not showing decline (1995 and 2005 depth to water was reported 25 ft (7.6m) (OWRD groundwater level database, accessed August 2006)), its population increased from 930 in 1990 to 1,101 in 2004 (U.S. Census, 2004).

Wells in the Cascade Locks area have open intervals in cemented gravel aquifers from approximately 12 to 100 ft (3.6 to 30.5 m) below ground surface; these are Quaternary gravel and alluvial deposits (Qs). Other open intervals range from 158 to 173 ft (48 to 53 m) below ground surface, intercepting Eagle Creek Formation conglomerates (OWRD well log database, 2006).

Transmissivity estimated from specific capacity for gravel deposit wells in Cascade Locks (Cascade Locks-1, HOOD 352 and Cascade Locks-2, HOOD 346) is 62,000 and 5,300 ft^2/d (5,800 and 500 m^2/d) respectively. Cascade Locks-1 in the Eagle Creek Formation has an estimated transmissivity of 100 ft^2/d (10 m^2/d) (OWRD well log database, 2006).

Volumetric analysis at Quaternary gravel wells shows aquifer storage is sufficient for ASR (Figure 7-3). The Eagle Creek Formation has insufficient storage for ASR. Brown's site rating system finds Cascade Locks gravel wells have 71% of optimal ASR parameters (Figure 7-4). The Eagle Creek Formation has 43%. Therefore, it is more likely an ASR project will succeed in the gravel aquifer than in the Eagle Creek aquifer.

There is potential for AR through surface spreading in the Cascade Locks area in permeable alluvial deposits overlying basement confining Eagle Creek formation, depending on the level of hydraulic connectivity to the Columbia River (Sceva, 1966).

Hood River

Hood River is located at the confluence of the Hood and Columbia Rivers. The city has surface water rights to19 cfs (46,493 m^3/d) of Cold Spring Creek and Laurel Creek. Population has increased from 4,632 in 1990 to 6,480 in 2004 (U.S. Census, 2004).

No municipal well logs were located for this study. However, domestic wells have open intervals from 54 to 600 ft (16 to 183 m) below the surface (OWRD well log database, 2006). They access Columbia River Basalt aquifers (Tcg, Tcw). Median hydraulic conductivity for this formation is reported as 5 ft/day (1.5 m/day) in The Dalles (Foxworthy, 1967). Transmissivity estimates range from 50 to 70 ft^2/d (5 to 7 m^2/d).

Volumetric analysis indicates aquifer storage is marginally suitable for the volume of water available for storage (Figure 7-3). Well inefficiency could account for ASR. Brown's site rating system finds Hood River has 57% of optimal ASR parameters, with low scores for transmissivity and the presence of species that may be threatened by river flow depletion (Figure 7-4).

Quaternary and Tertiary sediments west of Hood River may be suitable for surface spreading AR operations, based on permeability. However, these sedimentary aquifers must be investigated for hydraulic connection to the Columbia River.

Mosier

Mosier is located at the confluence of Mosier Creek and the Columbia River. The city does not have surface water rights at this time, but there is unallocated surface water available in Mosier Creek for storage. Water levels in the basalt aquifer have declined over the past decade, depth to water dropped from 25 to 75 ft (7.6 to 23 m) below the surface between 1995 and 2005. The area is over-drafted due to well discharge that is greater than the rate of natural groundwater recharge (Lite and Grondin, 1988).

Wells have open intervals varying from 120 to 404 ft (37 to 123 m) below the surface, with yields of 167 to 357 gpm (910 to 1,946 m^3/d; OWRD well log database, 2006). They access Columbia River Basalt (Tcg, Tcw). Specific capacity in the selected Mosier wells ranges from 22 to 80 gpm/ft (386 to1,433 m^2/d) (OWRD well log database, 2006).

Estimated transmissivity ranges from 8,900 to 21,400 ft^2/d (800 to 2,000 m^2/d). This suggests the wells access aquifers that are suitable for ASR, because they are within the ideal range of 5,000 to 25,000 ft^2/d (465 to 2,323 m^2/d; Brown, 2005). Lite and Grondin (1988) reported similar transmissivities for basalt aquifers in Mosier, ranging from 11,500 to 24,000 ft^2/d (1,068 to 2,230 m^2/d) in the Pomona basalt and 9,100 to 29,900 ft^2/d (845 to 2,778 m^2/d) in the Priest Rapids basalt.

Volumetric analysis indicates one city well in Mosier (Mosier-1, WASC 2856) is suitable for ASR and one is not (Mosier-2, WASC 2764), due to a lack of head space in the well. In light of recent groundwater declines, this may no longer be the case. Brown's site rating system finds Mosier has 50% to 56% of optimal ASR parameters. The site lost points for high well density, and the presence of threatened fish species.

Due to surficial geology in the Mosier area, AR is not likely to succeed. Columbia River Basalt lies at the surface, which has low vertical permeability.

The Dalles

The Dalles is located at the confluence of Fifteenmile Creek and the Columbia River. The Dalles has municipal surface water rights to Columbia River and Crow Creek water, and a treatment plant capable of processing 2.2 MGD (8,327 m^3/d).

Wells have open intervals varying from 62 to 224 ft (19 to 68 m) below the surface, with yields of 70 to 2,500 gpm (382 to 13,625 m^3/d; OWRD well log database, 2006). They access Columbia River Basalt aquifers (Tcw, Tcg). Estimated transmissivity for The Dalles-2 (WASC 2416) and The Dalles-1 (WASC 2419) is 900 and 68,800 ft^2/d (80 to 6,390 m^2/d), respectively.

Volumetric analysis indicates The Dalles-1 is suitable for ASR, while The Dalles-2 is not capable of storing water at the given rate (Figure 7-3). Brown's site rating system finds The Dalles-1 has 71% of optimal ASR parameters, while The Dalles-2 has 50% (Figure 7-4). A previous study by Foxworthy (1967) found the Columbia River Basalt in The Dalles suitable for ASR during pilot tests, as discussed in Chapter 2: Case Studies.

Due to surficial geology in and around The Dalles, AR is not likely to succeed. Columbia River Basalt lies at the surface, which has low vertical permeability.

Durfur

The town of Durfur is located up-stream from the confluence of Ramsey and Fifteenmile Creeks. The town has no surface or ground water rights at the present, but surface water is available for allocation from Fifteenmile Creek (WRIS, 2006). Water needs are met through domestic and irrigation wells, and irrigation districts.

No municipal well logs were located by this study, so a domestic well was selected to represent the local aquifer environment. A private well has open intervals from 120 to 300 ft (37 to 91 m) below the surface. It yields 160 gpm (872 m^3/d), and draws water from the Columbia River Basalt (Tcw, Tcg). Median hydraulic conductivity for this formation is 5 ft/d (1.5 m/d) (Foxworthy, 1967). Estimated transmissivity is 1,600 ft^2/d (150 m^2/d). This is below the target range for ASR

Volumetric analysis indicates Durfur's aquifer has insufficient storage for ASR (Figure 4-3). Durfur has 57% of optimal ASR parameters, with low scores for low transmissivity and the presence of threatened fish species (Figure 4-4).

Surficial Quaternary and Tertiary sediments (Qs, Ts) in Durfur may not be suitable for surface spreading AR operations, because the layer is thin and yields little groundwater (Oregon Water Resources Department, 1965), suggesting low infiltration rates.

CHAPTER 8
JOHN DAY BASIN

Basin Hydrology

The John Day Basin covers approximately 8,070 mi^2 (20,905 km^2) and is drained by the John Day River and its major tributaries: the North, Middle Fork and South Fork John Day Rivers. Watershed divides delineating the basin are found to the west at the crest of the Ochoco Mountains, to the south along the Aldrich and Strawberry Mountains, to the east in the Elkhorn Mountains and to the north at the Columbia River.

The climate is high desert. Average annual precipitation ranges from approximately 9 in (229 mm) at the northern end of the basin to 40 in (1,020 mm) in the mountains (Oregon Climate Service, 2007). Most precipitation occurs in the winter months as snow; during the summer and early fall there can be close to no rainfall. This indicates that the majority of groundwater recharge for the basin occurs as snow melts and infiltrates or flows off the highlands in the Blue and Ochoco Mountains.

Physical Setting

The John Day Basin is characterized by high desert plateaus and mountains formed by accretion of island archipelagos. These accreted terranes are overlain by "native" formations such as the Clarno, John Day and Columbia River Basalt formations. The western part of the basin, bounded by the Ochoco Mountains, is composed of exotic terranes accreted during the late Mesozoic to form the Blue Mountains. The Southern boundary of the basin is characterized by shallow marine forearc sediments such as limestone, mudstone, sand and siltstones. This area has been extensively folded and faulted (Orr and Orr, 2000). The northern end of the basin, as it flows into the Columbia River, includes a portion of the Deschutes-Umatilla Plateau's massive Columbia River Basalt Group.

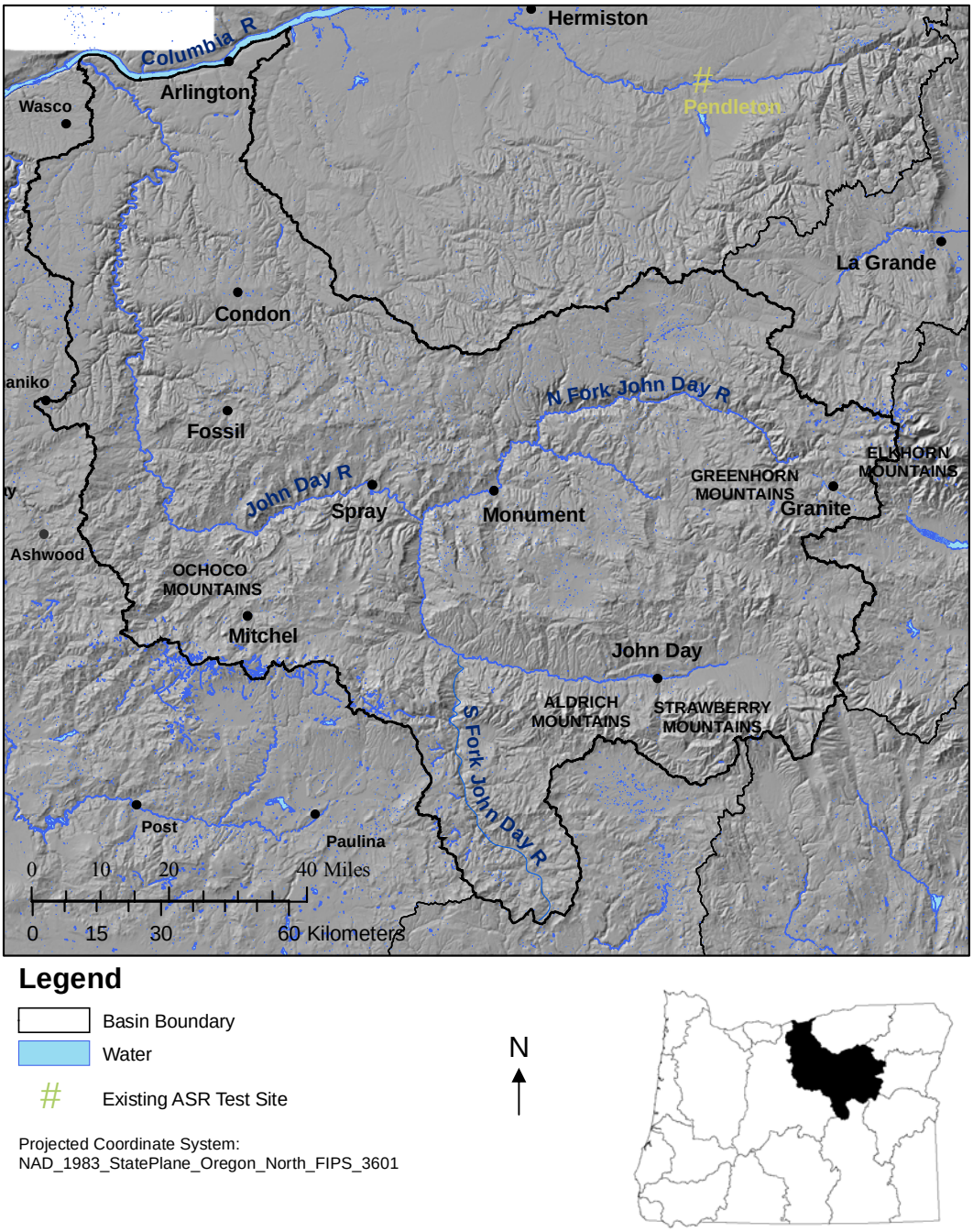


Figure 8-1. John Day Basin location map. Location of topographic features, rivers and towns in the John Day Basin that are examined in this study (Data sources: Oregon Geospatial Data Clearinghouse, 2006; Wright, 2006).

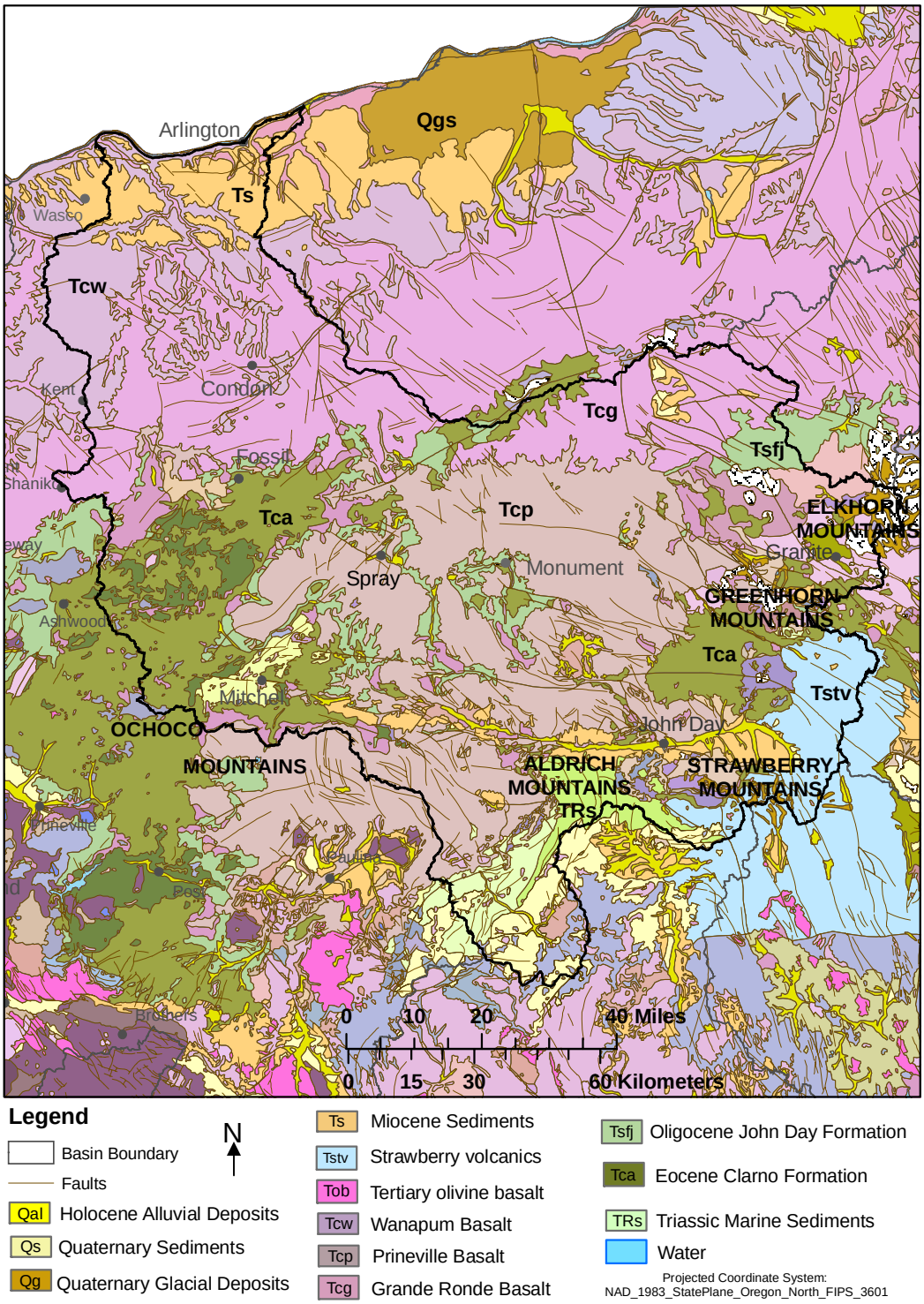


Figure 8-2. John Day Basin geology map. Geologic formations of importance to future ASR in the John Day Basin include Quaternary and Tertiary basalts (Data sources: Oregon Geospatial Data Clearinghouse, 2006; Walker and McLeod, 1991).

Hydrogeologic Units

Geologic units (Figure 8-2) are discussed in detail in the following section.

Clarno Formation

The Eocene Clarno Formation (Tca) extends from the Ochoco Mountains east into the Elkhorn Mountains. It is composed of lava, mud, ash flows, clay, siltstone and conglomerate. In the center of the basin it is overlain by Columbia River Basalt and Quaternary sediments. The Clarno Formation has a maximum thickness of 1,000 ft (305 m). Abundant fossils of tropical plants and land mammals can be found in this formation (Vallier and Brooks, 1986). Gonthier (1985) reported hydraulic conductivity to be 0.01 to 1 ft/d (0.003 to 0.3 m/d) and transmissivity to be less than 1,000 ft^2/d (93 m^2/d). These low values indicate it is unsuitable for ASR or AR projects, although there may be localized exceptions.

John Day Formation

The Oligocene John Day Formation (Tsfj) extends from the eastern Deschutes Basin, under the central John Day basin, and is exposed in the Elkhorn Mountains. It is composed of early Oligocene volcanic ash interbedded with sedimentary strata and basalt flows. Thickness reaches a maximum of 4,000 ft (1,219 m) at the eastern edge of the Deschutes Basin (Robinson et al., 1984). The John Day Formation's hydraulic conductivity ranges from 0.01 to 1 ft/day (0.003 to 0.3 m/day); transmissivity is less than 1,000 ft^2/d (305 m^2/d; Gonthier, 1985). Although there may be localized exceptions, this low permeability formation is not likely to be useful for ASR or AR projects.

Columbia River Basalt

Miocene Columbia River Basalt flows cover most of the John Day Basin as Grande Ronde Basalt (Tcg, 15.6-16.8 Ma), Prineville Basalt (Tcp, 15.77 Ma), and Wanapum Basalt (Tcw, 14.5- 15.2 Ma) (Beeson and Moran, 1979). Massive flows are separated by permeable interflow zones which are important groundwater sources throughout the basin. Unit thickness ranges up to approximately 3,000 ft (914 m) near the

Columbia River. This group is exposed from the Columbia River south to the range front of the Aldrich, Strawberry and Greenhorn Mountains. Hydraulic conductivity varies from 1 to 10 ft/d (0.3 to 3 m/d); well specific capacity is 4 to 10 gpm/ft (72 to 179 m^2/d); transmissivity is estimated from 1,000 to 10,000 ft^2/d (300 to 3,050 m^2/d) (Gonthier, 1985). Given appropriate local transmissivity and source water volume, this unit has potential for ASR use.

Tertiary Strawberry Volcanics

Miocene Strawberry volcanics (Tstv) occur south of the town of Granite, and they are exposed throughout the Strawberry Mountains and into Malheur Lake Basin. The Strawberry Volcanics are a product of the Miocene andesitic volcanic center that extends southwest to northeast through eastern Oregon, characterized by individual flows from 10 to 200 ft (3 to 61 m) thick; fine grained sedimentary interbeds may be useful aquifers in some locations (Gonthier, 1985). The Strawberry volcanics are over 1,000 feet (305 m) thick near Ironside Mountain (Walker, 1990). Hydraulic conductivity ranges from 1 to 10 ft/day (0.3 to 3 m/day); transmissivity is estimated from 1,000 to 10,000 ft^2/d (304 to 3,050 m^2/d) (Gonthier, 1985). This unit may be useful for ASR in areas with well confined interflow zones.

Quaternary and Tertiary Sedimentary and Volcaniclastic Deposits

Erosion of uplands, glacial deposits, alluvial activity and volcanic eruptions deposited the Miocene through Pleistocene sediments (Ts, Qs, Qg) found in the John Day River valley, including the Mascall and Alkali Canyon Formations. The Mascall Formation (Qs) appears most extensively from Mitchell east through John Day, and is characterized by sandstone, conglomerate and diatomite; in areas it includes clay layers which exhibit low hydraulic conductivity. The Alkali Canyon Formation (Ts), a basaltic cobble deposit found south and west of Arlington, is not used extensively for groundwater supply (Oregon Water Resources Department, 1986).

Volcanic ash flow tuff interbedded with poorly consolidated sand, gravel and mudstone is found in the Rattlesnake Formation; high permeability of the unconsolidated

materials is negated in places by relatively low permeability welded ash and clay layers. The Rattlesnake Formation (Ts) is found east of Mitchell, along the John Day River, to its headwaters in the Strawberry Mountains.

Sediments range from a few feet thick to several hundred feet thick (Oregon Water Resources Department, 1986). These deposits form unconfined aquifers throughout the basin; Quaternary alluvium is one of the most important aquifers in the basin. Hydraulic conductivity ranges from 10 to 500 ft/d (3 to 150 m/d); well specific capacity ranges from 5 to 40 gpm/ft (90 to 720 m^2/d) (Gonthier, 1985). Unconfined sedimentary aquifers may be useful for AR in areas with suitable transmissivity and source water quality.

Tectonic Structure Influencing Groundwater Flow

According to Whiteman et al. (1994), Quaternary faulting in the John Day Basin has been isolated to a set of NW trending faults near Condon, a parallel set in the Greenhorn and Strawberry Mountains, and along the John Day River trending east-west near the northern range front of the Aldrich and Strawberry Mountains. Folding and faulting in the Aldrich and Strawberry Mountains is unlikely to affect ASR, because the steep rugged terrain will negate aquifer recharge in this area.

ASR Assessment

The purpose of this section is to provide a general assessment of specific locations for their potential to employ ASR as a part of water supply systems. Site specific investigation is essential to determine if a recharge project is technically, economically, and environmentally feasible, but positive results from this study indicate the site possesses many of the necessary components for successful aquifer recharge.

Table 8-1: Summary of Analysis Methods. For more detail, see Chapter 3: Analysis Methods.

Method	Description	Result of Method
Volumetric Analysis	Mathematical comparison of aquifer storage capability to the volume of surface water available	If > 1, sufficient storage If = 1 marginal storage If < 1, insufficient storage
Brown's Site Rating System	Site is rated from 0 to 2 for each criteria such as distance to source water, water quality, groundwater flow rate, aquifer thickness	Produces % of ideal ASR parameters at a given site

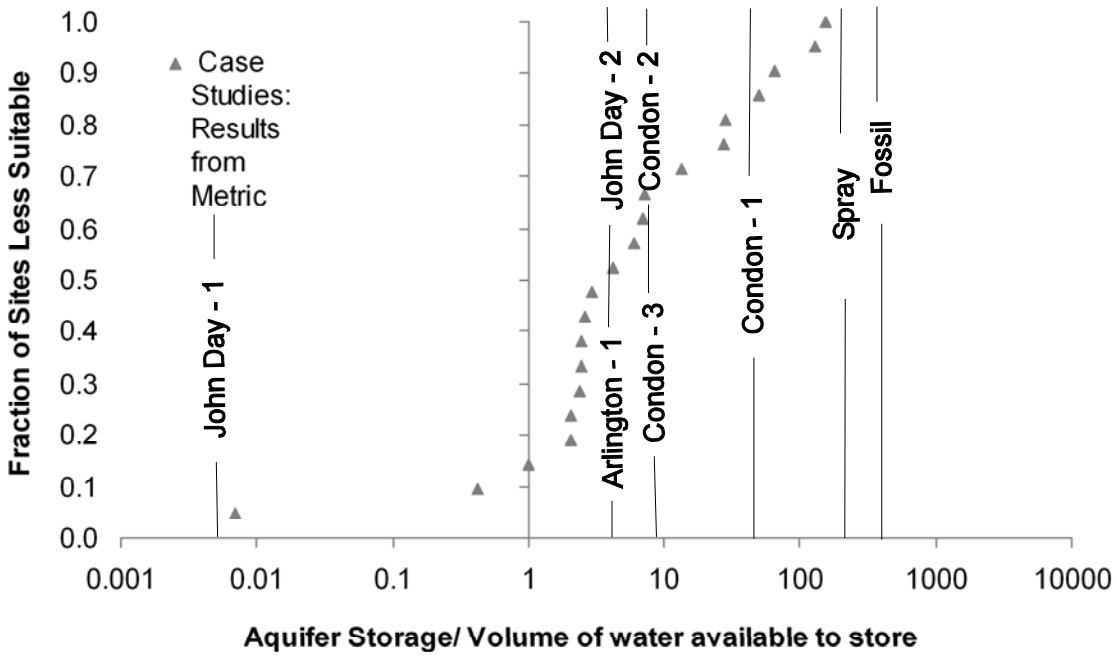


Figure 8-3: John Day Basin ASR metric results. Volumetric results for Arlington, John Day-2, Condon, Spray and Fossil indicate aquifer storage is sufficient for ASR. Results for John Day-2 indicate the aquifer has insufficient storage for injection of the available water. Data listed in Appendix B.

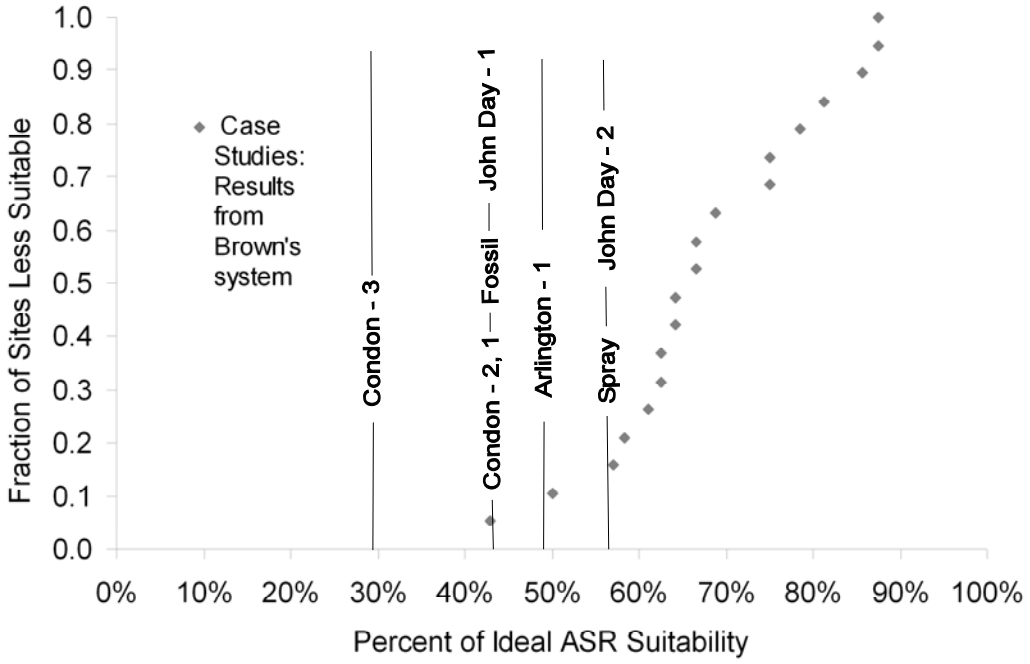


Figure 8-4: John Day Basin Brown's rating system results. John Day Basin sites have from 30 % to 57% of ideal conditions. 80% of case studies are greater than this basin's results. Data listed in Appendix C.

Arlington

Arlington is located on the banks of the Columbia River, approximately 9 mi (14.4 km) from the John Day River. Arlington groundwater levels are not showing significant decline (1979 depth to water was reported 180 ft (55 m), while 1990 was 185 ft (56 m) (OWRD groundwater level database, 2006). Its population increased from 425 in 1990 to 490 in 2004 (U.S. Census, 2004).

Arlington's municipal wells are screened at depths ranging from 60 to 619 ft (18 to 183 m), drawing water from Columbia River Basalts (Tcg). These wells have yields ranging from 200 to 930 gpm; relatively low yields for Columbia River Basalts indicate poor well efficiency or an area of abnormally low aquifer transmissivity. Transmissivity estimated for a municipal well (Arlington-1, GILL 166) is 1,400 ft^2/d (130 m^2/d). An industrial well was examined for comparison (Arlington-3, GILL 170) which is about

100 ft (30.4 m) deeper and has an estimated transmissivity of 37,700 ft^2/d (3,500 m^2/d). Improvement of the municipal well may increase the feasibility of ASR.

Arlington has water rights to 8.16 cfs (19,968 m^3/d) from the Columbia River. ASR may be a useful tool in this area. Close proximity to the source water from the Columbia River increases the feasibility of such a plan. According to Brown's site rating system, Arlington has 50% of ideal conditions for ASR (Figure 8-4). The site lost points for low transmissivity, moderate well density and water quality. Volumetric analysis indicates aquifer storage is sufficient for ASR (Figure 8-3).

There appears to be limited potential for AR through surface spreading in the Arlington area. Due to steep topography, infiltrated water may flow away too quickly to be recovered at the same location.

Condon

Condon is located about 33 mi (53 km) south of Arlington. The city has surface water rights to 1 cfs (2,447 m^3/d) from Hay Creek year round, as well as groundwater rights. Population has increased from 635 to 708 between 1990 and 2004 (U.S. Census, 2004).

Municipal wells have open intervals varying from 33 to 630 ft (10 to 192 m) below the surface; they access Columbia River Basalt (Tcg, Tcw) interflow zones and Quaternary sand and gravel aquifers (Qs, Qg). Well yields range from 90 to 300 gpm (491 to 1,635 m^3/d; OWRD well log database, 2006). Transmissivity estimated from specific capacity ranges from 1,300 ft^2/d (120 m^2/d) at the basalt well (Condon-1, GILL 205) to 2,800 ft^2/d (260 m^2/d) at the gravel well (Condon-3, GILL 505079).

Estimated transmissivity values for Condon aquifers are below the target range of 5,000 to 25,000 ft^2/d (465 to 2,323 m^2/d) for ASR (Brown et al., 2005). Although these values are not ideal, the amount of water currently available for storage is small and therefore volumetric analysis finds the aquifer is suitable for ASR (Figure 8-3). The well in the gravel aquifer has the most storage capacity because transmissivity is higher than in the basalt aquifer. Condon wells possess 29 to 43% of optimal parameters in Brown's

site rating system (Figure 8-4). Condon sites lost points for low transmissivity and the presence of fish species that may be adversely impacted by river withdrawals.

Fossil

The town of Fossil is located approximately 18 mi (29 km) south of Condon. Fossil has water rights to 0.2 cfs (489 m^3/d) from Stars Spring. Population increased slightly from 399 to 435 between 1990 and 2005 (U.S. Census, 2005).

Wells access Columbia River Basalt (Tcg) interflow zones, with well yields of 250 gpm (1,363 m^3/d; OWRD well log database, 2006). Transmissivity estimated from specific capacity is 600 ft^2/d (60 m^2/d). This is lower that Tigard's 870 ft^2/d (80 m^2/d; Golder Associates, 2001) and Baker City's 1,000 ft^2/d (90 m^2/d; Groundwater Solutions, 2003), and below the target range of 5,000 to 25,000 ft^2/d (465 to 2,323 m^2/d) for ASR. This low permeability may be the result of poor well efficiency. The available source water volume is quite small, which compensates for the aquifer's low transmissivity and enables a small scale project at this site.

Brown's site rating system finds Fossil has 43% of optimal ASR parameters (Figure 8-4). Fossil lost points for low transmissivity and high well density. AR may be feasible in surficial gravel aquifers; this would also avoid the expense of installing a water treatment plant for an ASR project, if water quality and vertical permeability is sufficient to meet AR needs.

John Day

The town of John Day is located on the John Day River. It is in the most populous part of the basin, with 1,836 residents in 1990 decreasing to 1,635 in 2004 (U.S. Census, 2004). The city has water rights to 3.5 cfs (8,565 m^3/d) from Long Gulch. Groundwater levels appear to be stable at the present; depth to water in 1995 was 6 ft (154 m), in 2005 it was 7 ft (155 m). Municipal wells have open intervals from 59 to 250 ft (18 to 76 m) below the surface; water-bearing layers are Columbia River Basalts (Tcp, Tcg), Quaternary and Tertiary sediments (Qs, Ts) with a yield of 850 gpm (4,633 m^3/d; OWRD well log database, 2006).

Transmissivity estimated from specific capacity for municipal wells in basalt ranges from 4,900 to 6,800 ft^2/d (450 to 630 m^2/d). These values are within the target range of 5,000 to 25,000 ft^2/d (465 to 2,323 m^2/d) for ASR (Brown et al., 2005).

Volumetric analysis indicates John Day-2 (GRAN 50574), which accesses basalt, is suitable for ASR (Figure 8-3). However, John Day-1 (GRAN 434) had no head space in the well at the time of drilling, which indicates ASR would not be feasible because groundwater levels are extremely close to the surface. Brown's site rating system finds John Day has 43 to 57% of optimal ASR parameters, with low scores for transmissivity and well density (Figure 8-4).

East-west trending faults parallel to the John Day River may truncate potential basalt storage zones, depending on the location of future ASR projects. Further field testing is necessary to determine the extent to which faulting influences the hydraulic connectivity of local aquifers.

AR may be possible in Quaternary sediments near John Day, if conditions are appropriate in alluvial deposits.

CHAPTER 9
KLAMATH BASIN

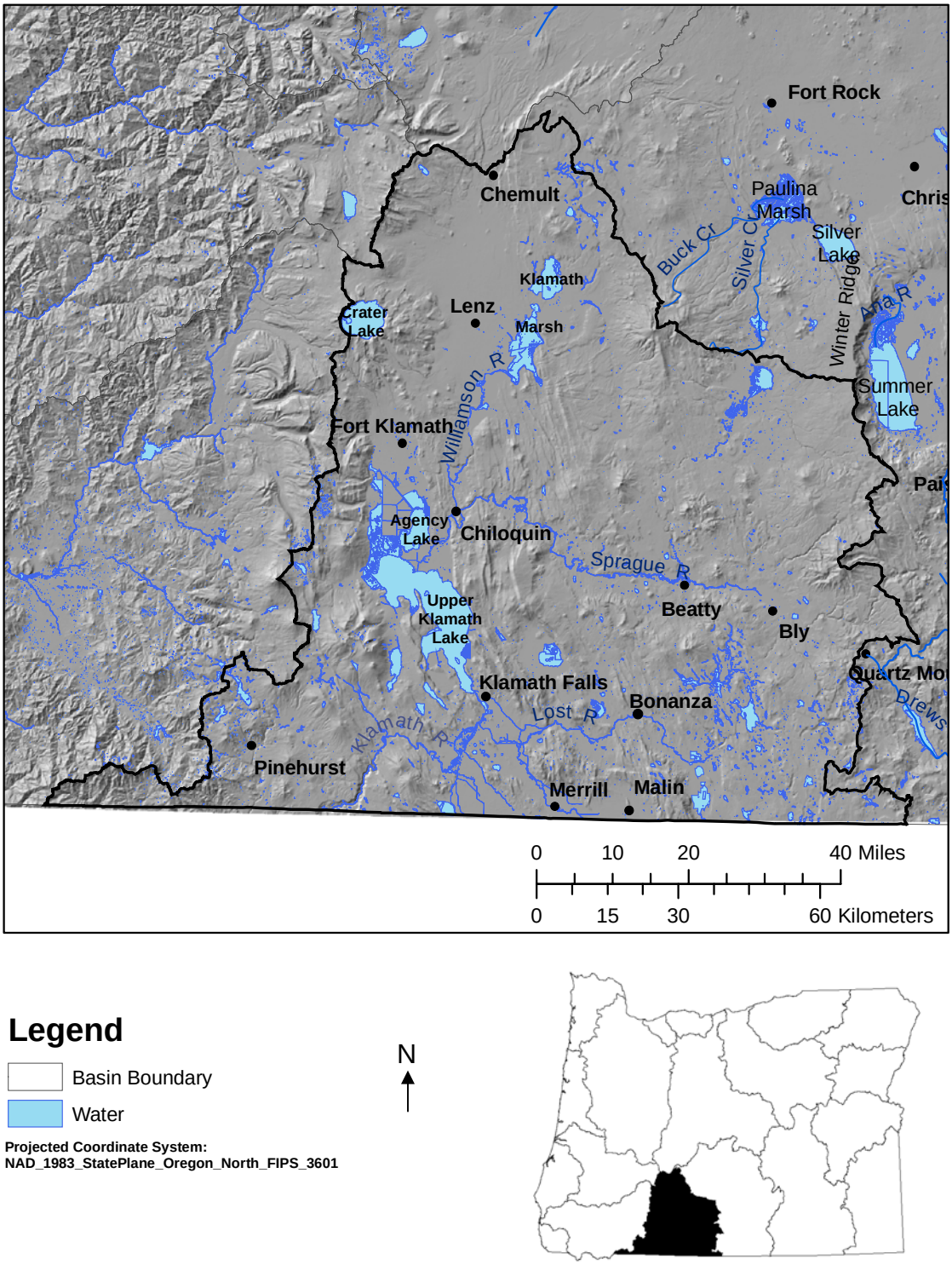
Basin Hydrology

The Klamath Basin covers approximately 5,680 mi^2 (14,724 km^2), extending from southwestern Oregon across the Oregon-California border. Watershed divides delineating the basin are found at the crest of the Cascade Range to the west and in volcanic highlands to the north and east. In this study, the southern basin boundary is political, not hydrologic. The Oregon portion of the basin includes the extensive wetlands of Klamath Marsh and Upper Klamath Lake. The basin is drained by the Williamson River from the north, the Sprague River from the east, and the Lost River from the southeast. The Klamath River flows south from Upper Klamath Lake into California.

The basin varies from alpine conditions in the Cascade Range to high desert in the central and eastern basin. Average annual precipitation ranges from approximately 10 in (254 mm) at Merrill, 18 in (460 mm) at Chiloquin, to 65 in (1,680 mm) at Crater Lake (Oregon Climate Service, 2007). Despite the low precipitation in the central and eastern basin, runoff and snowmelt from the Cascade Range feeds perennial streams and wetlands of the central Klamath basin. Groundwater recharge varies across the basin and over time. It is estimated at about 20% of precipitation basin-wide, with higher rates of recharge in the Cascade Range than in the dry, eastern portion of the basin (Gannett et al., 2007). In the unconfined sedimentary aquifers of the lowlands, some recharge from irrigation, canal leakage and stream loss also occurs. However, this is limited by the low permeability of lake deposits in the valleys formerly flooded by Klamath Lake.

Physical Setting

The Klamath basin includes volcanic Western Cascade highlands to the west, transitioning into extensional Basin and Range topography to the east. This eastern sections features northwest trending normal faults with characteristic up-thrown horsts



Legend

Basin Boundary

Water

Projected Coordinate System:
NAD_1983_StatePlane_Oregon_North_FIPS_3601

N

Figure 9-1. Klamath Basin location map. Location of topographic features, rives and towns in the Klamath Basin that are examined in this study (Data Sources: Wright, 2006; Oregon Geospatial Data Clearinghouse, 2006).

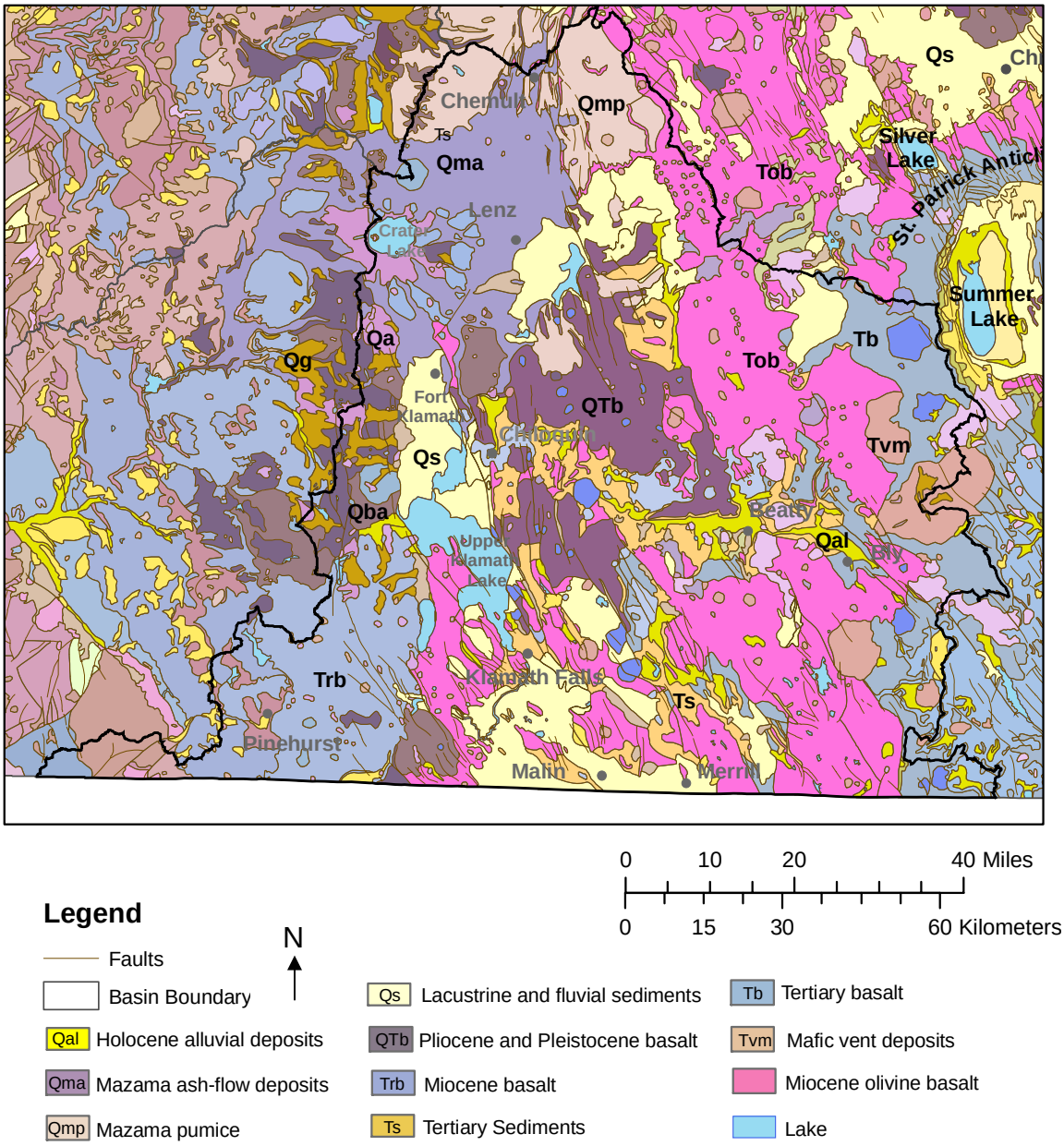


Figure 9-2. Klamath Basin geology map. Geologic formations of importance for future ASR in the Klamath Basin include basalts and basin fill sediments (Data sources: Walker and McLeod, 1991).

forming ridges and down-thrown grabens forming valleys. Grabens are filled with sediments of varying thickness and permeability, created by lake and river activity. Lacustrine deposits cover areas much larger than the present lakes, due to climate change and the Klamath Project's conversion of wetlands to agricultural fields. These sediments vary in grain size from fine clays to coarse gravels at depth.

Hydrogeologic Units

Major geologic units in the basin, listed from oldest to youngest include Tertiary basalt, rhyolite and andesite, Tertiary tuffs, and Tertiary and Quaternary alluvial and lacustrine sediments. The units are (Figure 9-2) discussed in relation to ASR in the following sections.

Tertiary basalt and rhyolite

Eocene through Miocene volcanics (Tb, Trb) of the Western Cascades are exposed in the western part of this basin. These units generally have low permeability and represent the western groundwater boundary for the Klamath Basin (Gannett et al., 2007). The basalts and rhyolites tend to have low yielding wells, and are not a likely target for ASR or AR.

Late Tertiary Volcanics

The most widely used aquifer in the basin is composed of Miocene through early Pleistocene basalt and andesite flows (Tob, Tvm, QTb). These units extend throughout much of the basin, with large exposures east of Fort Klamath. Permeability is locally minimized by hydrothermal alteration, and transmissivity ranges from 2,700 to 610,000 ft^2/d (250 to 57,000 m^2/d; Gannett et al., 2007). In addition to the unit's coincidence with population centers, its moderate to high transmissivity makes Late Tertiary volcanics potentially useful for ASR.

Quaternary air-fall and pyroclastic deposits

The eruption of Mt. Mazama (now Crater Lake) about 6,900 years ago, released high permeability air-fall materials including pumice and ash (Qmp, Qma), in addition to low permeability debris and pyroclastic flows. These units are exposed on the slopes surrounding Crater Lake and in smaller expanses in the Cascade Range as well as east of Fort Klamath. High permeability pumice may be suitable for AR or ASR, depending on local conditions.

Quaternary Sediments

River activity and lake deposition create the unconsolidated Pleistocene through Holocene sediments (Qal, Qs) that fill valleys throughout the basin. These units are widely accessed by shallow domestic and irrigation wells. In general, stream deposits tend to be more coarse-grained than lake deposits, and therefore more permeable, productive aquifers (Gannett et al., 2007). Unconfined sedimentary aquifers may be useful for ASR or AR in areas with suitable transmissivity, source water quality and availability.

Tectonic Structure Influencing Groundwater Flow

Klamath Basin includes a portion of the northern Basin and Range province, and displays extensional, north south trending normal faults. Faulting and folding influence basalt, andesite and tuffs. According to Gonthier (1985), faulting in the basalts limits groundwater flow by hydraulically disconnecting interflow zones, which are the main permeable sections of basalt flows in this area. There are also many areas in the basin where groundwater flow is not affected by faulting (Gannett et al., 2007). Normal faults in this basin also have shaped the surface water flow system by providing basin lowlands (or grabens) which collect the surface and groundwater runoff into lakes, rivers and unconfined aquifers. Site specific investigation is necessary to determine the fault effects on groundwater flow relevant to ASR or AR.

ASR Assessment

The purpose of this section is to provide a general assessment of specific locations for their potential to employ ASR as a part of water supply systems. Site specific investigation is essential to determine if a recharge project is technically, economically, and environmentally feasible, but positive results from this study indicate the site possesses many of the necessary components for successful ASR.

Table 9-1: Summary of Analysis Methods. For more detail, see Chapter 3: Analysis Methods.

Method	Description	Result of Method
Volumetric Analysis	Mathematical comparison of aquifer storage capability to the volume of surface water available	If > 1, sufficient storage If = 1 marginal storage If < 1, insufficient storage
Brown's Site Rating System	Site is rated from 0 to 2 for each criteria such as distance to source water, water quality, groundwater flow rate, aquifer thickness	Produces % of ideal ASR parameters at a given site

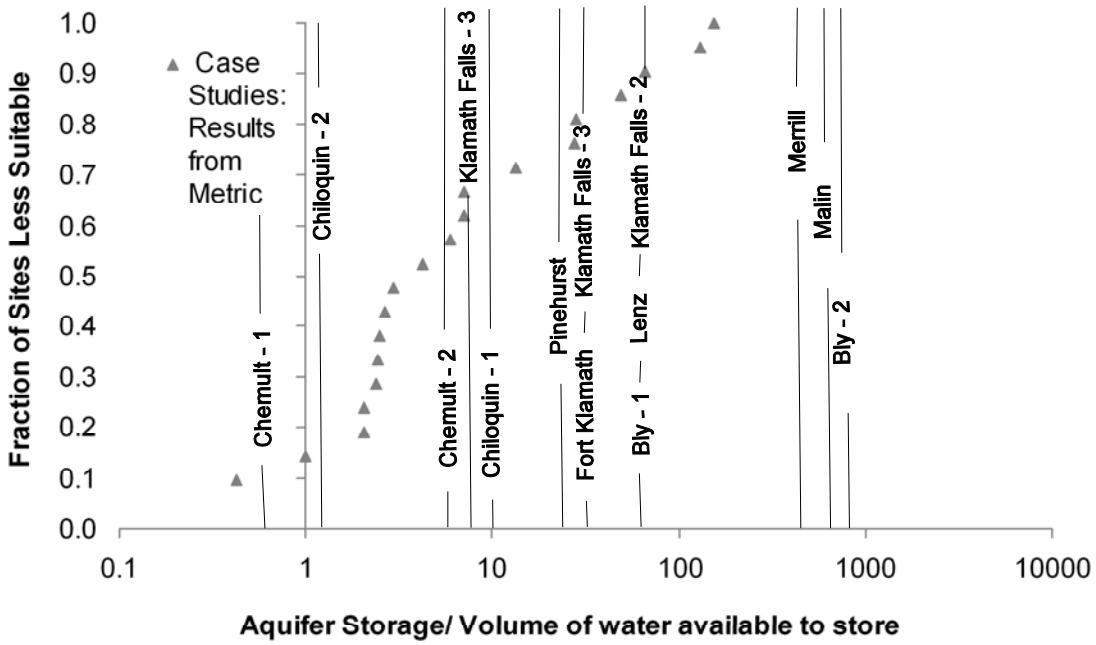


Figure 9-3: Klamath Basin ASR metric results. Aquifer storage is sufficient for ASR, except at Chemult-1 and Chiloquin-2. Data is listed in Appendix B.

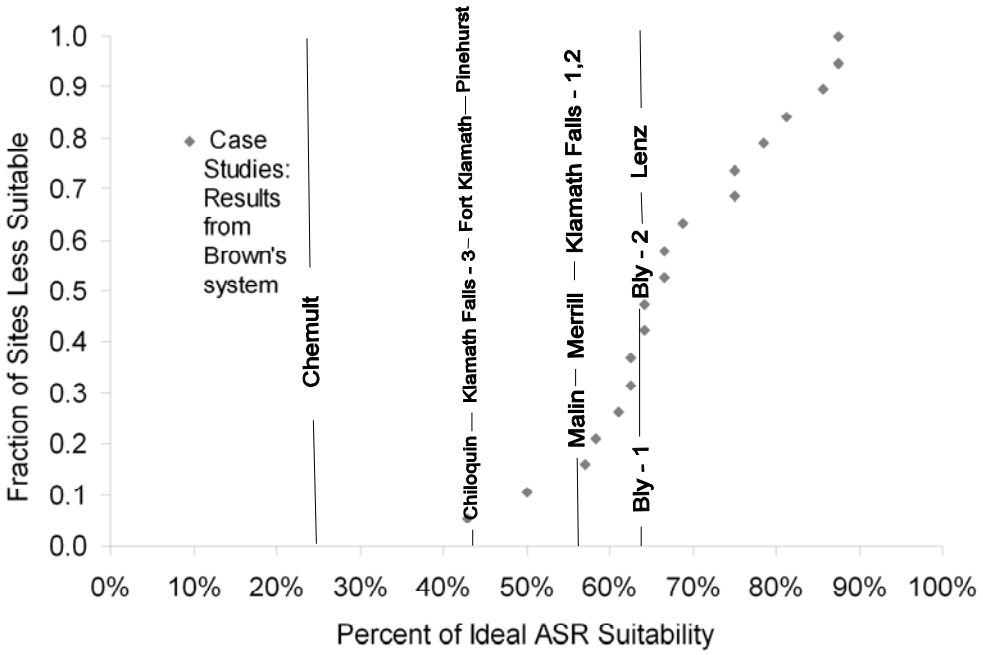


Figure 9-4: Klamath Basin Brown's rating system results. Klamath Basin sites have from 25 % to 63% of ideal conditions for ASR. 50% of case studies are greater than the results for this basin. Data is listed in Appendix C.

Lenz

Lenz is a small unincorporated community located in north-central Klamath Basin, between Klamath Marsh and Crater Lake. The nearest surface water source is greater than 3 mi (4.8 km) away, and water for domestic use is supplied by private wells. Population data was unavailable from the U.S. Census.

A large capacity irrigation well (KLAM 10202) accessing Late Tertiary basalt (QTb) was evaluated for ASR suitability in this agricultural context. It is screened at depths of approximately 90 to 300 ft (27 to 91 m) below the surface, and yielded 4,000 gpm (21,800 m^3/d) at the time of drilling. Transmissivity in the basalt is estimated by this study as 24,500 ft^2/d (2,300 m^2/d) from specific capacity data, which is within the ideal ASR range of 5,000 to 25,000 ft^2/d (465 to 2,323 m^2/d).

The town of Lenz currently has no surface water rights, and the lack of major perennial streams in the vicinity (Oregon Geospatial Data Clearinghouse, 2006) is a significant barrier to ASR. Volumetric analysis (Figure 9-3) indicates the irrigation well

(KLAM 10202) could store water at the rate of 1 cfs (2,447 m^3/d) in the basalt aquifer, despite the limited head space in the well (10 ft or 30 m). According to Brown's ASR site rating system, Lenz has 63% of ideal conditions for ASR, although the lack of an obvious surface water source means other appropriate parameters are negated, and this site fails Brown's test (Figure 9-4). Future efforts, if deemed necessary, could bring water in from a neighboring community to remedy this shortcoming. Access to source water for injection or infiltration is the largest barrier to ASR or AR in this area.

Fort Klamath

Fort Klamath is an unincorporated community situated between Crater Lake and Upper Klamath Lake, on the Wood River. The town currently has no surface water rights, but 1 cfs (2,447 m^3/d) from the Wood River is available for storage during winter months (OWRD WARS, accessed 2007). Due to the recent changes in surface water regulation, the feasibility of using this source would have to be carefully examined. Population is stable around 3,300 (U.S. Census, 2004).

A municipal well (KLAM 10189) was examined for ASR suitability. It has a large yield (750 gpm or 4,087 m^3/d), and has open intervals from 100 to 200 ft (30 to 61 m) below the surface. The well draws water from Quaternary sand and gravel aquifers (Qs, Qg) (OWRD well log database, 2007). Transmissivity is estimated at 2,800 ft^2/d (260 m^2/d) from specific capacity data. This value falls below the target range for ASR of 5,000 to 25,000 ft^2/d (465 to 2,323 m^2/d), but is similar to Seattle's sand and gravel ASR site which has a transmissivity of 3,000 ft^2/d (278 m^2/d).

Volumetric analysis (Figure 9-3) indicates the aquifer storage is sufficient to inject 1 cfs (2,447 m^3/d) for 120 days. Source water availability will ultimately determine whether ASR is possible. Fort Klamath has 50% of ideal conditions for ASR according to Brown's site rating system, receiving low scores for transmissivity, the presence of threatened species, and hydraulic gradient (Figure 4-4). AR may be feasible in Quaternary sediments of the Wood River Valley, although the shallow water table may limit this possibility.

Klamath Falls

Located at the south end of Upper Klamath Lake, Klamath Falls sits in the alluvium filled lowlands of the northern Basin and Range Province. The City of Klamath Falls currently has surface water rights to 2 cfs (4,894 m^3/d) from Klamath Lake (OWRD WRIS, accessed 2007). Population increased from 17,737 to 19,882 residents between 1995 and 2005 (U.S. Census, 2006).

Three municipal wells were examined for ASR potential in Klamath Falls to assess the different aquifer environments in this area. Two utilize Tertiary basalt aquifers (Tob), while the third draws water from a Tertiary and Quaternary sedimentary aquifer (Ts, Qs). Municipal well Klamath Falls-1 (KLAM 10179) utilizes a basalt aquifer (Tob) at depths from 125 to 215 ft (38 to 77 m) below the surface, with a well yield of 90 gpm (490 m^3/d; OWRD well log data, 2007). Transmissivity estimated from specific capacity is 7,000 ft^2/d (650 m^2/d). This is within the ideal range of 5,000 to 25,000 ft^2/d (465 to 2,323 m^2/d) for ASR, but at the time of drilling there was only 4 ft (1.2 m) of head space in the well, which is does not allow for head rise during injection. This suggests ASR may not be feasible at this well, if current water levels are similar.

Gannett et al. (2007) reported aquifer test results at Klamath Falls-2 (KLAM 12050, another Tertiary basalt well) that that found the transmissivity to be 3,800 ft^2/d (350 m^2/d) at this well. This well is significantly deeper than KLAM 10179, with open intervals from 190 to 900 ft (60 to 274 m) below the surface. However, the transmissivity falls below the ideal range for ASR, and below many of the basalt ASR sites in Oregon. Therefore, this well may not be the best choice for a large ASR project.

The third well, Klamath Falls-3 (KLAM 12167), which uses a Tertiary and Quaternary sand and clay aquifer (Ts, Qs) from 62 to 422 ft (19 to 129 m) below the surface, has the lowest transmissivity of the aquifers examined for Klamath Falls. Estimated from specific capacity, transmissivity in this aquifer is approximately 2,800 ft^2/d (260 m^2/d). This makes it the least suitable for ASR of the wells examined for Klamath Falls.

Volumetric analysis indicates aquifer storage is sufficient to inject 1 cfs (2,447 m^3/d) injected for 120 days. Klamath Falls-2 (KLAM 12050) has most favorable results

due to a greater depth to water, which allows for the water level to rise in the well during injection (Figure 9-3). Brown's site rating system finds the basalt wells have 56% of optimal ASR parameters, while the sand and clay well has 44% (Figure 9-4). AR may be feasible in surficial sand and gravel aquifers, depending on vertical permeability, water quality, and the location of other wells that might inadvertently access the stored water.

Pinehurst

Pinehurst sits about 8 mi (13 km) north of the Oregon and California border on Jenny Creek in the foothills of the Cascade Range. The town has no surface water rights, but there is currently 1 cfs (2,447 m^3/d) available from Jenny Creek (OWRD WARS, accessed 2007). Population data for this unincorporated community is unavailable from the U.S. Census.

An irrigation well (JACK 21221) was selected as representative of local agricultural wells. It accesses a Tertiary rhyolite and basalt aquifer (Trb) from 24 to 140 ft (7 to 43 m) below the surface, and yields 30 gpm (164 m^3/d; OWRD well log database, 2007). Transmissivity estimated from the well's specific capacity is 2,200 ft^2/d (200 m^2/d). This is below the target range of 5,000 to 25,000 ft^2/d (465 to 2,323 m^2/d) for ASR.

Volumetric analysis (Figure 9-3) indicates aquifer storage is suitable to inject 1 cfs (2,447 m^3/d) for 120 days. According to Brown's site rating system, Pinehurst has 43% of optimal ASR parameters (Figure 9-4). The site lost points for having a high well density, low transmissivity and the presence of threatened fish species. Because this site does not have a community water system, ASR implementation would require the installation of surface water treatment facilities and water quality monitoring systems. On the agricultural scale, this may be prohibitively expensive. AR may avoid the water treatment barrier, and could utilize surficial sand and gravel aquifers, depending on vertical permeability and water quality.

Bly

Bly is a small, unincorporated rural community located in the alluvial valley of Sprague River. The town of Bly has no surface water rights, but there is 1 cfs (2,447 m^3/d) available for storage from the Sprague River (OWRD WARS, accessed 2007). Population in 2000 was stable at 486 (U.S. Census, 2000). Municipal water is supplied by groundwater from a basalt aquifer.

Two basalt wells with varying depths were examined for ASR suitability. Municipal wells Bly-1 (KLAM 2160) and Bly-2 (KLAM 51725) draw water from Tertiary basalt (Tob) at depths of 50 to 204 ft and 40 to 455 ft (15 to 67 m; 33 to 149 m) below the surface, respectively. Well yields are quite different: 125 gpm (681 m^3/d) at Bly-1 and 1,450 gpm (7,903 m^3/d) at Bly-2 (OWRD well log database, 2007). Transmissivities estimated from the well specific capacities are 9,800 ft^2/d (at Bly-1) and 14,650 ft^2/d (at Bly-2) (900 and 1,400 m^2/d). Both are within the ideal range for ASR, although Bly-2 has significantly higher transmissivity than Bly-1.

Volumetric analysis indicates aquifer storage is suitable to inject 1 cfs (2,447 m^3/d) for 120 days at both wells. Bly-2 has higher transmissivity, and a greater depth to water than Bly-1, suggesting it is more suitable for ASR (Figure 9-3). Brown's site rating system finds Bly has 63% of optimal ASR parameters (Figure 9-4). The site lost points for the presence of threatened species that may suffer from a decrease in river flow, but it scored high for appropriate transmissivity, proximity to the surface water source and appropriate aquifer thickness. AR may be feasible in the surficial sand and gravel aquifers, depending on vertical permeability, water quality and whether the water infiltrated into the aquifer will discharge into the nearby Sprague River before it can be recovered for municipal use.

Merrill

The town of Merrill is situated just north of the Oregon-California border. The town sits in the alluvial valley of Lost Creek. Merrill has no municipal surface water rights, but there is 1 cfs (2,447 m^3/d) available for storage from Lost Creek (OWRD WARS, accessed 2007). Population is stable around 897 (U.S. Census data, 2006).

Domestic, irrigation wells and private surface water supplies provide local water at this time. However, Gannett et al. (2007) found that due to increased groundwater use in this area, groundwater levels declined 10 to 15 ft (3 to 4.6 m) between the spring months of 2001 and the spring of 2004. This indicates that natural groundwater recharge is less than groundwater discharge to wells and streams, due to a combination of climatic influence and groundwater pumping habits. ASR and AR may be useful in this area to replenish the over-pumped groundwater resources.

A deep, large capacity irrigation well (KLAM 14959) was chosen to investigate the ASR potential in this area. It draws water from a Tertiary basalt aquifer (Tob) at depths of 760 to 1,012 ft (230 to 380 m) below the surface, with a well yield of 2,450 gpm (13,352 m^3/d; OWRD well log data, 2007). Transmissivity estimated from the well's specific capacity is 29,500 ft^2/d (2,750 m^2/d). This is above the ideal range of 5,000 to 25,000 ft^2/d (465 to 2,323 m^2/d), but ASR tests in The Dalles, Pendleton and Beaverton, Oregon utilizing basalt aquifers have demonstrated that ASR is feasible with transmissivities greater than 25,000 ft^2/d (2,323 m^2/d), given other appropriate parameters.

Injection at a rate of 1 cfs (2,447 m^3/d) for 120 days during the winter season is feasible according to volumetric analysis of this site (Figure 9-3). Brown's site rating system finds Merrill has 56% of optimal ASR parameters (Figure 9-4). The site scored poorly for transmissivity above the ideal threshold and the presence of threatened species that could be affected by decreased river flows. AR may be able to recharge surficial alluvial aquifers, depending on vertical permeability and water quality.

Malin

Malin is also located just north of the Oregon-California border, in an alluvium filled valley near Merrill. The city has surface water rights to 4 cfs (9,788 m^3/d) from Mills Creek (OWRD WRIS, accessed 2007). Population has decreased slightly from 725 in 1990 to 638 in 2004 (U.S. Census, 2006). However, due to surface water regulation enacted in response to a prolonged drought, groundwater pumping in this area has increased by approximately 50% between 2001 and 2007 (Gannett et al., 2007). Like

Merrill, Malin has experienced groundwater declines of more than 15 ft (4.5 m) between 2001 and 2004. This decline, in essence, creates storage space in the aquifer for ASR. This is true providing the decline has not caused land subsidence or aquifer compaction, which could permanently decrease its permeability and therefore its storage capabilities.

A deep irrigation well (KLAM 14821) in Malin accesses Tertiary basalt (Tob), Tertiary and Quaternary (Ts, Qs) sediment layers at depths from 19 to 647 ft (6 to 197 m) below the surface. Well yield at the time of drilling was 975 gpm (5,314 m^3/d; OWRD well log data, 2007), while transmissivity estimated from specific capacity is 17,900 ft^2/d (1,660 m^2/d). This is within the ideal range for ASR.

Volumetric analysis indicates aquifer storage is suitable to inject ½ of the municipal winter surface water rights for 120 days (Figure 9-3). Brown's site rating system finds Malin has 56% of optimal ASR parameters (Figure 9-4). However, the site fails this system because the surface water available within the existing surface water rights is greater than 3 mi (4.8 km) from the potential injection well. This means that a project utilizing this specific well would have to install a system to transport and treat the surface water up to drinking water standards before ASR could begin. AR may be less expensive, and could utilize surficial gravel aquifers, depending on vertical permeability and water quality.

Chemult

Chemult is a small, unincorporated rural community located in the foothills of the Cascade Range, northeast of Crater Lake. The town has no surface water rights, and there is no obvious surface water source within 3 miles (4.6 km; OWRD WARS, accessed June 2007). Population in 2004 was stable at 297 (U.S. Census, 2006). There is no municipal water system in the area, and domestic wells with yields less than 20 gpm (109 m^3/d) are typical.

Two wells drawing water from volcaniclastic units were examined; a shallow fire department well and a deeper domestic well were chosen to represent hydrogeologic environments in the area. Fire department well Chemult-1 (KLAM 51568) draws water from Quaternary volcaniclastics (Qmp) at depths of 18 to 22 ft (5.5 to 6.7 m) below the

surface, and yields 1 gpm (OWRD well log data, 2007). Transmissivity estimated from specific capacity is 200 ft^2/d (20 m^2/d). This falls significantly below the target range for ASR, in addition to being a shallow aquifer would likely be influenced by other wells in the area (there are 25 other wells within a square mile that appear to use the same aquifer layer).

The second well, Chemult-2 (KLAM 54538), is a domestic well which yields 10 gpm (54.5 m^3/d), and has a higher transmissivity than the fire department well. Its transmissivity is estimated at 2,100 ft^2/d (200 m^2/d) in the volcaniclastic deposits (Qmp). While this still falls below the ideal range for ASR, this is similar to transmissivity found at ASR sites in Alamogordo, New Mexico and Lancaster, California.

Volumetric analysis indicates aquifer storage is suitable to inject 1 cfs (2,447 m^3/d) for 120 days at Chemult-2 (KLAM 54538), while Chemult-1 is not suitable (KLAM 51568; Figure 9-3). This calculation overlooks the fact that there is not an obvious surface water source at this site. However, small agricultural projects with existing surface water rights may be feasible. Brown's site rating system finds Chemult has 25% of optimal ASR parameters (Figure 9-4). The site lost points for the presence of threatened species that may suffer from a decrease in river flow, low transmissivity, distance to surface water source and aquifer thickness less than 25 ft (7.6 m). AR may be able to replenish surficial sand and gravel aquifers, depending on vertical permeability, water availability.

Chiloquin

Located near the convergence of the Wood and Williamson Rivers, Chiloquin was originally a trading post and lumber mill town. Population in 2004 was stable with 708 residents in the incorporated section of Chiloquin, although the surrounding areas are experiencing growth (U.S. Census, 2004). The town has no municipal water supply system, and no surface water rights, but there is 1 cfs (2,447 m^3/d) available for storage from the Williamson River from January to March (OWRD WARS, accessed June 2007). Domestic wells with yields less than 20 gpm (109 m^3/d) are typical in this area.

Two domestic wells were examined by this study for ASR suitability. Chiloquin-1 (KLAM 951) draws water from shale and Quaternary basalt (Qtb), while Chiloquin-2 (KLAM 53392) accesses three layers of Tertiary and Quaternary sand and clay (Ts, Qs) to depths of 330 ft (100 m) below the surface. Transmissivity estimated from specific capacity is 260 ft^2/d (25 m^2/d) at the basalt well and 150 ft^2/d (14 m^2/d) at the sand and clay well. Both fall significantly below the target range for ASR, and are not likely to be feasible ASR sites.

Volumetric analysis (Figure 9-3) indicates the aquifer storage is suitable to inject 1 cfs (2,447 m^3/d) for 120 days at Chiloquin -1 (KLAM 951, the basalt well), while it Chiloquin-2 is marginally suitable (KLAM 53392, sand and clay well). Brown's site rating system finds Chiloquin has 44% of optimal ASR parameters (Figure 9-4). The site lost points for the presence of threatened species that may suffer from a decrease in river flow, low transmissivity, and a high hydraulic gradient. AR may be able to utilize surficial sand and gravel aquifers, depending on vertical permeability and horizontal flow rates.

CHAPTER 10
MALHEUR LAKE BASIN

Hydrologic Description

Malheur Lake Basin covers approximately 10,035 mi^2 (25,990 km^2). Major rivers include the Silvies River flowing from the north, Silver Creek from the northwest, Kiger Creek and Donner and Blitzen River from the south off the Steens Mountains. The basin is unique because it is a closed basin, meaning rivers emerge in the highlands and flow toward central lakes. Water escapes the basin only by evaporation from the lake surfaces and transpiration. Many of these lakes are ephemeral, lasting for a short season while the rivers feeding them run. Watershed divides delineating the basin are found to the north in the Strawberry and Aldrich Mountains, to the northwest in the Ochoco Mountains, to the east in volcanic highlands, and to the west at Hart Mountain and other uplands. To the south, the state line is the political basin boundary, but uplands in Nevada form the hydrologic boundary.

In this high desert climate, average annual precipitation ranges from 6.7 in (170 mm) at Andrews, to 10.5 in (267 mm) at Burns to 35 in (890 mm) in the Steens Mountains (Oregon Climate Service, 2007). Groundwater recharge occurs by percolation of winter precipitation into the fractured volcanic highlands. Snowmelt and stream flow also replenish unconfined sedimentary aquifers in the lowlands (Gonthier et al., 1977).

Physical Setting

This closed basin consists of flat-lying young alluvial valleys, dunes, playas and lake beds, surrounded by higher elevation eroded and glaciated fault block terrains. These uplands include the intensely glaciated Steens Mountains. As shown in Figure 10-1, population centers are located in the valleys.

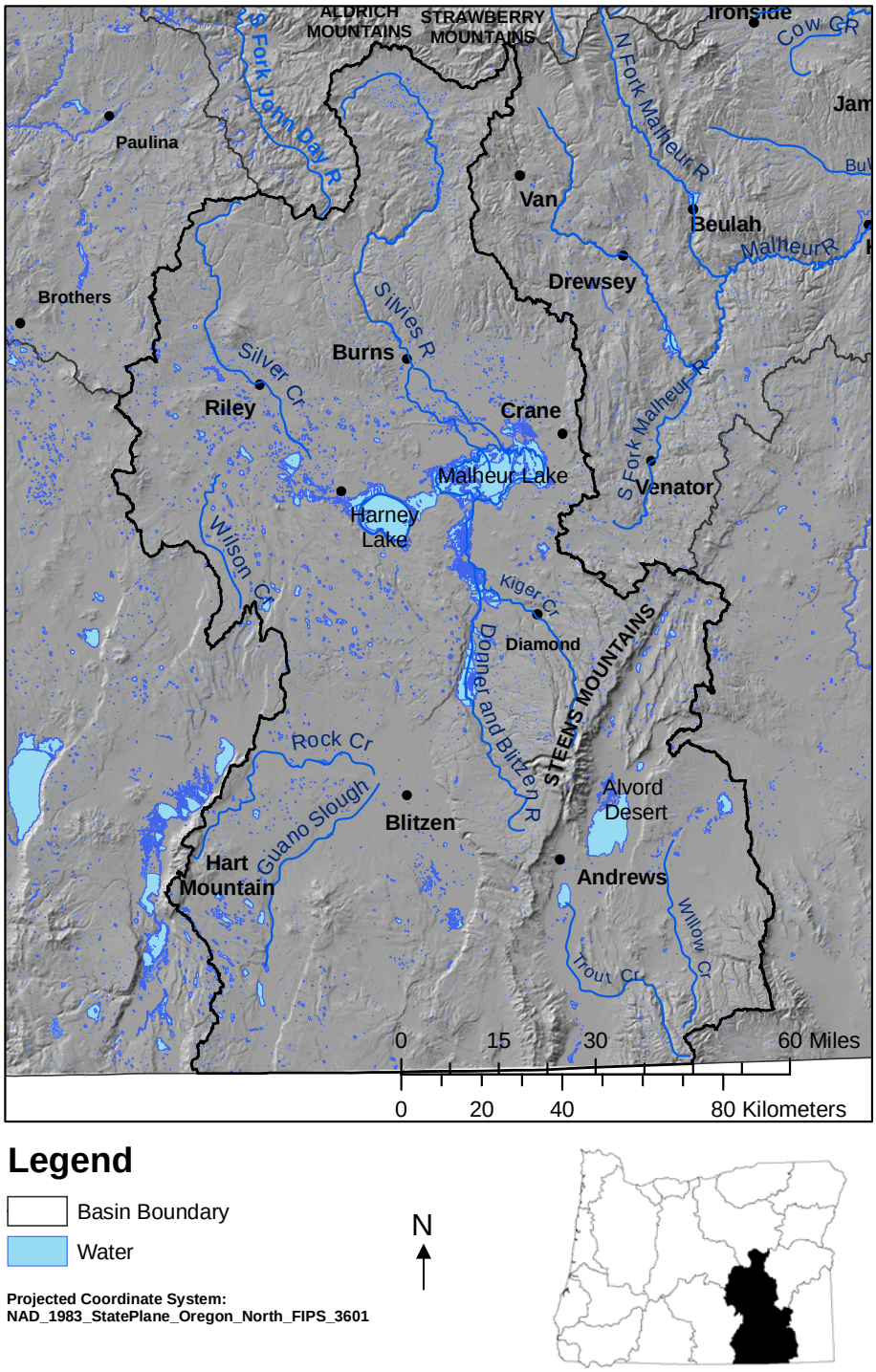


Figure 10-1. Malheur Lake Basin location map. Location of topographic features, rivers and towns that are examined in this study (Data sources: Wright, 2006; Oregon Geospatial Data Clearinghouse, 2006).

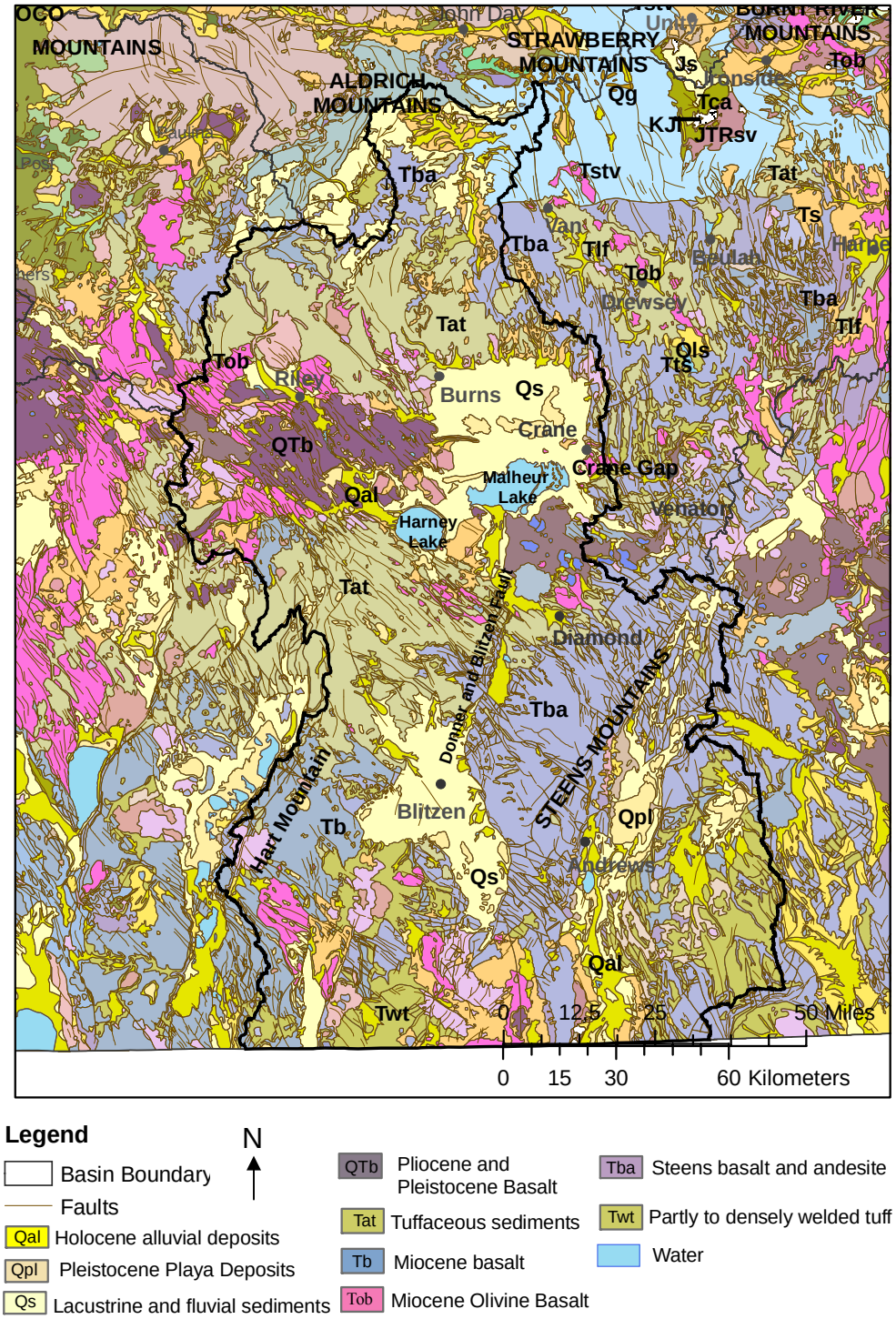


Figure 10-2. Malheur Lake Basin Geology map. Geologic formations of importance to future ASR include basalts and sediments (Data sources: Walker and McLeod, 1991; Oregon Geospatial Data Clearinghouse, 2006).

Hydrogeologic Units

Major geologic units in the basin, from oldest to youngest include Tertiary basalt and andesite, Tertiary tuffs, Tertiary and Quaternary alluvium and playa sediments. Major geologic units are (Figure 10-2) discussed in detail in the following section.

Tertiary Basalt and Andesite

Eocene through Pleistocene basalt and andesite lava flows (Tb, Tob, Tba, QTb) are exposed along the northeast and southwest basin boundaries. The Eocene Steens Basalt is included in this group, which is distinguished by fluid, basaltic andesite flows ranging up to 900 feet thick (274 m). This unit generally lacks interflow zones, due to its rapid emplacement, which indicates an overall low horizontal permeability (Johnson et al., 1998). These basalts are faulted throughout the extensional province, and groundwater flow is limited by this faulting (Gonthier, 1985). The basalts and andesites are largely undeveloped by wells, and are an unlikely target for ASR due to their low permeability.

Tertiary Tuff

Miocene pyroclastic and volcanically-derived sedimentary rocks, in addition to welded tuffs (Tat, Twt), are exposed in the highlands north and northwest of Burns and also southwest of Harney Lake. Smaller exposures can be found southwest of the Alvord Desert. These units range in thickness from 20 to 80 ft (6 to 24.4 m; Leonard, 1970). The tuffs are generally clayey, fine-grained and considered poor aquifers. Therefore, they are generally not suitable for ASR or AR.

Tertiary and Quaternary Sediments

Glacial events, fluvial activity, and ephemeral lakes have created the unconsolidated Pleistocene to Holocene sediments (Qpl, Qs, Qal) found near Harney and Malheur Lakes, and in the Donner and Blitzen River and Alvord Creek valleys. These unconsolidated units are the main source of groundwater for wells in the basin. The largest expanse is found between Burns and Crane, where sand, gravel, alluvial silt and

clay surround Malheur and Harney Lakes. Thickness ranges from 50 to 300 ft (15 to 90 m) in this area (Piper et al., 1939). According to Leonard (1970), gravel is concentrated in alluvial fans. The lake valley aquifer (Qpl, Qs) is largely clay, up to 300 feet (90 m) thick. There is a thin veneer of wind-blown sand overlying the lacustrine clay. Hydraulic conductivity in the sediments ranges from 25 to 150 ft/d (7.6 to 46 m/d); while transmissivity in the valley- fill aquifer system ranges from 2,000 to 4,000 ft^2/d (Leonard, 1970).

Unconfined sedimentary aquifers may be useful for AR in areas with suitable vertical transmissivity, source water quality and availability. However, the thick surficial deposits of low permeability clay found in many areas may prevent adequate infiltration to recharge underlying sands and gravels. ASR may be possible if stored water can be protected from access by other wells.

Tectonic Structure Influencing Groundwater Flow

The Malheur Lake Basin is located in the northern Basin and Range province, and displays extensional normal faulting south of Malheur and Harney Lakes. Faulting influences basalt, andesite and tuffaceous sediments in the upland areas (Figure 10-2), and has created steep walled valleys in the Alvord Desert, Catlow Valley and Guano Valley. The eastern boundary is defined by a north-south trending fault block (Leonard, 1970).

However, basalts, andesites and tuffs are largely untapped by wells in this basin. Valley alluvial deposits, which are the main source of groundwater, appear to be unaffected by these structures. The fact that this is a closed basin may be favorable for ASR operations, because stored water is not likely to flow away from the recharge site if it is near the center of the basin.

ASR Assessment

The purpose of this section is to provide a general assessment of specific locations for their potential to employ ASR as part of a water supply system. Site specific investigation is essential to determine if ASR or AR is technically, economically, and

environmentally feasible. Positive results from this study indicate that a site possesses many of the necessary components for successful aquifer recharge.

Table 10-1: Summary of Analysis Methods. For more detail, see Chapter 3: Analysis Methods.

Method	Description	Result of Method
Volumetric Analysis	Mathematical comparison of aquifer storage capability to the volume of surface water available	If > 1, sufficient storage If = 1 marginal storage If < 1, insufficient storage
Brown's Site Rating System	Site is rated from 0 to 2 for each criteria such as distance to source water, water quality, groundwater flow rate, aquifer thickness	Produces % of ideal ASR parameters at a given site

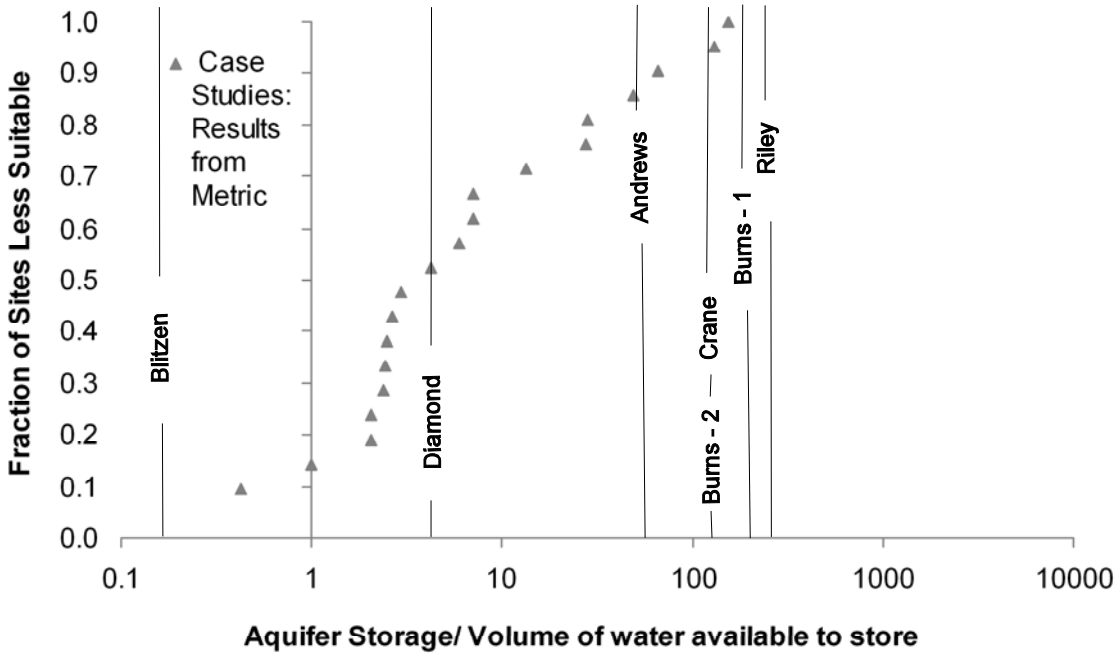


Figure 10-3: Malheur Lake Basin ASR metric results. Volumetric results for Burns, Diamond, Andrews and Crane show the aquifers suitable storage for ASR. However, the well in Blitzen does not look suitable. Data listed in Appendix B.

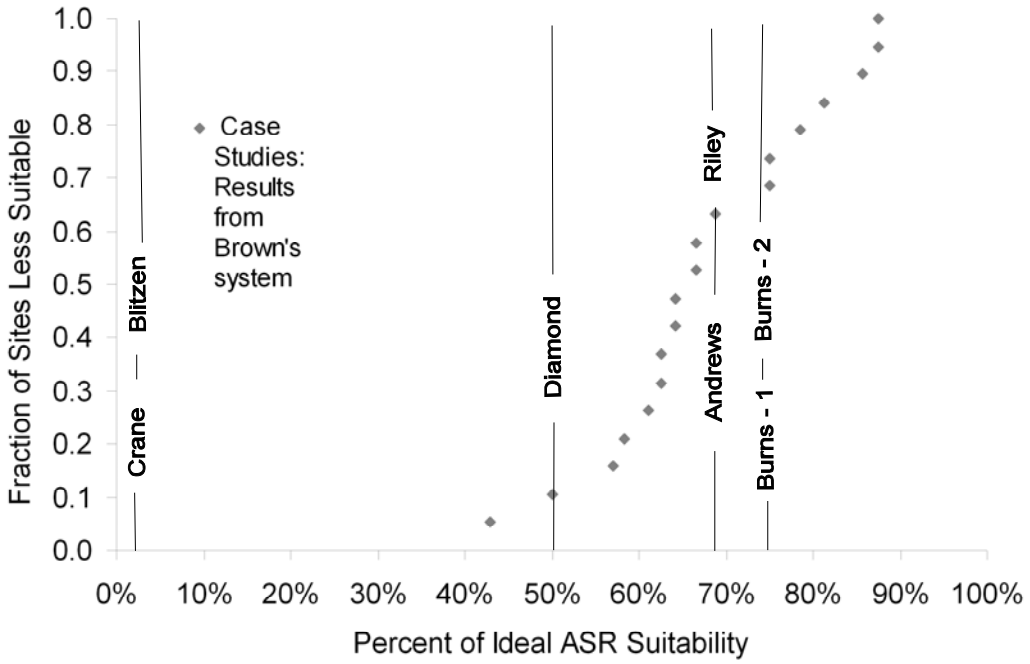


Figure 10-5. Malheur Lake Basin Brown's rating system results. Malheur Lake Basin sites have from 0 % to 75% of ideal conditions. 30% of case studies are greater than the results for this basin. Data listed in Appendix C.

Burns

Located in north-central Malheur Lake Basin, Burns sits on the banks of the Silvies River. Groundwater levels in the unconfined Quaternary sedimentary aquifer (Qs) have not changed significantly in the past decade, according to an OWRD observation well (HARN 463) records. Depth to water was 8 ft in 1995 and 10 ft in 2005 (2.4 and 3 m). Since municipal wells draw water from a similar shallow sand and gravel aquifer, it is assumed the groundwater levels are stable. Population in the city of Burns decreased from 2,913 in 1990 to 2,755 in 2004 (U.S. Census, 2004). The lack of population growth does not indicate an immediate need for increased municipal water supply. However, climate or rural water use patterns may change in the future with unknown impacts on the water supply and demand balance.

The Burns sand and gravel (Qs, Qal) municipal wells (Burns-1, HARN 290 and Burns-2, HARN 478) are screened at depths ranging from 140 to 290 ft (43 to 146 m)

below the surface. These wells have yields of 1,500 and 1,737 gpm (8,175 and 9,467 m^3/d), respectively. Transmissivity in the sediments is estimated as 15,000 and 24,000 ft^2/d (1,400 and 2,300 m^2/d) from specific capacity data. The City of Burns currently has no surface water rights, but the Silvies River has water available for storage from January to March (OWRD WARS, accessed 2007).

Piper et al. (1939) observed hydraulic influence of the Silvies River on wells located four miles from the river. This suggests injected water may be discharged into the river rather than remaining in groundwater storage as intended. Transmissivity is within the ideal range of 5,000 to 25,000 ft^2/d (465 to 2,323 m^2/d). AR depends on the permeability of surficial layers; if there is a thick clay layer preventing infiltration it is not likely to succeed.

Volumetric analysis (Figure 10-3) shows aquifer storage is sufficient to inject 1 cfs (2,447 m^3/d) in sedimentary aquifers. The lack of head space in the two wells limits the aquifer storage, but high transmissivity compensates for this shortcoming. According to Brown's site rating system, Burns has 75% of ideal conditions for ASR (Figure 10-4). Hydraulic connection to the Silvies River may preclude ASR, despite other favorable factors, but local investigation is necessary.

Crane

The town of Crane is located northeast of Malheur Lake, more than 3 mi (4.8 km) from the nearest surface water source (Malheur Slough). The town sits at the foot of the Crane Creek Mountains. Groundwater levels have remained stable or risen in nearby OWRD observation well (HARN 1387). Depth to water was 55 ft (17 m) in 1995 and 40 ft (12 m) in 2005 (OWRD, 2006). The town has no ground or surface water rights, but water is available from Malheur Slough (OWRD WARS, accessed 2007).

An irrigation well (HARN 1061) has open intervals from 35 to 125 ft (11 to 38 m) below the surface, utilizing the Quaternary sand and gravel aquifer (Qs). Well yield was 1,500 gpm (8,175 m^3/d) at the time of installation (OWRD well log database, 2007). Transmissivity is estimated at 16,400 ft^2/d (1,500 m^2/d) from specific capacity data. This value falls within the ideal range for ASR of 5,000 to 25,000 ft^2/d (465 to 2,323 m^2/d).

Volumetric analysis indicates the aquifer has sufficient storage to inject 1 cfs (2,447 m^3/d) injected for 120 days (Figure 10-3). Water availability will ultimately determine whether ASR is possible. Crane fails Brown's site rating system because the distance to available surface water is greater than three miles. This does not mean a pipeline is impossible, but rather expensive. AR suitability will depend on the infiltration rate of surficial sediments and also the availability of recharge water.

Riley

Riley is situated in the alluvial filled lowlands of Silver Creek. The town currently has no surface water rights, although there is water available for storage from Silver Creek (OWRD WARS, accessed 2007).

An irrigation well (HARN 156) accesses water-bearing layers in Quaternary playa deposit sandstone (Qpl, Qs) at depths from 25 to 295 ft (7.6 to 90 m) below the surface, with a well yield of 2,763 gpm (15,058 m^3/d; OWRD well log database, 2007). Transmissivity estimated from well specific capacity is 13,000 ft^2/d (1,200 m^2/d). This is within the ideal range of 5,000 to 25,000 ft^2/d (465 to 2,323 m^2/d) for ASR.

Volumetric analysis of this site indicates the aquifer storage is suitable to inject 1 cfs (2,447 m^3/d) injected for 120 days. Brown's site rating system finds Riley has 69% of optimal ASR parameters. AR could utilize surficial gravel aquifers, depending on vertical permeability and water quality.

Diamond

Located on Kiger Creek where it flows out of the Steens Mountains, Diamond is an historic mining town. The town currently has no surface water rights, although there is water available for storage in Kiger Creek (OWRD WARS, accessed 2007). Current population data is unavailable for the town. Climate, agricultural activity or population change could create the need for water storage options in the future.

An irrigation well (HARN 50010) draws water from Quaternary sand and gravel (Qal) at depths from 80 to 320 ft (24 to 98 m) below the surface. At the time of installation, the well yielded 250 gpm (1,363 m^3/d; OWRD well log data, 2007).

Transmissivity estimated from specific capacity is 2,400 ft^2/d (230 m^2/d). This is below the ideal range for ASR.

Volumetric analysis indicates the aquifer storage is sufficient to inject 1 cfs (2,447 m^3/d) for 120 days (Figure 10-3). In Brown's site rating system, Diamond has 50% of ideal ASR parameters (Figure 10-4). Given the narrow river valley, AR utilizing the surficial Quaternary alluvium aquifer may not be feasible. The aquifer is most likely hydraulically connected to the river, but local investigation is critical to determine if this is true.

CHAPTER 11
MALHEUR RIVER BASIN

Hydrologic Description

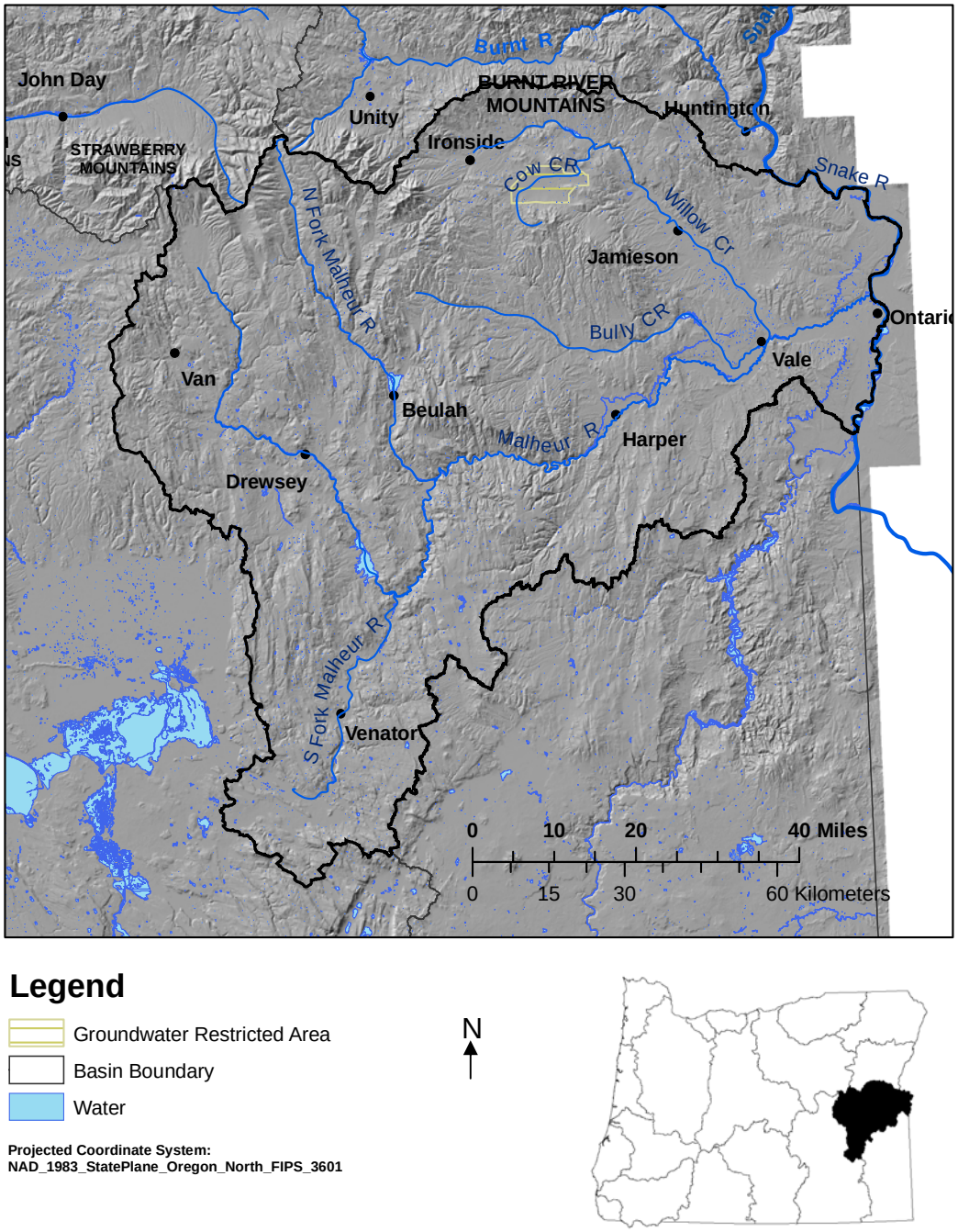
The Malheur River Basin covers approximately 5,051 mi^2 (13,082 km^2) and includes three major subbasins. The easternmost section is drained by Willow Creek, the middle by the Bully Creek, and the remainder is drained by the Malheur River and its South Fork. The rivers flow south and then east toward their confluence with the Snake River. Watershed divides delineating the basin are found to the north in the Burnt River and Strawberry Mountains, to the south and west in the volcanic highlands, and to the east at the Snake River.

The climate is high desert. Average annual precipitation ranges from approximately 40 in (1,020 mm) in the Strawberry Mountains, 13.5 in (343 mm) at Ironside to 8.4 in (213 mm) at Ontario (Oregon Climate Service, 2007).

Physical Setting

The basin varies from flat alluvial valleys to dissected volcanic uplands. Valleys range in width from less than two to over five miles, and contain distinct terraces. Uplands range from nearly flat plateaus to rolling hills (Gannett, 1990). Figure 11-1 illustrates the variety in the terrain and the fact that population centers are concentrated in alluvial valleys.

Groundwater Restricted Areas (Figure 11-1) are administrative regions designated by OWRD because they are experiencing long-term groundwater level declines. Further allocation within these areas is currently suspended, and some existing water rights have been limited to protect the resource.



Legend

- Groundwater Restricted Area
- Basin Boundary
- Water

N

Projected Coordinate System:
NAD_1983_StatePlane_Oregon_North_FIPS_3601

Figure 11-1. Malheur River Basin location map. Location of topographic features, rivers and towns that are examined by this study (Data sources: Oregon Geospatial Data Clearinghouse, 2006; Wright, 2006).

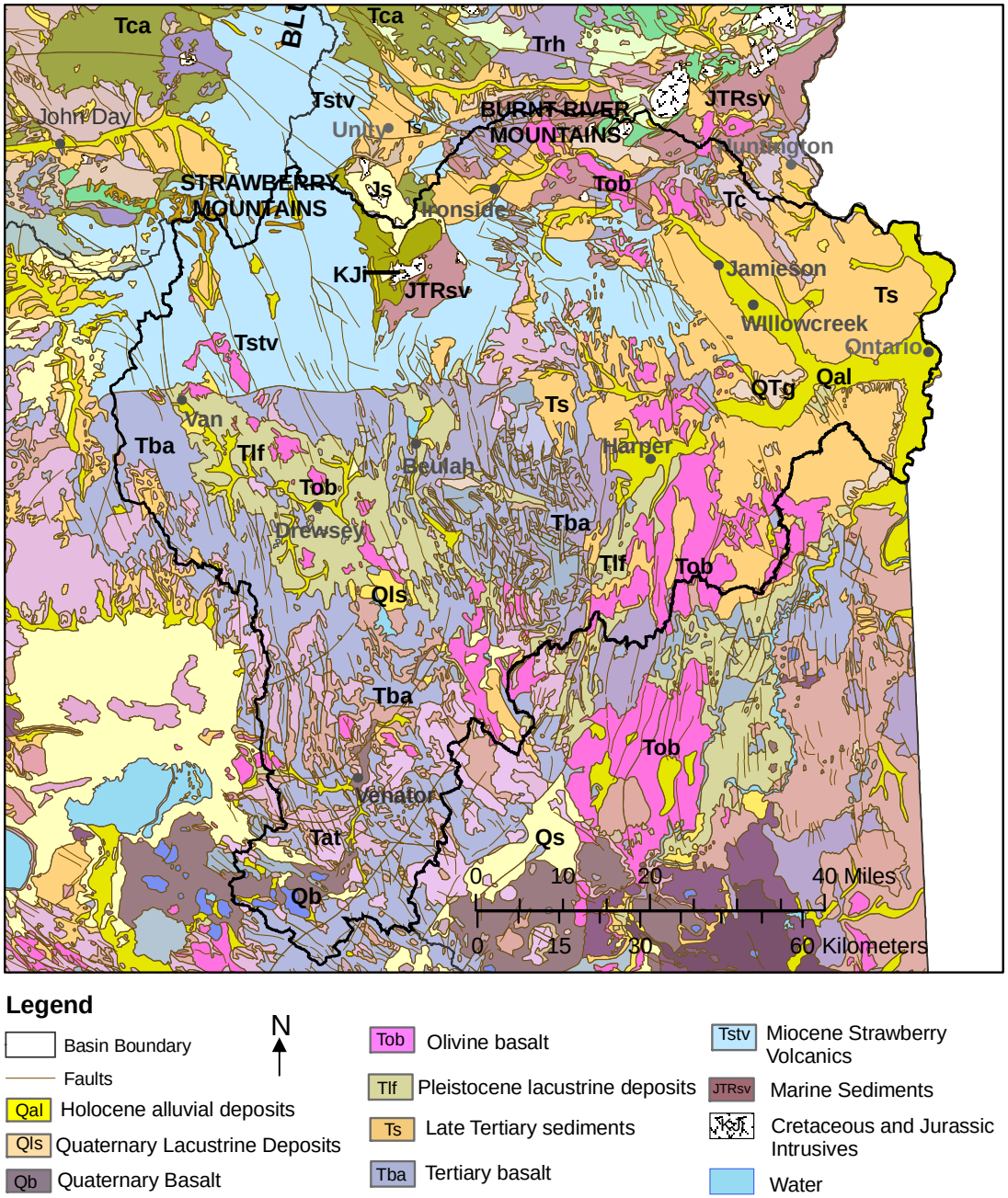


Figure 11-2. Malheur River Basin geology map. Geologic formations of importance to future ASR in the Malheur River Basin include basalts and alluvium (Data sources: Oregon Geospatial Data Clearinghouse, 2006; Walker and McLeod, 1991).

Hydrogeologic Units

Major geologic units in the basin, from oldest to youngest include Pre-Tertiary metamorphic and igneous basement rocks, Jurassic sedimentary rocks, Tertiary basalt and andesite, Tertiary and Quaternary sediments. Major geologic units are (Figure 11-2) discussed with respect to ASR in the following section.

Pre-Tertiary Basement Rocks

Jurassic through Cretaceous units include metamorphic and intrusive igneous rocks (JTRsv, KJi). They are exposed in the Burnt River Mountains at the northern edge of the basin. These units are of unknown thickness, and have fracture dominated porosity (water flows through fractures in the rock more than through pore spaces within the rock matrix). Therefore this unit will be generally unsuitable for ASR.

Tertiary Basalt and Andesite

Tertiary basalt and andesite lava flows (Tba, Tob, Tstv) overlie low permeability basement units. Massive lava flows are separated by permeable interflow zones, which provide small amounts of recharge to the overlying unconsolidated deposits (Gonthier et al., 1977). Thickness ranges from 0 to 5,000 ft (0 to 1,524 m). These units are exposed throughout the uplands of the central and western basin, but they are largely undeveloped by wells. Hydraulic conductivity is unknown.

Tertiary Sediments

Prehistoric lakes created the late Tertiary tuffaceous siltstones and other fine-grained lacustrine deposits (Tlf, Ts) found in the Willow Creek, Bully Creek and the lower Malheur River valleys. The largest exposure extends from north of Jamieson through Ontario and west to Harper. Lacustrine siltstones are generally of low permeability, but the unit does contain lenses of sand that can be productive aquifers for irrigation wells (Gannett, 1990). Wells that pump water from this unit are unusual in the basin, but rare cases with appropriate transmissivity may be suitable for small ASR projects.

Quaternary Sediments

Quaternary alluvium and lacustrine deposits (Qls, Qal) are exposed along Willow Creek, Bully Creek and in places along the Malheur River. Near Ontario, these sediments occur as silt over sand and gravel. Quaternary alluvium ranges in thickness from 250 ft (76.2 m) near Drewsey to about 50 ft (15.2 m) near Ontario (Gonthier et al., 1977; Gannett, 1990). Hydraulic conductivity in the silt ranges from 7 to 31 ft/d (2.3 to 9.3 m/d). Hydraulic conductivity in the sand and gravel is an order of magnitude higher, ranging from 440 to 670 ft/d (134 to 204 m/d), while transmissivity ranges from 6,000 to 32,000 ft^2/d (557 to 2,973 m^2/d; Gannett, 1990). These units are presently the main source of groundwater for wells in the basin.

The water table in the Quaternary alluvium is within a few feet of the surface in many areas. In the Ontario area, drainage wells are commonly used to dewater basements and fields. Previous investigations have also found a direct hydraulic connection between the silt, sand and gravel layers (Gannett, 1990). These factors may prevent ASR or AR. Artificially raising an already shallow water table could create unwanted springs at the surface, as injected water moves into the aquifer.

Tectonic Structure Influencing Groundwater Flow

Faulting in the Malheur River Basin mainly influences basalt and andesite of the upland areas (Figure 11-2). However, as mentioned in the previous section, these units are largely untapped by wells in this basin. Their affect on groundwater flow in the basalts and andesites is unknown. Valley alluvial deposits, which are the main source of groundwater and the main candidate for ASR or AR, appear to be unaffected by these structures (Gannett, 1990).

ASR Assessment

The purpose of this section is to provide a general assessment of specific locations for their potential to employ ASR as part of a water supply system. Site specific investigation is essential to determine if a recharge project is technically, economically,

and environmentally feasible. Positive results from this study indicate local sites possess many of the necessary components for successful ASR.

Table 11-1: Summary of Analysis Methods. For more detail, see Chapter 3: Analysis Methods.

Method	Description	Result of Method
Volumetric Analysis	Mathematical comparison of aquifer storage capability to the volume of surface water available	If > 1, sufficient storage If = 1 marginal storage If < 1, insufficient storage
Brown's Site Rating System	Site is rated from 0 to 2 for each criteria such as distance to source water, water quality, groundwater flow rate, aquifer thickness	Produces % of ideal ASR parameters at a given site

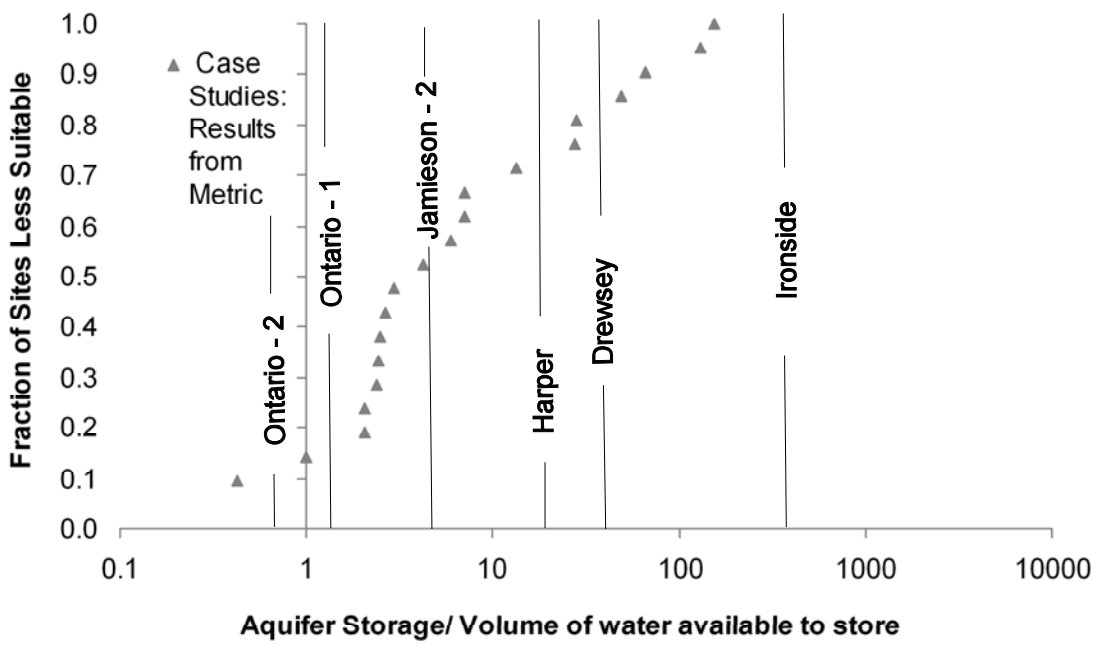


Figure 11-3: Malheur River Basin ASR metric results. Volumetric results indicate the aquifer storage is sufficient for Jamieson, Drewsey and ironside. However, Ontario marginal to insufficient storage. Data listed in Appendix B.

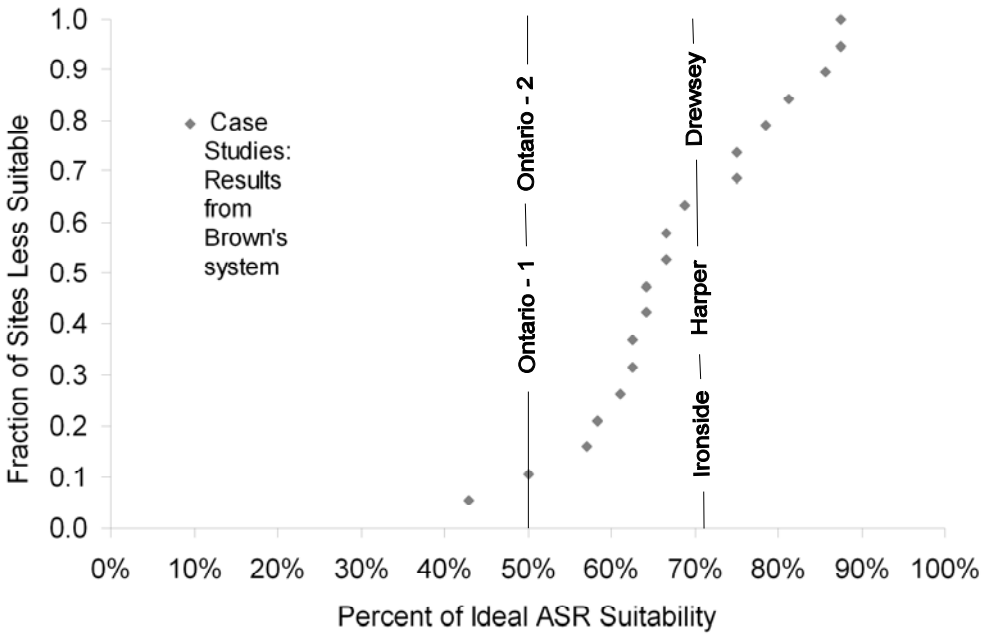


Figure 11-4: Malheur River Basin Brown's rating system results. Malheur River Basin sites have from 50 % to 71% of ideal conditions. 30% of case studies have results greater than the range of results for this basin. Data listed in Appendix C.

Ontario

Ontario is situated on the eastern boundary of the Malheur River Basin, 0.8 mi (1.3 km) from the Snake River. Groundwater levels in an unconfined sedimentary aquifer have not changed significantly in the past decade. Depth to water was 11 ft (3.3 m) in 1985 and 12 ft (3.7 m) in 1995, according to OWRD observation well (MALH 1693) records. Ontario's municipal wells access what is assumed to be the same stable shallow Quaternary sand and gravel aquifer. Population in the city of Ontario increased from 9,392 in 1990 to 11,125 in 2004 (U.S. Census, 2004).

Ontario's Quaternary sedimentary (Qal) municipal wells (Ontario-1, MALH 1276 and Ontario-2 MALH 1284) are screened at depths ranging from 18 to 40 ft (5.5 to 12 m) below the surface. These wells have yields of 1,300 and 835 gpm (7,085 and 4,551 m^3/d), respectively. Transmissivity in the sediments is estimated by this study as 15,300 and 9,500 ft^2/d (1,400 and 900 m^2/d) from specific capacity data. Gannett (1990) calculated transmissivity as 6,000 to 32,300 ft^2/d depending on the aquifer's thickness.

These values fall within the ideal range of 5,000 to 25,000 ft^2/d (465 to 2,323 m^2/d) for ASR.

The City of Ontario has surface water rights to 20 cfs (49,185 m^3/d) from the Snake River, and a water treatment plant with 13 MGD capacity (OWRD WRIS, accessed 2007). However, other factors make ASR unlikely to succeed in this area. Depth to water in city wells (MALH 1276 and 1284) was 5 and 3 ft (1.2 to 0.9 m), respectively, at the time of drilling. This means the aquifer's storage may be insufficient. Springs that would allow stored water to escape could develop. Static water levels in municipal wells are below the Snake River level, which indicates groundwater flows from the river toward the well (Gannett, 1990). If the groundwater level were raised by ASR, flow direction could be reversed and stored water released into the river.

Water quality is also a concern; Gannett (1990) reported widespread nitrate and pesticide contamination from agricultural runoff in the shallow sand and gravel aquifer. Due to water quality concerns, AR is also unlikely to be viable for drinking water in this area, unless significant groundwater remediation occurs.

Brown's site rating system finds Ontario has 50% of ideal conditions for ASR. The site scored low for high well density and an aquifer less than 25 ft (7.6 m) in thickness. Volumetric analysis (Figure 11-3) indicates aquifer storage is marginal to insufficient for ASR. The site may be more suitable if the injection volume is reduced.

Ironside

Located on Willow Creek, Ironside sits in a 0.6 mile wide Quaternary alluvium filled basin. Population was steady at 87 residents in 2004 (U.S. Census, 2004). Groundwater levels have also remained stable in a nearby observation well (MALH 28), with a depth to water of 18 ft (5.5 m) in 1995 and 20 ft (6m) in 2005 (OWRD groundwater level data, accessed 2006).

The city has no surface water rights, and (OWRD WARS, accessed 2007) surface water is entirely allocated in nearby Willow Creek. Dickson Reservoir is located 4.5 mi (7.2 km) upstream from Ironside. The existing reservoir provides storage presently, and combined with the small population there does not appear to be an immediate need for

water supply expansion for municipal uses. However, circumstances and need may change in the future.

An irrigation well (MAHL 51791) has open intervals from 63 to 103 ft (19.2 to 31 m) below the surface, drawing water from the Tertiary sand and gravel aquifer (Ts). The well yield is 1,600 gpm (8,720 m^3/d; OWRD well log database, 2007). Transmissivity in the sand and gravel aquifer is estimated at 12,800 ft^2/d (1,200 m^2/d) from specific capacity data. This is within the ideal range for ASR of 5,000 to 25,000 ft^2/d (465 to 2,322 m^2/d).

Volumetric analysis (Figure 11-3) indicate the aquifer storage is sufficient to inject 1 cfs (2,447 m^3/d) for 120 days. This is calculated while ignoring the fact that water is fully allocated for Willow Creek, as an experiment to test solely for aquifer suitability. Ironside has 71% of optimal ASR parameters in Brown's site rating system (Figure 11-4). The lack of water availability may preclude ASR or AR.

Drewsey

Drewsey is located in the western Malheur River Basin, about 0.4 mi (0.7 km) from Malheur River. The town sits in a 1 mi (1.6 km) wide Quaternary alluvium filled basin, which overlies older, fine-grained lake deposits. The city currently has no surface water rights, and the water in nearby Stinkingwater Creek is completely allocated. The Sitz Reservoir, which lies 6 mi (9.6 km) up stream may provide all the water storage currently required. However, climate change or dam failure may create the need for alternative storage at some time in the future. Population had decreased by 6.5% to 127 in 2005 (U.S. Census, 2006).

An irrigation well (HARN 50760) has open intervals in the Tertiary basalt aquifer (Tob, Tba) from depths of 60 to 270 ft (18.2 to 82.3 m) below the surface, and has a well yield of 150 gpm (818 m^3/d; OWRD well log data, 2006). Transmissivity estimated from well specific capacity is 8,100 ft^2/d (750 m^2/d). This is within the ideal range for ASR.

Volumetric analysis indicates aquifer storage is suitable to inject 1 cfs (2,447 m^3/d) for 120 days (Figure 11-3). Brown's site rating system finds Drewsey has 71% of optimal ASR parameters (Figure 11-4). To realize this potential for ASR, a surface water

source must be obtained. AR could utilize surficial gravel aquifers, but given the close proximity to the river, these aquifers are subject to storage loss to surface water.

Harper

Harper is located on the Malheur River. Population was stable at 260 residents in 2004 (U.S. Census, 2004). Harper has no surface water rights, and (OWRD WARS, 2007) there is currently no water available from Malheur River at Harper.

A municipal well (MALH 1761) has open intervals from 13 to 55 ft (4 to 16.8 m) below the surface. Water-bearing layers are reported as Quaternary gravel and Tertiary shale (Qal, Tlf) which yield 390 gpm at the well (2,126 m^3/d; OWRD well log database, 2007). Transmissivity estimated from specific capacity of the municipal well is 9,700 ft^2/d (900 m^2/d). This is within the ideal range for ASR of 5,000 to 25,000 ft^2/d (465 to 2,322 m^2/d).

Volumetric analysis indicates Harper's municipal well is suitable for ASR(Figure 11-3). Brown's site rating system finds Harper has 71% of optimal ASR parameters, but the lack of source water may negate these positive results. AR may be possible in overlying alluvial deposits, if infiltration rates are appropriate.

CHAPTER 12
MIDDLE COAST BASIN

Basin Hydrology

The Middle Coast Basin covers approximately 2,340 mi^2 (5,900 km^2) of the central Oregon Coast. Watershed divides delineating the basin are found at the crest of the Coast Range to the east and the Pacific Ocean to the west. Several rivers originate in the Coast range and wind through steep valleys to the Pacific Ocean, including the Siletz, Yaquina, Alsea and Siuslaw Rivers.

The climate is extremely moist, which is typical of the Coast Range. Average annual precipitation ranges from approximately 60 in (1,520 mm) at Newport, to 90 in (2,290 mm) inland at Alsea (Oregon Climate Service, 2007). Rainfall is greater on the west facing slopes than on the eastern slopes, as storms typically move inland from the ocean. Most of the precipitation occurs between October and June, July through September can be dry. This dry period coincides with the time of greatest water consumption in the area due to summer tourism.

Physical Setting

The Middle Coast Basin includes Coast Range marine sequences, intrusive basalts and younger beach and alluvial deposits. Local pockets of productive aquifers exist within a generally unproductive groundwater environment. Faults, fractures and shear zones have created a secondary porosity in cemented sand and siltstones that represent localized productive groundwater sources.

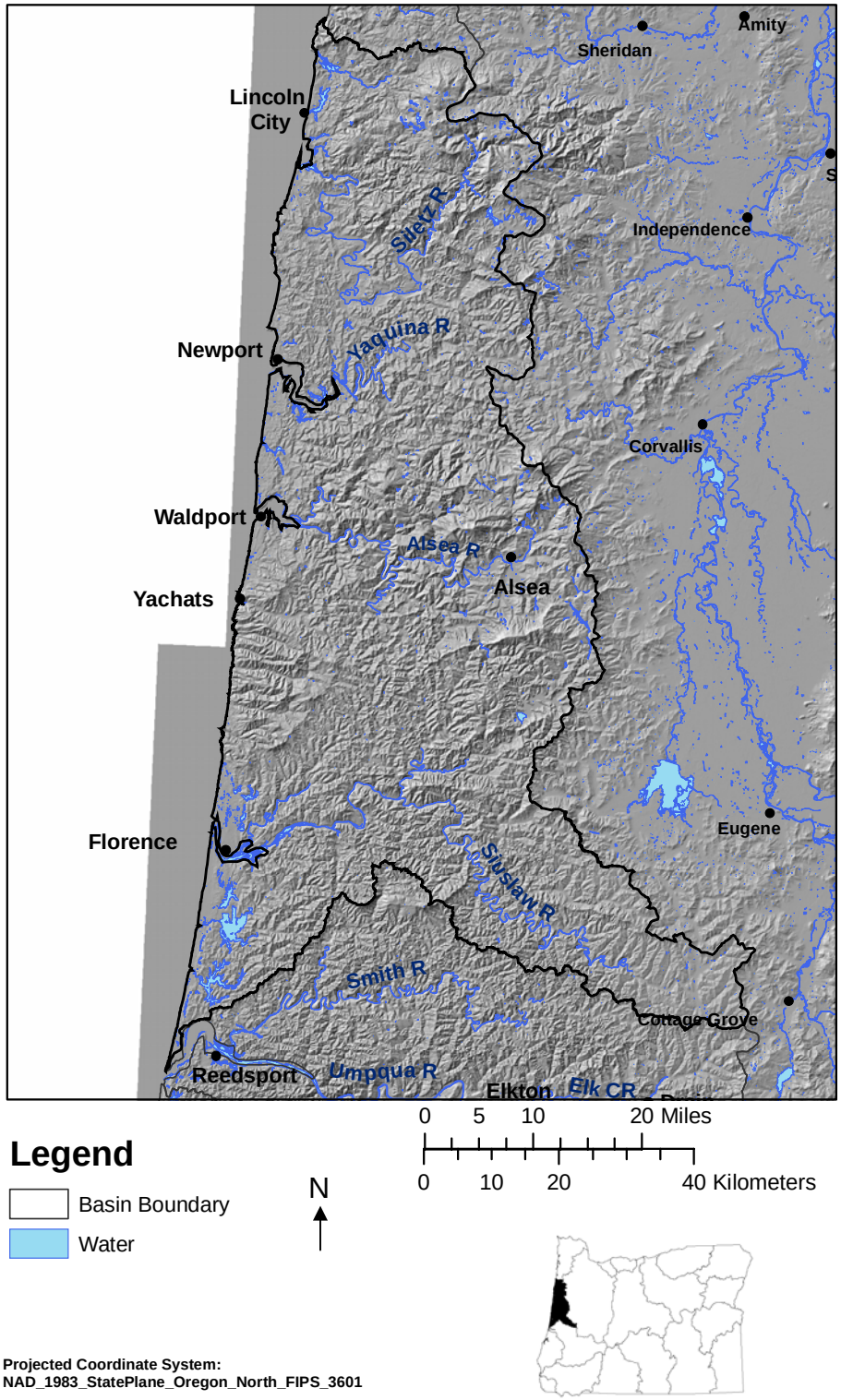


Figure 12-1. Middle Coast Basin location map. Location of topographic features, rivers and cities in the Middle Coast Basin that are examined in this study (Data sources: Wright, 2006; Oregon Geospatial Data Clearinghouse, 2006).

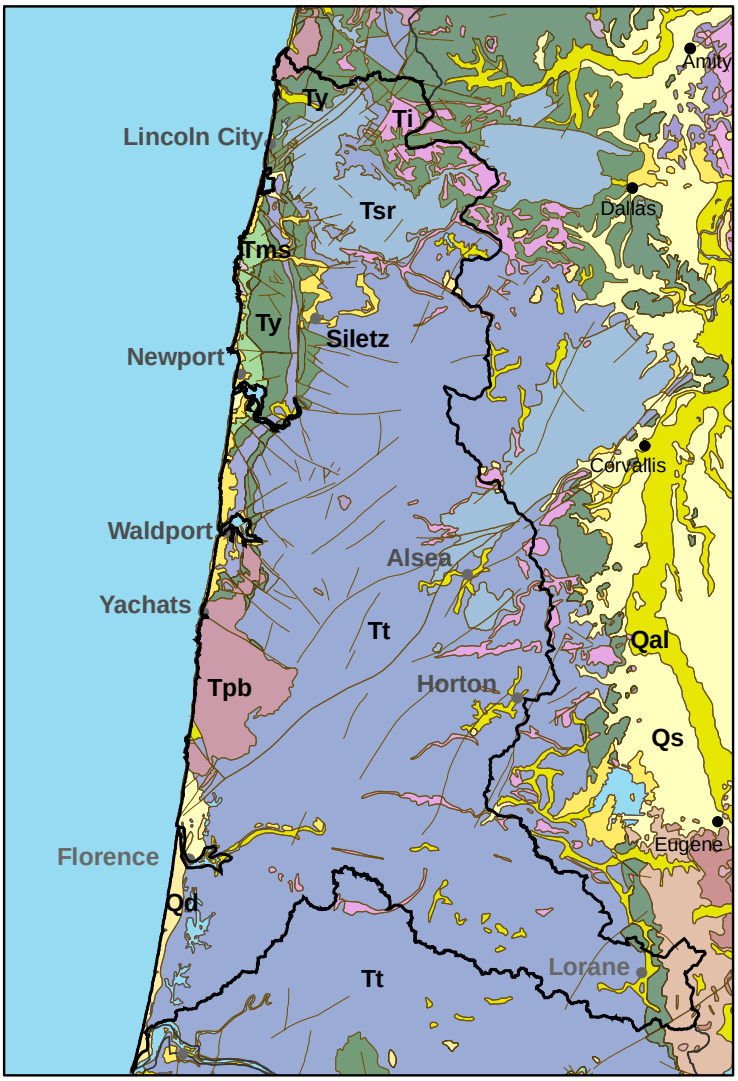


Figure 12-2. Middle Coast Basin geology map. Geologic formations of importance to future ASR projects in Middle Coast Basin include basalts and basin fill sediments (Data sources: Walker and McLeod, 1991; Oregon Geospatial Data Clearinghouse, 2006).

Hydrogeologic Units

Major geologic units in the basin, from oldest to youngest, include Jurassic metamorphic and sedimentary rocks, Cretaceous sedimentary rocks, Tertiary marine volcanics and sediments, and Quaternary alluvial and marine deposits (Figure 12-2). These units are grouped and discussed in relation to ASR in the following sections.

Tertiary Marine Deposits

Eocene through Miocene marine sequences (Tms, Tt, Tsr, Ty) include sandstone, siltstone and volcanics. These units are exposed throughout the Coast Range to the coastline, and have been affected by the gradual eastward tilting of the Coast Range block (Reillinger and Adams, 1982). Sandstones are generally tuffaceous, deposited by rivers and through the air during the eruption of Western Cascade Volcanic centers during Tertiary time. Total combined maximum thickness for the marine sequence is approximately 15,000 ft (6,000 m; Snavely et al., 1975). These units yield enough water in some places for domestic use (1 to 10 gpm, or 5.45 to 54.5 m^3/d), but do not as a general rule support large capacity municipal or industrial wells. Thrust and normal faults throughout the Coast Range, in addition to jointing, represent the preferential flow paths through many of these low permeability marine sediment units. ASR is unlikely to succeed in this area due to the unpredictable fracture flow paths and overall low permeability of these units.

At depths greater than about 200 ft below the surface, native groundwater becomes increasingly saline, with median dissolved solids concentration of 300 mg/L and a maximum reported concentration of 70,000 mg/L (McFarland, 1983). This water quality issue, combined with low to variable hydraulic conductivity of 0.1 to 10 ft/d (0.03 to 3 m/d), indicates that deep marine sediments are not a preferred unit for ASR. However, experience in Florida saline aquifers indicates it is feasible to maintain a "bubble" of potable, injected water within a brackish aquifer (Pyne, 1995 and 2005). The tradeoff is that some of the injected water may be lost to mixing with the poor quality marine sediment water during storage. This loss will have to be carefully evaluated by

interested parties to decide whether it is economically and environmentally acceptable.

Intrusives and basalts

Local exposures of basalts form present day sea stacks and resistant headlands along the Middle Coast. Upper Eocene basalts found near Yachats (Tpb) were erupted underwater on the shallow continental slope, as a broad shield with thickness up to 2,000 ft (610 m; Armentrout and Suek, 1985). These basalts provide water for domestic use in the Yachats area, at rates of less than 50 gpm (273 m^3/d; OWRD well log database, 2007). Smaller mafic intrusions (Ti) are exposed on the east slope of the Coast Range, but their permeability is unknown.

Quaternary Sediments

Erosion of the region by rivers and ocean activity has created and deposited the unconsolidated Pleistocene through Holocene sediments (Qal, Qt, Qd) that line the coast of the basin. These units are widely accessed by shallow domestic and irrigation wells, and they represent the most productive aquifers in the basin. Unconfined to semi-confined sedimentary aquifers may be useful for ASR or AR in areas with suitable transmissivity, source water quality and availability. Well density (the number of wells using the same aquifer that may be close enough to withdraw stored water) will need to be examined to evaluate the security of stored water, in addition to the aquifer's likelihood to discharge into surface water.

Tectonic Structure Influencing Groundwater Flow

Located east of the Juan de Fuca subduction zone, where oceanic crust is colliding with and sinking below the coasts of Oregon, Washington and British Columbia, the Middle Coast Basin displays large and small scale structures resulting from this compressional environment. The basin scale up-warp that is presently lifting and tilting the Coast Range to the east has subsequently created smaller scale jointing and fracture patterns to relieve the stress imposed by subduction. Faults extend throughout the Coast range, trending northeast- southwest and northwest southwest, with displacements as

large as 3 mi (4.8 km; Orr and Orr, 2000). Because the marine sediments that dominate this region's geology have low permeability, these structural forces have generally increased groundwater flow by creating preferential flow paths. This also means that ASR may be hindered by the unpredictable fracture patterns in the marine sediments. While joints, fractures and faults may increase groundwater flow through the low permeability sediments, water in these structures may flow quickly and find escape routes to the surface which would be undesirable for seasonal storage. Local investigation is necessary to determine the structures' effects on groundwater flow relevant to specific ASR or AR sites.

ASR Assessment

The purpose of this section is to provide a general assessment of specific locations for their potential to employ ASR as a part of water supply systems. Site specific investigation is essential to determine if a recharge project is technically, economically, and environmentally feasible, but positive results from this study indicate the site possesses many of the necessary components for successful ASR.

Table 12-1: Summary of Analysis Methods. For more detail, see Chapter 3: Analysis Methods.

Method	Description	Result of Method
Volumetric Analysis	Mathematical comparison of aquifer storage capability to the volume of surface water available	If > 1, sufficient storage If = 1 marginal storage If < 1, insufficient storage
Brown's Site Rating System	Site is rated from 0 to 2 for each criteria such as distance to source water, water quality, groundwater flow rate, aquifer thickness	Produces % of ideal ASR parameters at a given site

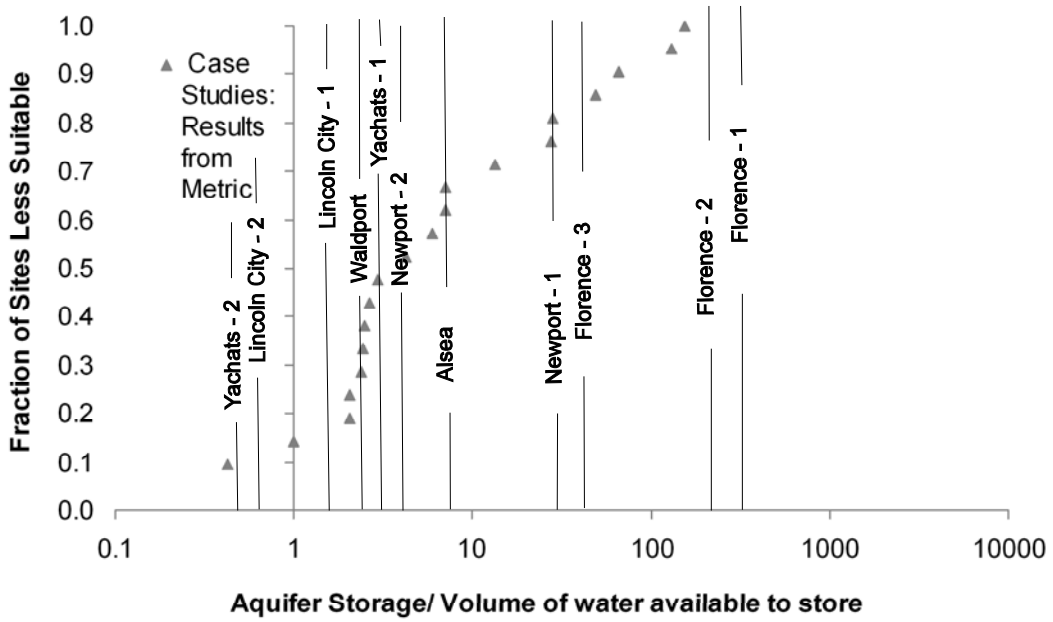


Figure 12-3: Middle Coast Basin ASR metric results. Volumetric results for Florence, Newport, Alsea, Waldport, Yachats-1 and Lincoln City-1 indicate aquifer storage is sufficient for ASR. Results for Yachats-2 and Lincoln City-2 wells indicate they are marginally suitable for ASR. Data listed in Appendix B.

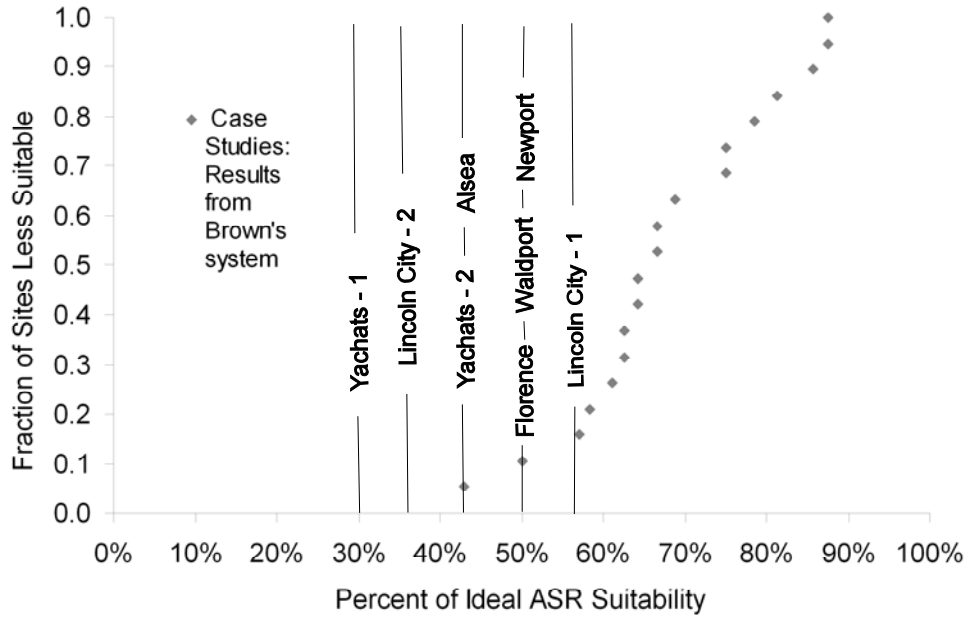


Figure 12-5: Middle Coast Basin Brown's site rating system results. Sites have from 28 % to 57% of ideal conditions. 80% of case studies' results are greater than the results for this basin. Data listed in Appendix C.

Florence

Florence is located at the mouth of the Suislaw River, among an extensive stretch of coastal dunes. This unique area is a tourist destination for ATV enthusiasts as well as other coastal outdoor activities. The population is growing rapidly, with 5,162 residents in 1990 and 8,122 in 2006 (U.S. Census, 2006). Housing on the fringe of the fragile dune area has also increased over recent decades. Water is managed by the city public works department, which draws on surface water and from a dune well field. The city water treatment plant has a 3 MGD (11,355 m^3/d) capacity, and it is situated near the dune well field to process water for the municipality. The city also has surface water rights to 0.8 cfs (1,958 m^3/d) from Munsel Creek.

The most likely site for ASR is at the City of Florence water treatment plant, therefore, nearby municipal wells in the dune area were selected for ASR suitability analysis.

Three municipal wells in the Quaternary dunes (Qd) were examined, with well yields ranging from 220 to 420 gpm (1,200 to 2,289 m^3/d) and depths ranging from 76 to 180 ft (23 to 55 m) below the surface (OWRD well log database, 2007). Transmissivity estimated from specific capacity ranges from 3,400 to 4,700 ft^2/d (300 to 430 m^2/d), which is below the ideal ASR range of 5,000 to 25,000 ft^2/d (465 to 2,323 m^2/d).

Overall, Florence shows moderate suitability for ASR. According to Brown's site rating system, Florence has 50% of ideal conditions for ASR. The town lost points for well density greater than 5 wells per square mile (although the wells are all owned by the City of Florence, which negates this criterion in this particular case), the presence of threatened fish species, and low transmissivity. However, the existing treatment plant and water pipelines provide high quality water for storage, which is advantageous for ASR. Volumetric analysis indicates that aquifer storage at all three wells is to inject ½ of Florence's surface water right for 120 days (Figure 12-3).

Yachats

Yachats, located at the mouth of the Yachats River, is a small community that hosts some coastal tourism. The town presently has no surface water rights, but there is 1

cfs (2,447 m^3/d) available from Yachats River for municipal use (OWRD WRIS, accessed 2007). There are no wells owned by the city, and water is provided by domestic wells. Population was stable at 644 in 2006.

A domestic well, Yachats-1 (LANE 6824), was examined for ASR suitability. It has open intervals from approximately 52 to 66 ft (16 to 20 m) below the surface, drawing water from a basalt aquifer (OWRD well log database, 2007). Based on geologic maps of the area the aquifer is likely Yachats Basalt (Tpb), which is a broad shield intrusion. Transmissivity is estimated at 1,500 ft^2/d (140 m^2/d) from specific capacity data. This value falls below the target range for ASR, although it is similar to the value found at Dallas, Oregon ASR aquifer tests. Transmissivity at the Dallas site was reported around 1,300 ft^2/d (120 m^2/d) in the Siletz River Basalt, and pilot testing indicated the aquifer may be hydraulically suitable for municipal scale ASR (Golder Associates, 2005).

A second, deeper well in Yachats was selected to examine whether the aquifer properties change significantly with increased depth and thickness. Domestic well Yachats-2 (LANE 6813) has open intervals from 30 to 280 ft (9 to 85 m) below the surface, but the well yields 4 gpm (21.8 m^3/d), much less than the shallow well completed in the same Yachats basalt unit. Transmissivity estimated at this well is 70 ft^2/d (7 m^2/d), which below the target range for ASR, suggesting ASR is not feasible in the deeper layers of the Yachats basalt, at least at this particular well.

Volumetric analysis (Figure 12-3) at Yachats-2 (the deeper well) indicate aquifer storage is insufficient to inject 1 cfs (2,447 m^3/d) for 120 days. At Yachats-1, the aquifer is suitable to inject 1 cfs (2,447 m^3/d) due to its higher transmissivity. Yachats has 29 to 43% of ideal conditions for ASR according to Brown's site rating system, with low scores for transmissivity and the presence of threatened fish species. AR is not likely at this location, because the basalt's vertical permeability is limited to fractures and joints.

Waldport

Located at the mouth of the Alsea River, Waldport sits on Quaternary terrace deposits of the central Oregon coast. The City of Waldport currently has surface water

rights to 7.4 cfs (40.3 m^3/d) from Weist Creek and Eckman Slough (OWRD WRIS, accessed 2007). Population increased from 1,595 to 2,051 between 1990 and 2006 (U.S. Census, 2006). No municipal wells were located by this study, so a domestic well was chosen to represent local hydrogeologic environments.

A domestic well (LINC 168) utilizes the Quaternary sand aquifer (Qs), which likely represents the Quaternary coastal terrace deposits. Open intervals from depths of 80 to 85 ft (24 to 26 m) below the surface yielded 30 gpm (165 m^3/d) at the time of installation (OWRD well log database, 2007). Transmissivity estimated from specific capacity is 800 ft^2/d (70 m^2/d). This is below the ideal range of 5,000 to 25,000 ft^2/d (465 to 2,323 m^2/d) for ASR, although it is similar to transmissivity of a sand and sandstone aquifer used in Denver, Colorado for ASR. Local investigation is necessary.

Volumetric analysis indicates the aquifer is suitable to inject ½ of the water treatment plant capacity for 120 days (Figure 12-3). Brown's site rating system finds both wells have 50% of optimal ASR parameters (Figure 12-4). The Waldport sites lost points for low transmissivity and an aquifer thickness less than 25 ft 7.6 m). AR may be feasible in surficial Quaternary terrace deposits, depending on the extent of their hydraulic connection to surface waters of the river and estuary.

Newport

The city of Newport sits north of Newport Bay near the mouth of the Yaquina River. Like most coastal towns in Oregon, the city experiences a population boom in the summer tourism months, which coincides with the driest portion of the year. The City of Newport manages water treatment and distribution, using surface water from Big Creek (10 cfs or 24,470 m^3/d within their water right). The water treatment facilities currently have a 3.5 MGD capacity. The population of Newport increased from 8,437 residents in 1990 to 9,896 in 2006 (U.S. Census, 2006).

Parks Department well, Newport-2 (LINC 1290), was selected as representative of the largest capacity wells in the area. This well has open intervals from depths of 77 to 87 ft (23 to 27 m) below the surface and a well yield of 60 gpm (327 m^3/d; OWRD well log database, 2007). Transmissivity in the Quaternary terrace sand aquifer (Qt),

estimated from the well's specific capacity is 1,600 ft^2/d (150 m^2/day). This is below the target range of 5,000 to 25,000 ft^2/d (465 to 2,323 m^2/d) for ASR.

A second Parks Department well, Newport-1 (LINC 1291), was also examined for ASR suitability. The well is open to a similar Quaternary terrace sand aquifer (Qt) from the depth of 84 to 94 ft (26 to 29 m) below the surface, and yields 25 gpm (136 m^3/d). Estimated transmissivity is higher than the first well examined, at 3,347 ft^2/d (311 m^2/d), although this is also below the target range for ASR.

Volumetric analysis indicates the aquifer storage is suitable to inject ½ of the water treatment plant's capacity for 120 days at both wells, although Newport-1 is more suitable due to the greater depth to water at this well (Figure 12-3). According to Brown's site rating system, Newport has 50% of optimal ASR parameters (Figure 12-4). The site lost points for low transmissivity and an aquifer thickness less than 25 ft (7.6 m). AR may also be feasible in this area in the shallow surficial sand and gravel aquifers, depending on local vertical permeability and proximity to surface water discharge points.

Lincoln City

Lincoln City is located just north of mouth of the Siletz River. The community shares the same surface water sources. Population in Lincoln City grew from 5,892 to 7,944 between 1990 and 2006 (U.S. Census, 2006). However, it should be noted that on weekends the town's population often doubles with visitors. This means the water supply system must be flexible enough to meet this rapid fluctuation in consumer demand. No municipal well logs were located by this study that provided sufficient information for ASR suitability analysis, therefore, a domestic well was examined.

Domestic well Lincoln City-1 (LINC 613) draws water from Quaternary sand and claystone (Qs, Qt) at depths of 26 to 60 ft (8 to 18 m) below the surface. Well yield at the time of installation was 40 gpm (218 m^3/d) OWRD well log database, 2007). Transmissivity estimated from the well's specific capacity is 1,600 ft^2/d (150 m^2/d), which is below the ideal range for ASR.

Volumetric analysis indicates the aquifer storage is suitable to inject 3 MGD (11,355 m^3/d) for 120 days (Figure 16-3). Brown's site rating system finds Lincoln City

has 36 to 57% of optimal ASR parameters (Figure 16-4). The site lost points for the presence of threatened species that may suffer from a decrease in river flow, well density greater than 5 wells per square mile and low transmissivity. AR may be feasible in this area, in the small areas of Quaternary sediments near the coast and river, depending on whether the water infiltrated into the aquifer will discharge into the nearby bay before it can be recovered for municipal use.

Alsea

The small community of Alsea, situated on the Alsea River was chosen to sample the ASR potential in the eastern portion of the Middle Coast Basin. The town currently has no surface water rights, but there is 1 cfs (2,447 m^3/d) available from Alsea River for municipal use (OWRD WRIS, accessed 2007). There are also no wells owned by the city, and water is provided by domestic wells. Population was stable at approximately 1,150 in 2006.

A domestic well (BENT 7527) with open intervals from approximately 40 to 113 ft (12 to 34 m) below the surface draws water from a Tertiary marine sediment aquifer (Tt) (OWRD well log database, accessed 2007). Transmissivity is estimated at 900 ft^2/d (80 m^2/d) from specific capacity data. This value falls below the ideal range for ASR, although it is similar to that found in South Goulbourne Island, Australia sandstone ASR aquifer tests. Transmissivity at the Australian site was reported around 750 ft^2/d (70 m^2/d) in the Marligur Sandstone, and pilot testing found the aquifer suitable for municipal scale ASR (Pavelic et al., 2002).

Volumetric analysis (Figure 12-3) at Alsea indicate the aquifer's available storage is sufficient to inject 1 cfs (2,447 m^3/d) for 120 days. Alsea has 43% of ideal conditions for ASR according to Brown's site rating system, with low scores for transmissivity and the presence of threatened fish species. AR is not likely at this location, based on the steep, narrow character of the river valley at this point. Any surficial river sediments are most likely directly connected to the river, and water infiltrated at the surface is likely to discharge to the river before it is recovered for municipal use

CHAPTER 13
NORTH COAST BASIN

Basin Hydrology

The North Coast Basin covers approximately 2,556 mi^2 (6,620 km^2) of the Oregon Coast. Watershed divides delineating the basin are found at the crest of the Coast Range to the east and the Pacific Ocean to the west. Several rivers originate in the Coast range and wind through steep valleys to the Pacific Ocean, including the Lewis and Clark, Necanicum, Nehalem, Trask and Nestucca Rivers.

The climate is extremely moist, which is typical of the Coast Range. Average annual precipitation ranges from approximately 50 in (1,270 mm) at Clatskanie, to 90 in (2,290 mm) at Manzanita (Oregon Climate Service, 2007). Rainfall is greater on the west facing slopes than on the eastern slopes, as storms typically move inland from the ocean. Most of the precipitation occurs during between October and June, while July through October can be dry. This dry period coincides with the time of greatest water consumption in the area due to summer tourism.

Physical Setting

The basin includes the rugged, heavily vegetated Coast Range, transitioning abruptly into massive headlands and sandy beaches (Figure 13-1).

Hydrogeologic Units

The North Coast Basin includes Coast Range marine sequences, intrusive basalts and younger beach and alluvial deposits. Local pockets of productive aquifers exist within a generally unproductive groundwater environment. Faults, fractures and shear zones have created a secondary porosity in cemented sand and siltstones that represent localized productive groundwater sources.

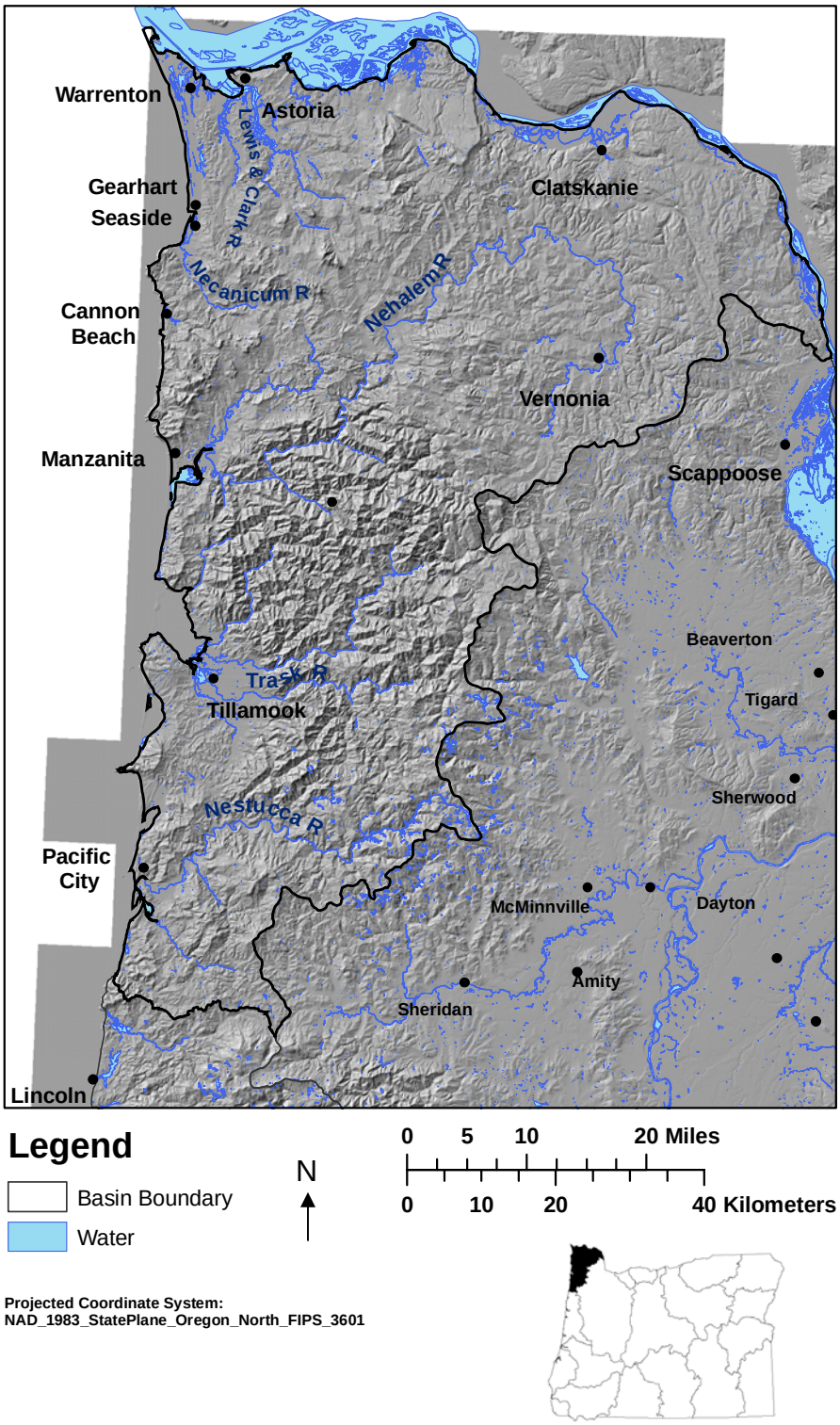


Figure 13-1. North Coast Basin location map. Location of topographic features, rivers and towns that are examined in this study (Data sources: Wright, 2006; Oregon Geospatial Data Clearinghouse, 2006).

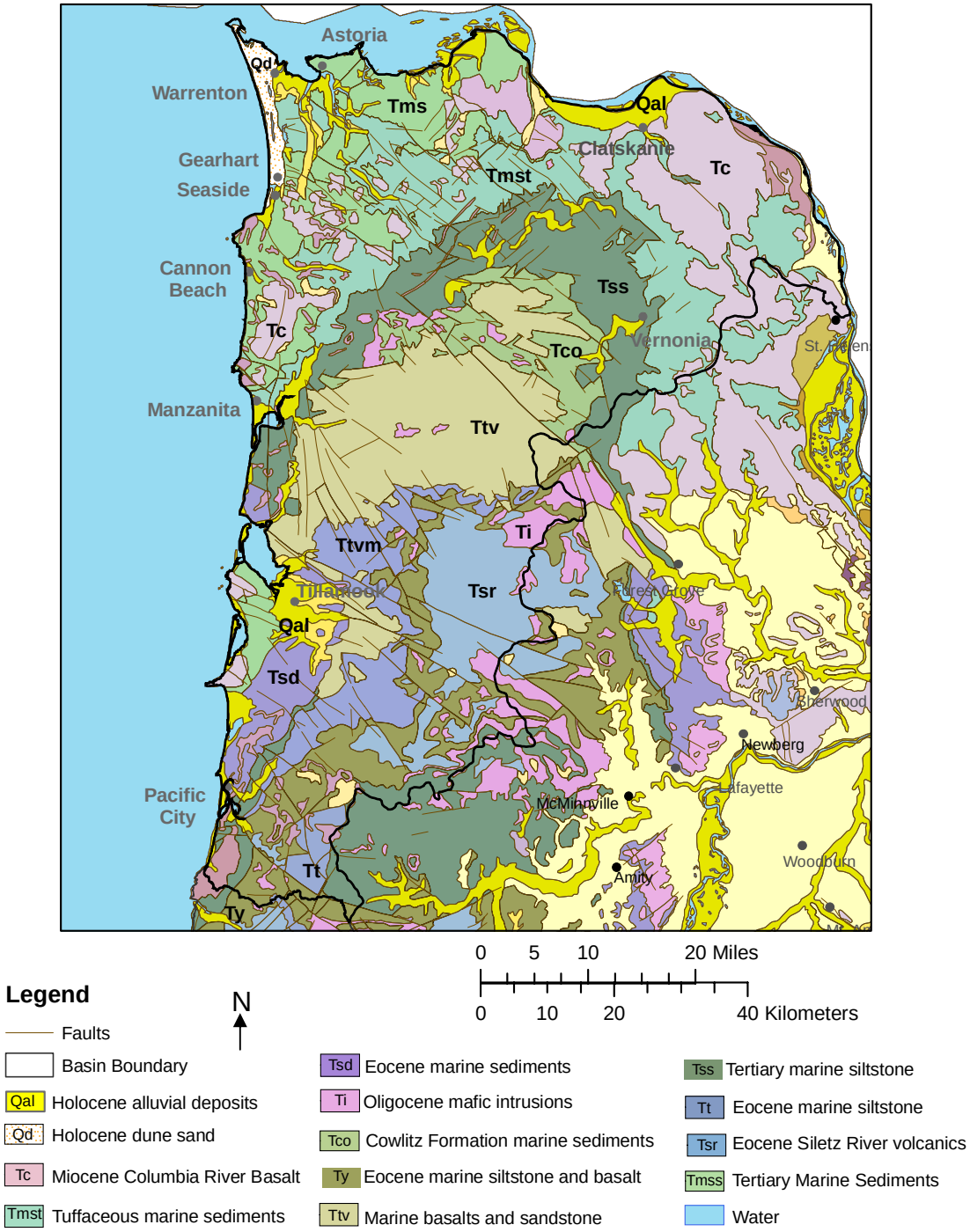


Figure 13-2. North Coast Basin geology map. Geologic formations of importance to future ASR in the North Coast Basin include basalts and basin fill sediments (Data sources: Walker and McLeod, 1991; Oregon Geospatial Data Clearinghouse, 2006).

Major geologic units in the basin, from oldest to youngest, include Tertiary marine volcanics and sediments, Tertiary intrusives and flood basalt flows, Quaternary alluvium and dune deposits. The units (Figure 13-2) are grouped and discussed in relation to ASR in the following sections

Tertiary Marine Deposits

Marine sequences (Tms, Tsd, Tco, Ttv, Tss, Tmss, Tmst, Tt, Tsr, Ty) include sandstone, siltstone, shale and volcanic rocks. These units occur throughout the Coast Range to the beaches, and have been affected by the gradual eastward tilting of the Coast Range block (Reillinger and Adams, 1982). Sandstones are generally tuffaceous, deposited by rivers and through the air during the eruption of Western Cascade Volcanic centers during Tertiary time. Total combined maximum thickness for the marine sequence is approximately15,000 ft (6,000 m; Snavely et al., 1975). These units yield enough water in some places for domestic use (1 to 10 gpm; 5.45 to 54.5 m^3/d), but do not as a general rule support large capacity municipal or industrial wells. Crustal shortening caused by the Juan de Fuca subduction zone, located off the Oregon Coast, has caused both thrust and normal faults throughout the Coast Range, as well as jointing. These structures represent the preferential groundwater flow paths through many of these low permeability marine sediment units. ASR is unlikely to succeed in the marine sediments due to the unpredictable fracture flow paths and overall low permeability of these units.

At depths greater than about 200 ft (61 m) below the surface, native groundwater becomes increasingly saline, with median dissolved solids concentration of 300 mg/L and a maximum reported concentration of 70,000 mg/L (McFarland, 1983). This water quality issue, combined with variable hydraulic conductivity of 0.1 to 10 ft/d (0.03 to 3 m), indicates that deep marine sediments present unique challenges for ASR. However, experience in Florida saline aquifers indicates it is feasible to maintain a “bubble” of potable, injected water within a brackish aquifer (Pyne, 1995 and 2005). The trade-off is that some of the injected water may be lost to mixing with the poor quality marine

sediment water during storage. This loss will have to be carefully evaluated by interested parties to decide whether it is economically and environmentally acceptable.

Intrusives and basalts

Local exposures of basalts form present day sea stacks and resistant headlands along the North Coast. Columbia River Basalts (Tc) are exposed between St. Helens and Clatskanie, as well as in the headlands between Manzanita and Cannon Beach. Interflow zones of the basalt may be suitable for ASR, but local investigation is necessary. Smaller mafic intrusions (Ti) are exposed on the east slope of the Coast Range; their permeability is unknown.

Quaternary Sediments

Erosion of the region by rivers and ocean currents has created and deposited the unconsolidated sediments (Qal, Qd) that line the rivers and coast of the basin. These units are widely accessed by shallow domestic and irrigation wells, and they represent the most productive aquifers in the basin. Alluvium is present in narrow ribbons along many of the rivers, but its direct connection to surface water makes it unlikely to be suitable for ASR or AR.

Extensive dune deposits (Qd) stretch from Seaside north to the Columbia River. Frank (1970) found the Pleistocene and Holocene deposits of the Clatsop Plains Sand Dune area have sub-angular to rounded grains predominantly composed of quartz. This study also found the aquifer has a thickness exceeding 100 ft (30.5 m) and an average transmissivity of 27,000 gpd/ft (336 m^2/d). Dune sands were found to absorb approximately 80% of annual precipitation, and the groundwater table fluctuates in direct relation to rainfall events. This unit is a main water bearing unit in the North Coast Basin, and may be useful for ASR or AR in areas with suitable transmissivity, source water quality and availability.

Tectonic Structure Influencing Groundwater Flow

Located east of the Juan de Fuca subduction zone, where oceanic crust is colliding with and sinking below the coasts of Oregon, Washington and British Columbia, the North Coast Basin displays large and small scale structures resulting from this compressional environment. The basin scale up-warp that is presently lifting and tilting the Coast Range to the east has subsequently created smaller scale jointing and fracture patterns to relieve the stress imposed by subduction. Faults extend throughout the Coast Range, trending northeast-southwest and northwest-southwest, with displacements as large as 3 mi (4.8 km; Orr and Orr, 2000). These structural forces have generally increased groundwater flow in the regional marine sediments by creating preferential flow paths. This also means that ASR may be hindered by the unpredictable fracture flow patterns in the marine sediments. While joints, fractures and faults may increase groundwater flow through the low permeability sediments, water in these cracks may flow quickly and find escape routes to the surface which would be undesirable for seasonal storage. Local investigation is necessary to determine the fault effects on groundwater flow relevant to specific ASR or AR sites.

ASR Assessment

The purpose of this section is to provide a general assessment of specific locations for their potential to employ ASR as a part of water supply systems. Site specific investigation is essential to determine if a recharge project is technically, economically, and environmentally feasible, but positive results from this study indicate the site possesses many of the necessary components for successful ASR

Table 13-1: Summary of Analysis Methods. For more detail, see Chapter 3: Analysis Methods.

Method	Description	Result of Method
Volumetric Analysis	Mathematical comparison of aquifer storage capability to the volume of surface water available	If > 1, sufficient storage If = 1 marginal storage If < 1, insufficient storage
Brown's Site Rating System	Site is rated from 0 to 2 for each criteria such as distance to source water, water quality, groundwater flow rate, aquifer thickness	Produces % of ideal ASR parameters at a given site

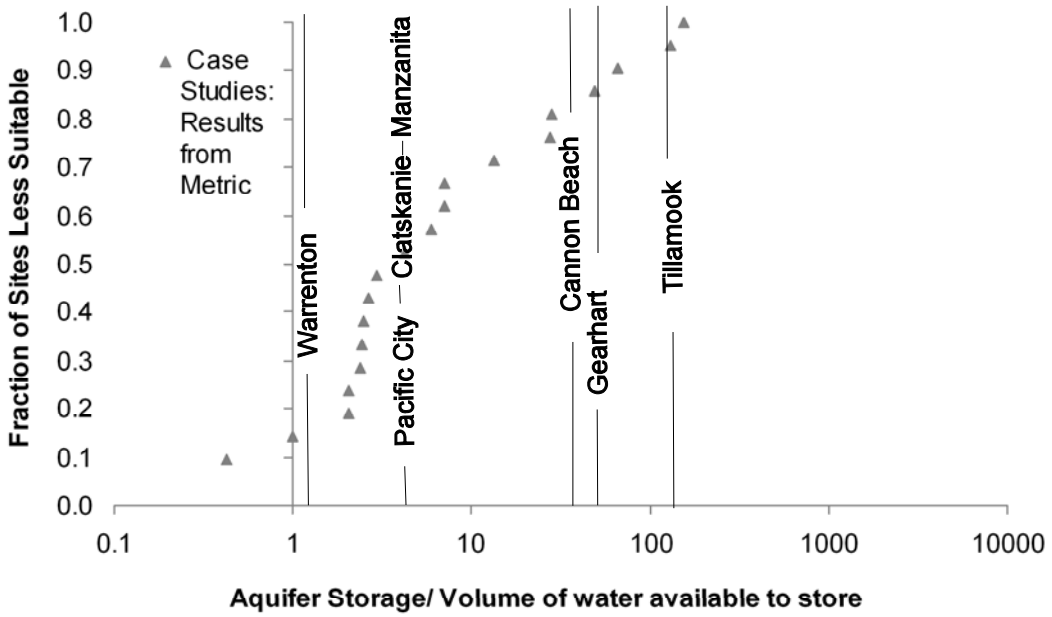


Figure 13-3: North Coast Basin ASR metric results. Aquifer storage is sufficient for ASR at all the sites selected by this study. Data listed in Appendix B.

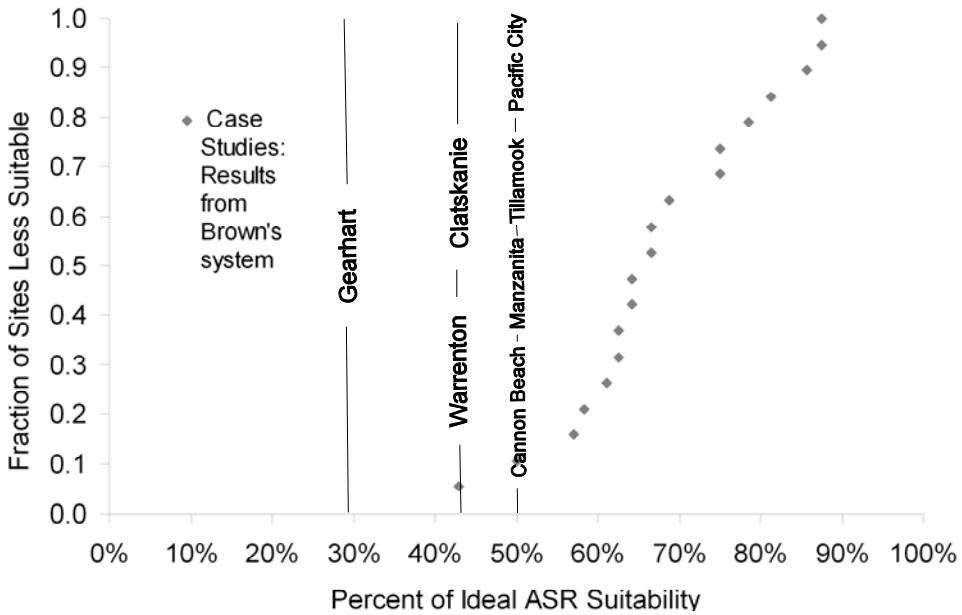


Figure 13-4: North Coast Basin Brown's rating system results. Sites have from 29 % to 50% of ideal conditions. 90% of case studies' results are greater than results for this basin's potential sites. Data listed in Appendix C.

Warrenton

Warrenton is located at the mouth of the Columbia River, among extensive coastal dunes. This area is a tourist destination for ATV enthusiasts as well as other coastal outdoor activities. The population increased from 2,681 residents in 1990 and 4,394 in 2006 (U.S. Census, 2006). The city has surface water rights to 20 cfs (48,940 m^3/d) from Lewis and Clark River.

A well installed by the U.S. Geological Survey (CLAT 304) in the Quaternary dunes (Qd) was selected because there was a pump test reported that provided useful information about the aquifer hydraulics. Frank (1970) reported the test results for this well; transmissivity was estimated at 3,500 ft^2/d (323 m^2/d). This is below the ideal range of 5,000 to 25,000 ft^2/day (465 to 2,323 m^2/d) for ASR. The static water level of 11.5 ft (3.5 m) does not allow much room for head rise during injection.

According to Brown's site rating system, the site has 43% of ideal conditions for ASR. The town lost points for the presence of threatened fish species and low

transmissivity. Volumetric analysis indicates aquifer storage is marginally sufficient to inject 10 cfs (24,470 m^3/d) for 120 days (Figure 12-3).

Clatskanie

Clatskanie is situated at the mouth of the Clatskanie River, on the Columbia River. The town presently has surface water rights to 1.4 cfs (3,426 m^3/d) from Roaring creek (OWRD WRIS, accessed 2007). Population is stable with 1,629 residents in 1990 and 1,645 in 2006.

No municipal well logs were located by this study, so a representative domestic well (COLU 2541) was examined for ASR suitability. It has open intervals from approximately 88 to 118 ft (27 to 36 m) below the surface, drawing water from a sandstone aquifer (OWRD well log database, accessed 2007). Based on geologic maps of the area the aquifer is Tertiary marine sediments (Tmst). Transmissivity is estimated at 500 ft^2/d (40 m^2/d) from specific capacity data. This value falls below the ideal range for ASR of 5,000 to 25,000 ft^2/d (465 to 2,323 m^2/d).

Volumetric analysis (Figure 13-3) indicate the aquifer storage is sufficient to inject ½ of the surface water rights for 120 days. The site has 43% of ideal conditions for ASR according to Brown's site rating system, with low scores for transmissivity and more than 5 wells per square mile (Figure 13-4). AR may be feasible in the alluvial deposits, but careful investigation of the potential for leakage to surface water must occur.

Gearhart

Located at the mouth of the Necanicum River, Gearhart sits on Quaternary dune deposits of the North Oregon Coast. The City of Gearhart does not currently have surface water rights (OWRD WRIS, accessed 2007). Population increased from 1,027 to 1,106 between 1990 and 2006 (U.S. Census, 2006).

A city-owned test well (CLAT 52022) draws water from a Quaternary dune (Qd) aquifer. Open intervals from depths of 75 to 95 ft (23 to 29 m) below the surface yielded 90 gpm (491 m^3/d) at the time of installation (OWRD well log database, 2007).

Transmissivity estimated from specific capacity is 1,600 ft^2/d (150 m^2/d). This is below the ideal range for ASR, although it is similar to transmissivity of a sand and sandstone aquifer used in Denver, Colorado for ASR.

Volumetric analysis indicates the aquifer is suitable to inject 1 cfs (2,447 m^3/d) for 120 days (Figure 13-3). Brown's site rating system finds Gearhart has 29% of optimal ASR parameters (Figure 13-4). The site sites lost points for low transmissivity, lack of a current surface water source and an aquifer thickness less than 25 ft (7.6 m). AR may be feasible in surficial Quaternary dune deposits, depending on the extent of their hydraulic connection to surface waters of the river and estuary.

Cannon Beach

The town of Cannon Beach sits between Ecola State Park and Haystack Rock. Like many coastal towns in Oregon, the city experiences a population boom from July to September, which coincides with the driest portion of the year. The City of Cannon Beach manages water treatment and distribution, using surface water from Ecola Creek Springs (1 cfs or 2,447 m^3/d within their water right), as well as West Fork Ecola Creek. The population increased from 1,221 to 1,720 residents between 1990 and 2006 (U.S. Census, 2006).

A municipal well (CLAT 164), was selected as representative of wells in the area. It has open intervals from depths of 36 to 43 ft (11 to 13 m) below the surface and yields 120 gpm (654 m^3/d; OWRD well log data, 2007). Transmissivity in the Quaternary alluvium (Qal) and Columbia River Basalt (Tc) aquifer, estimated from specific capacity is 13,500 ft^2/d (700 m^2/d). This is within the target range of 5,000 to 25,000 ft^2/d (465 to 2,323 m^2/d) for ASR.

Volumetric analysis (Figure 13-3) indicates the aquifer storage is suitable to inject 0.5 cfs (1,224 m^3/d) for 120 days. According to Brown's site rating system, Cannon Beach has 50% of optimal ASR parameters (Figure 13-4). The site lost points for the presence of threatened fish species in the rivers and an aquifer thickness less than 25 ft (7.6 m). AR may also be feasible in this area in the shallow surficial sand and gravel

aquifers, depending on local vertical permeability and proximity to surface water discharge points.

Manzanita

The resort town of Manzanita is located just north of Nehalem Bay. The town has surface water rights to 2.5 cfs (6,118 m^3/d) from Anderson Creek (OWRD WRIS, accessed 2007). The population in Manzanita grew from 513 to 630 between 1990 and 2006 (U.S. Census, 2006). No municipal well logs were located by this study.

A domestic well (TILL 1122) draws water from Quaternary alluvial sand (Qal) at depths of 27 to 52 ft (8 to 16 m) below the surface. Well yield at the time of installation was 50 gpm (273 m^3/d; OWRD well log database, 2007). It appears to be representative of other wells in the area in terms of the aquifer used for domestic water supplies, and the dominant geology of the area, which is largely sand formations. Transmissivity estimated from the well's specific capacity is 3,300 ft^2/d (90 m^2/d). This is below the ideal range for ASR, although it is similar to conditions found in Denver, Colorado, where ASR has succeeded in a partially confined sand aquifer with transmissivity of 1,000 ft^2/d (93 m^2/d).

Volumetric analysis indicates aquifer storage is sufficient to inject 1/2 the surface water rights for 120 days (Figure 13-3). Brown's site rating system finds Manzanita has 50% of optimal ASR parameters (Figure 13-4). The site lost points for low transmissivity, with moderate scores for all other parameters. AR may be feasible in the Quaternary alluvium, depending on whether the water infiltrated into the aquifer will discharge into the nearby bay before it can be recovered for municipal use.

Tillamook

The town of Tillamook is situated at the mouth of the Trask River. The town currently has surface water rights to 1 cfs (2,447 m^3/d) from Killam and Fawcett Creeks for municipal use (OWRD WRIS, accessed 2007). Population increased from 4,000 to 4,424 between 1990 and 2006 (U.S. Census, 2006).

A Tillamook Water Commission well (TILL 654) was chosen to represent the local aquifer environment. It draws water from a gravel Quaternary alluvial aquifer (Qal) at the rate of 1,320 gpm (7,194 m^3/d; OWRD well log database, accessed 2007). Transmissivity is estimated at 8,500 ft^2/d (800 m^2/d) from specific capacity data. This value falls within the target range of 5,000 to 25,000 ft^2/d (465 to 2,323 m^2/d).

Volumetric analysis (Figure 13-3) indicates the aquifer storage is sufficient to inject 1/2 cfs (1,224 m^3/d) for 120 days. The site has 50% of ideal conditions for ASR according to Brown's site rating system, with low scores for the presence of threatened fish species and an aquifer less than 25 ft (7.6 m) thick. AR is may be a useful water storage tool at this location, based on the flat, wide character of the river valley east of the bay.

Pacific City

The town of Pacific City sits at the mouth of the Nestucca River. The town has water rights to approximately 2.7 cfs (6,607 m^3/d) from Horn Creek, a tributary of the Nestucca River (OWRD WRIS, 2007). The population was stable at 1,027 residents in 2006 (U.S. Census, 2006).

A municipal well (TILL 115), owned by Pacific City Water District, was selected as representative of large-capacity wells in the area. It has open intervals from depths of 45 to 75 ft (14 to 23 m) below the surface and yields 125 gpm (681 m^3/d; OWRD well log database, 2007). Transmissivity in the Quaternary alluvial sand aquifer (Qal) is estimated from specific capacity as 2,700 ft^2/d (250 m^2/d). This is below the target range of 5,000 to 25,000 ft^2/d (465 to 2,323 m^2/d) for ASR.

Volumetric analysis (Figure 13-3) indicates the aquifer's storage is suitable to inject ½ the surface water rights injected for 120 days. According to Brown's site rating system, Pacific City has 50% of optimal ASR parameters (Figure 13-4). The site lost points for the presence of threatened fish species in the rivers and low transmissivity. AR may also be feasible in this area in the shallow surficial sand and gravel aquifers, depending on local vertical permeability and proximity to surface water discharge points.

CHAPTER 14
OWYHEE BASIN

Hydrologic Description

The Oregon portion of the Owyhee Basin covers approximately 6,200 mi^2 (16,000 km^2). The Owyhee River originates in Nevada, with additional subbasins in western Idaho. In Oregon, the Owyhee River tributaries include the West Little Owyhee River from the southeast, Crooked Creek from the southwest and Jordan Creek from the east. The river flows north to its confluence with the Snake River at Adrian, Oregon. Watershed divides delineating the basin are found in volcanic hills to the north and west, but the south and east boundaries are political, not hydrologic.

The Owyhee plateau has a high desert climate, with precipitation occurring largely in the form of snow. Average annual precipitation ranges from approximately 8 in (200 mm) throughout the central lowlands to 11 in (280 mm) near Basque (Oregon Climate Service, 2007). Groundwater recharge occurs by percolation of winter precipitation into the fractured volcanic highlands; snowmelt and stream flow also replenish unconfined sedimentary aquifers in the lowlands (Gonthier et al., 1977).

Physical Setting

The Owyhee basin is characterized by flat volcanic plateaus which have been eroded into dramatic canyons by fluvial activity. Volcanic centers extending from the Steens Mountains south across the border into Nevada produced hundreds of feet of basalt, andesite , rhyolite and tuffs. Another series of volcanics extends from Adrian to Jordan Valley. As shown in Figure 14-1, small population centers are located in alluvial valleys. The land in this basin is approximately 78% federally owned (Owyhee Local Advisory Committee, 2003).

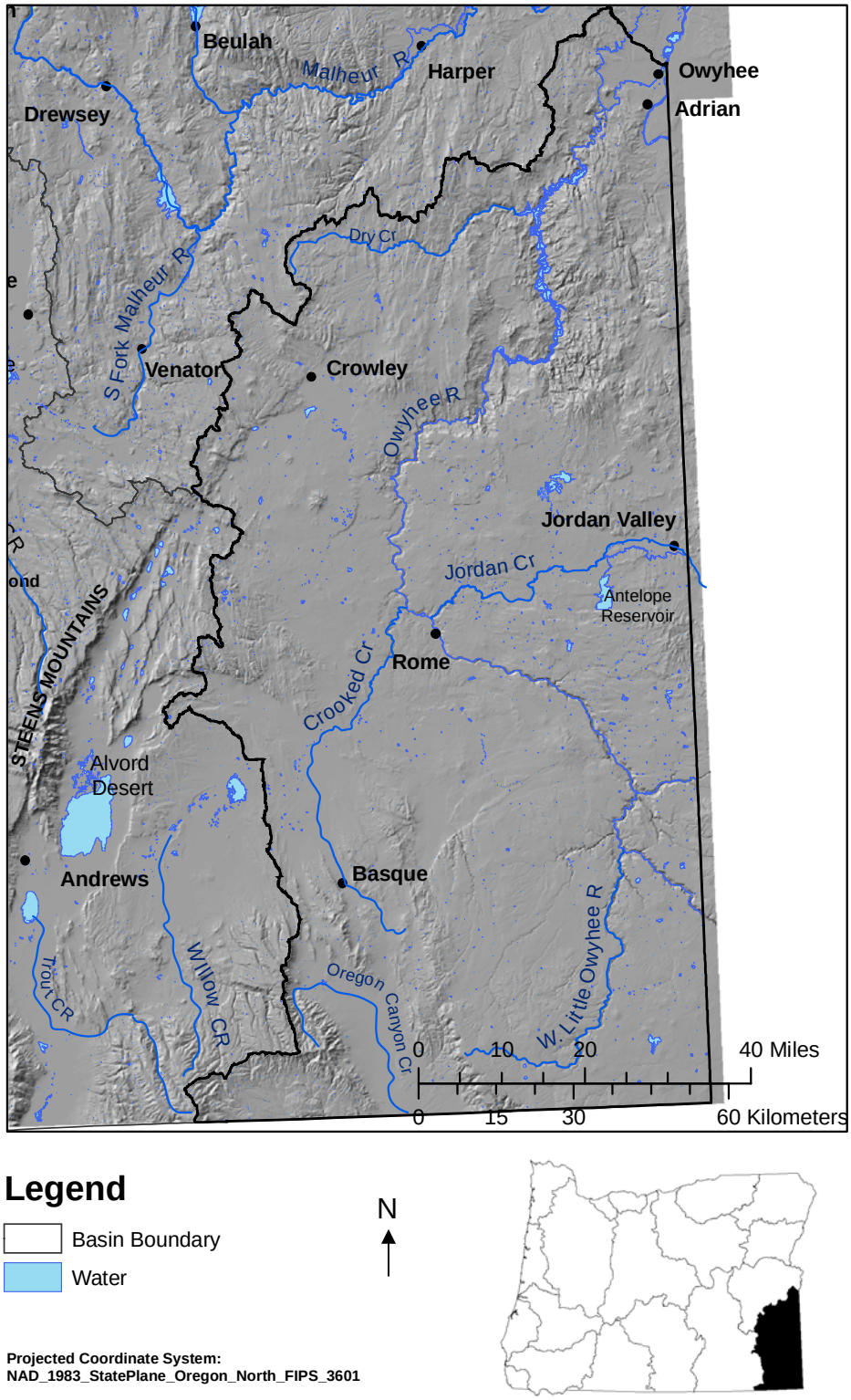
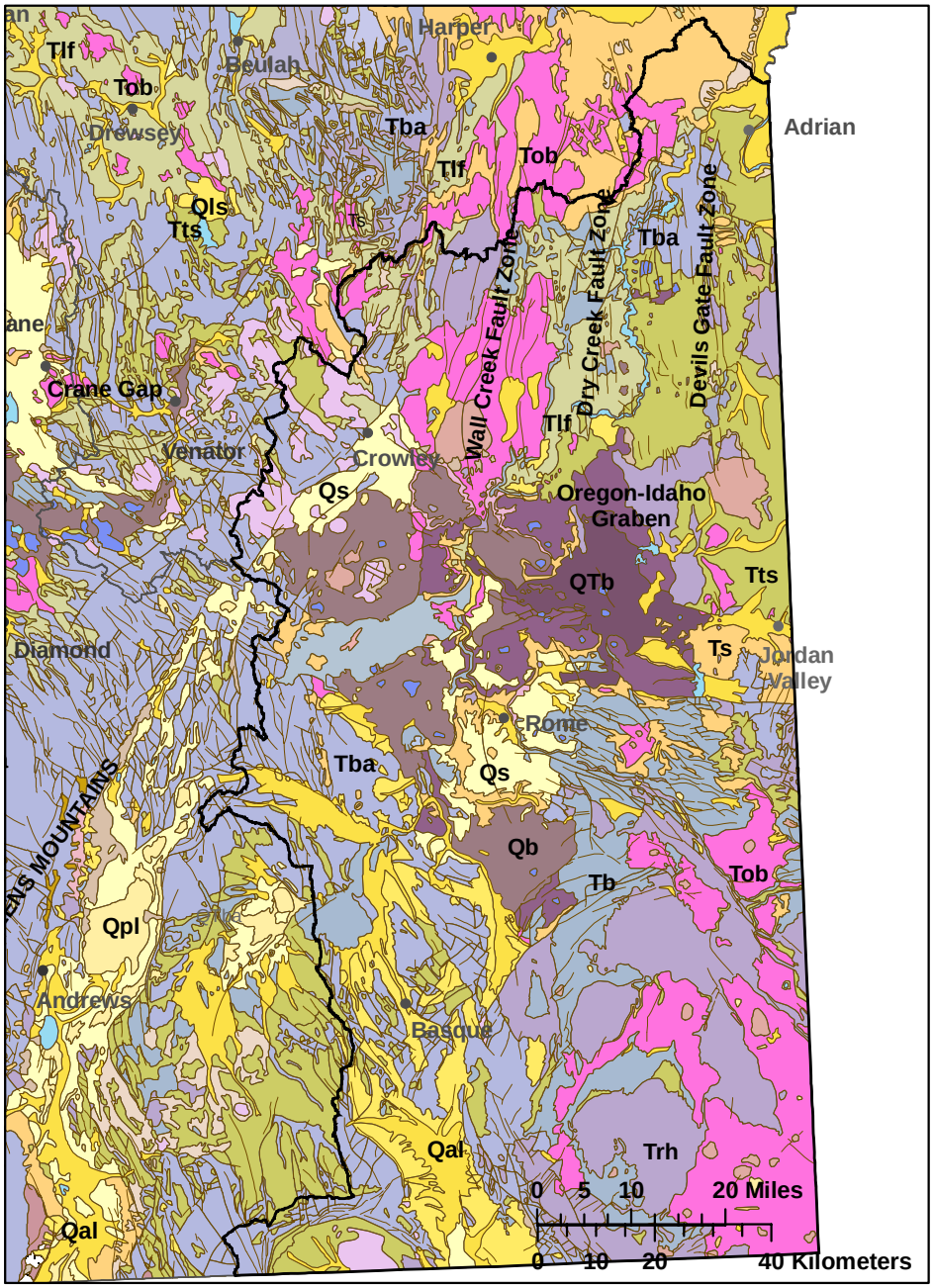


Figure 14-1. Owyhee Basin location map. Location of topographic features, rivers and towns that are examined in this study (Data sources: Wright, 2006; Oregon Geospatial Data Clearinghouse, 2006).



Legend

- Basin Boundary
- Faults
- Qal Holocene alluvial deposits
- Qs Lacustrine and fluvial sediments
- Qb Quaternary Basalt
- N
- QTb Pliocene and Pleistocene Basalt
- Trh Miocene Rhyolite and Dacite
- Tb Miocene basalt
- Tba Miocene basalt and andesite
- Tob Miocene Olivine Basalt
- Ts Tertiary Sediments
- Tlf Tertiary Lacustrine and Fluvial Deposits
- Tts Tuffaceous Sedimentary Rocks
- Lake

Figure 14-2. Owyhee Basin geology map. Geologic formations of importance to future ASR include basalts and sediments (Data sources: Walker and McLeod, 1991; Oregon Geospatial Data Clearinghouse, 2006).

Hydrogeologic Units

Major geologic units exposed in the basin, from oldest to youngest include Tertiary basalt, andesite, and rhyolite, Tertiary tuffs, Tertiary and Quaternary sediments. Major geologic units (Figure 14-2) are discussed in detail in the following section.

Tertiary Basalt, Andesite and Rhyolite

Miocene to Pleistocene basalt, andesite and rhyolite (Tob, Tb, Tba, Trh, QTb) flows dominate the surficial geology in this basin. These units extend across the entire basin, overlain by younger sediments in valleys and volcanic tuffs in the northeast. These igneous units may constitute the basement rocks in this northern section of the Basin and Range Province, which is characterized by high heat flow and anomalously thin crust. The Steens Basalt (Tba) is included in this group, characterized by fluid, andesitic basalt flows ranging in thickness up to 3,000 ft (914 m). The Steens Basalt generally lacks interflow zones, due to its rapid emplacement, which indicates an overall low horizontal transmissivity (Johnson et al., 1998). Members of this group of igneous rocks are faulted throughout this extensional province, and groundwater flow is assumed to be limited by this faulting (Gonthier, 1985). The basalts and rhyolites are largely undeveloped by wells. These units are not likely targets for ASR due to their overall low permeability, but there may be local exceptions.

Tertiary Tuff

Miocene pyroclastic and volcanically-derived sedimentary rocks, in addition to welded tuffs (Tts), are exposed from Jordan Valley to north of Adrian, with smaller exposures in the southwest corner of the basin. These units range in thickness from 0 to 1,000 ft (0 to 305 m) thick (Ferns, 1997). The tuffs are generally clayey, fine-grained and considered poor aquifers. For these reasons they are not likely targets for ASR or AR.

Tertiary and Quaternary Sediments

Holocene rivers and Pleistocene to Holocene lakes have created the unconsolidated sediments (Qal, Qs, Tlf, Ts) which overlie older units along Jordan River,

Owyhee River, Oregon Canyon Creek and Crooked Creek. The largest expanse is near Basque, where sand, gravel, alluvial silt and clay surround Crooked and Oregon Canyon Creeks. Thickness is greater than 300 ft (91 m) in Basque, Adrian, Rome and Jordan Valley (OWRD well log database, 2007). Hydraulic conductivity in the sediments ranges from 25 to 150 ft/d (7.6 to 46 m/d); while transmissivity in valley fill aquifer systems ranges from 1,000 to 15,000 ft^2/d (93 to 1,394 m^2/d; Gonthier, 1985). These units are the main source of groundwater for wells in the basin.

Unconfined sedimentary aquifers may be useful for AR in areas with suitable transmissivity, source water quality and availability. However, nitrate levels in surficial aquifers may preclude AR (Connor and Perry, 1999). Water quality will require careful examination before the storage can begin. ASR may also be possible in areas with sufficient transmissivity and source water.

Tectonic Structure Influencing Groundwater Flow

The Owyhee Basin is part of the northern Basin and Range province, and displays extensional normal faulting. Faulting influencing basalt and andesite is most notable in fault zones from Jordan Valley north to Adrian, and in the extensional basin that trends southeast from Basque to Nevada (Figure 14-2). An arcuate fault located 9 mi (14.4 km) east of Basque stratigraphically separates basalt flows and tuffaceous sediments by as much as 150 ft (46 m; Ferns, 1997). The northern half of the Owyhee Basin contains three major fault zones: Wall Creek, Dry Creek and Devil's Gate Fault Zones, which are all included in the Oregon-Idaho graben. According to Ferns (1997), the graben structure is filled with over 6,000 ft (1,829 m) of Miocene volcanic and volcaniclastic materials and lies between Jordan Valley and Adrian. However, as mentioned in the previous section, basalt, andesite, rhyolite, and tuffs are largely untapped by wells in this basin. The effect of these structures on groundwater flow is unknown. Valley alluvial deposits, which are the main source of groundwater, appear to be overlying these structures.

ASR Assessment

This purpose of this section is to provide a general assessment of specific locations for their potential to employ ASR as part of a water supply system. Site specific investigation is essential to determine if an ASR project is technically, economically, and environmentally feasible, but positive results from this study indicate that local sites possess many of the necessary components for successful ASR.

Table 14-1: Summary of Analysis Methods. For more detail, see Chapter 3: Analysis Methods.

Method	Description	Result of Method
Volumetric Analysis	Mathematical comparison of aquifer storage capability to the volume of surface water available	If > 1, sufficient storage If = 1 marginal storage If < 1, insufficient storage
Brown's Site Rating System	Site is rated from 0 to 2 for each criteria such as distance to source water, water quality, groundwater flow rate, aquifer thickness	Produces % of ideal ASR parameters at a given site

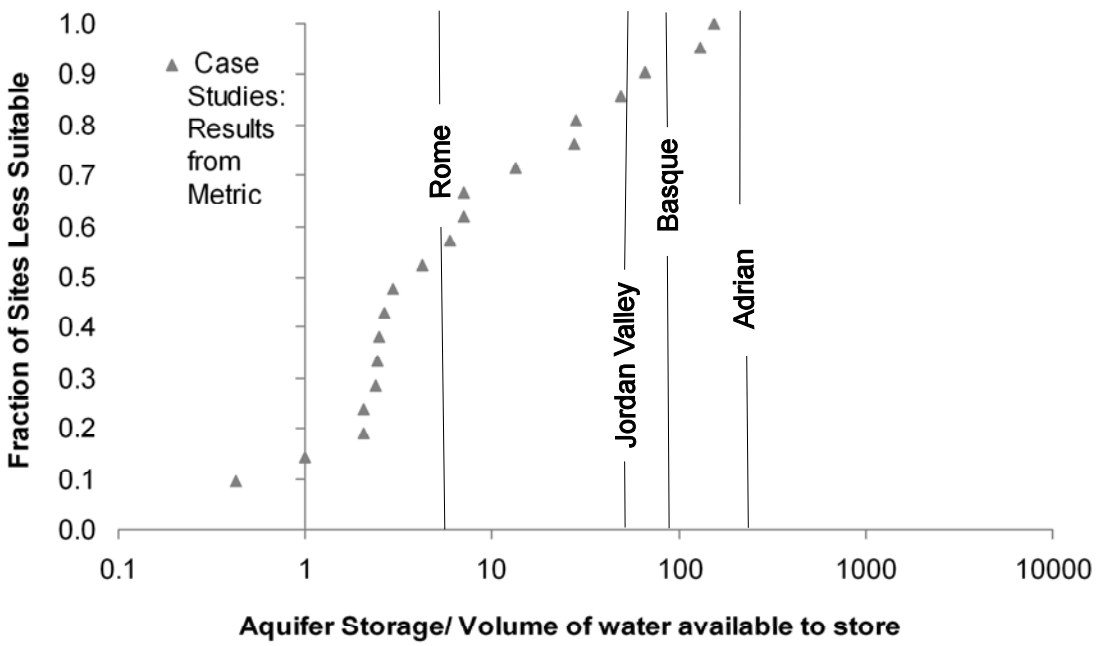


Figure 14-3: Owyhee Basin ASR metric results. Adrian, Rome, Basque and Jordan Valley have sufficient aquifer storage for ASR. Data listed in Appendix B.

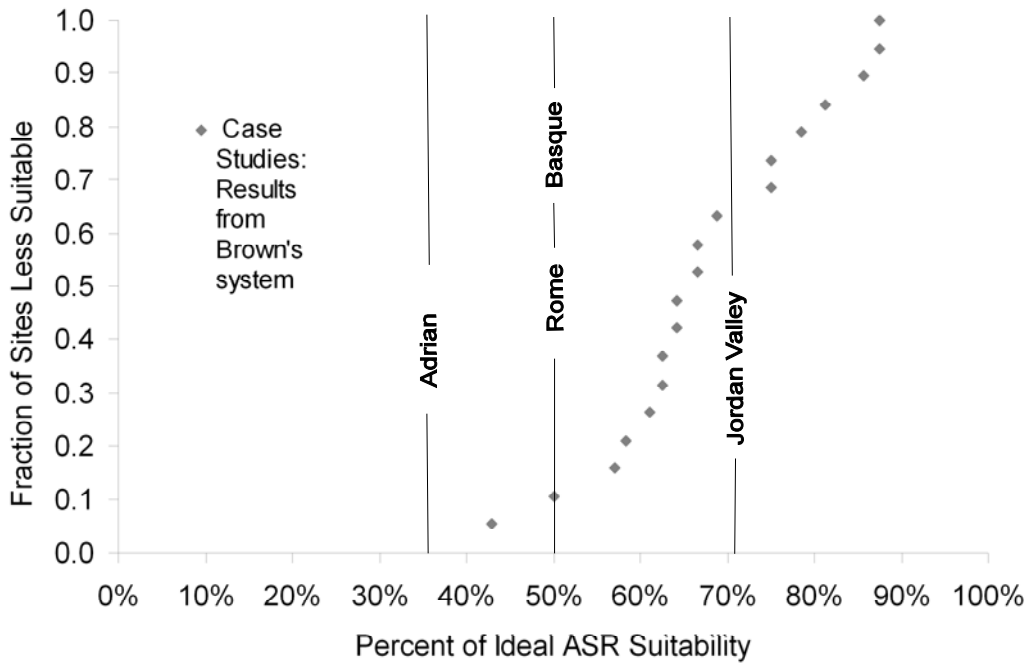


Figure 14-4: Owyhee Basin Brown's rating system results. Sites have from 36 % to 71% of ideal conditions. 60% of case studies' results are within the range of results for this basin. Data listed in Appendix C.

Adrian

Adrian is located in northeastern Owyhee Basin, near the confluence of the Owyhee and Snake Rivers. Population in the city remains stable around 730 residents (U.S. Census, 2004). Population is not likely to be the driver for water storage infrastructure investment, but climate change, rural land use evolution and the aging of surface water reservoirs may dictate storage expansion in the future.

Adrian's Tertiary and Quaternary sand and gravel (Ts, Qal, Qg) municipal well (MAHL 52787) is screened at depths ranging from 165 to 215 ft (15 to 66 m) below the surface. The well yields 150 gpm (818 m^3/d). Transmissivity in the sediments is estimated by this study as 3,200 ft^2/d (300 m^2/d) from specific capacity data, which is below the ideal range for ASR. However, ASR sites in Seattle, Washington and Washoe County, Nevada utilize unconsolidated sediments with similar transmissivity.

The City of Adrian currently has no surface water rights, but the Owyhee River has water available for storage (OWRD WARS, 2007). However, water quality in the Owyhee River has been poor in recent years, with higher than ideal temperature and toxic levels of bacteria (Owyhee Local Advisory Committee, 2003). The Owyhee River is over 3 mi (4.8 km) from Adrian, so piping and water treatment costs may prevent using this river as the source. The Snake River is about one mile away and, therefore, may be a more desirable source.

Volumetric analysis indicates aquifer storage is sufficient to store 1 cfs (2,447 m^3/d) (Figure 14-3). According to Brown's site rating system, Adrian has 36% of ideal conditions for ASR (Figure 14-4). This low score results from low transmissivity in the aquifer and the prohibitive distance to the Owyhee River source water. Despite volumetric compatibility, other factors may render ASR economically infeasible.

Rome

Situated in the center of the Owyhee Basin, Rome is located about 0.5 mi (0.8 km) from Owyhee River. The town has no surface water rights, but water is available for storage from the Owyhee River (OWRD WARS, accessed 2007).

An irrigation well (MAHL 2435) draws water from the Tertiary and Quaternary sand and gravel aquifer (Ts, Qs), at depths from approximately 22 to 398 ft (7 to 637 m) below the surface. At the time of drilling the well yielded 20 gpm (109 m^3/d; OWRD well log database, 2007). Transmissivity is estimated at 400 ft^2/d (40 m^2/d) from specific capacity data. This value falls well below the target range of adequate transmissivity for ASR, and below the transmissivity at any ASR site found by this study.

Hardy et al. (2004) found elevated levels of E. coli year round, and elevated nitrogen and phosphorus levels during spring flows of the Owyhee River. Water treatment could remediate these contamination issues, or winter withdrawal may avoid the high nitrate and phosphorus loads depending on the timing of application on the land and release into the surface water. Site specific testing is necessary to evaluate these water quality issues.

The aquifer's available storage is greater than the volume required to inject 1 cfs (2,447 m^3/d) for 120 days, according to volumetric analysis (Figure 14-3). When evaluated with Brown's site rating system, Rome has 50% of the best conditions for ASR. Low transmissivity and the presence of threatened fish species in the Owyhee River species contributed to this moderate score.

Basque

With its name rooted in the area's history of Basque settlers, the ranching community of Basque is located on Crooked Creek. It sits on alluvium-filled lowlands of the northern Basin and Range Province. Basque currently has no surface water rights, although there is water available in Crooked Creek for storage (OWRD WARS, 2007).

No municipal wells were located by this study, and irrigation wells generally report low yields. Irrigation well (MAHL 2471) was chosen as representative of the area, accessing a Tertiary gravel aquifer (Ts) from depths of 270 to 300 ft (82 to 91 m) below the surface. The well yielded 100 gpm (545 m^3/d) when it was installed (OWRD well log database, 2007). Transmissivity estimated from well specific capacity is 1,500 ft^2/d (130 m^2/d). This is below the ideal range of 5,000 to 25,000 ft^2/d (465 to 2,323 m^2/d), but similar to Myrtle Beach, South Carolina's ASR site. That site utilizes unconsolidated

sediments with transmissivity of 10.76 ft^2/d (148 m^2/d), but the ASR project has been successfully operating for over 10 years (Petkewich, 2004).

Volumetric analysis indicates the aquifer storage is sufficient to inject 1 cfs (2,447 m^3/d) for 120 days (Figure 14-3). Basque has 50% of optimal ASR parameters, according to Brown's site rating system (Figure 14-4). Low transmissivity and the presence of threaten fish species decreased the score. AR may be feasible in surficial alluvial aquifers, depending on vertical permeability and water quality.

Jordan Valley

Situated at the Oregon-Idaho border, Jordan Valley sits in the alluvial filled lowlands of Jordan Creek. This small town's population decreased from 364 to 232 residents between 1990 and 2006 (U.S. Census data, 2004). The city of Jordan Valley currently has one municipal well and no surface water rights.

Since no municipal well logs were identified, a large capacity irrigation well (MAHL 2430) was selected to examine the aquifer properties in this area. The well has open intervals in a Tertiary sand, clay and gravel aquifer (Ts) at depths from 75 to 382 ft (23 to 116 m) below the surface. The well yields 1,800 gpm (9,810 m^3/d; OWRD well log database, 2006). Transmissivity estimated from specific capacity at this well is 7,400 ft^2/d (700 m^2/d), which is within the ideal range for ASR.

Volumetric analysis indicates aquifer storage is sufficient to inject 1 cfs (2,447 m^3/d; for 120 days (Figure 14-3). Brown's site rating system finds Jordan Valley has 71% of optimal ASR parameters (Figure 14-4). AR may be feasible in surficial gravel aquifers, depending on vertical permeability and water quality.

CHAPTER 15
POWDER BASIN

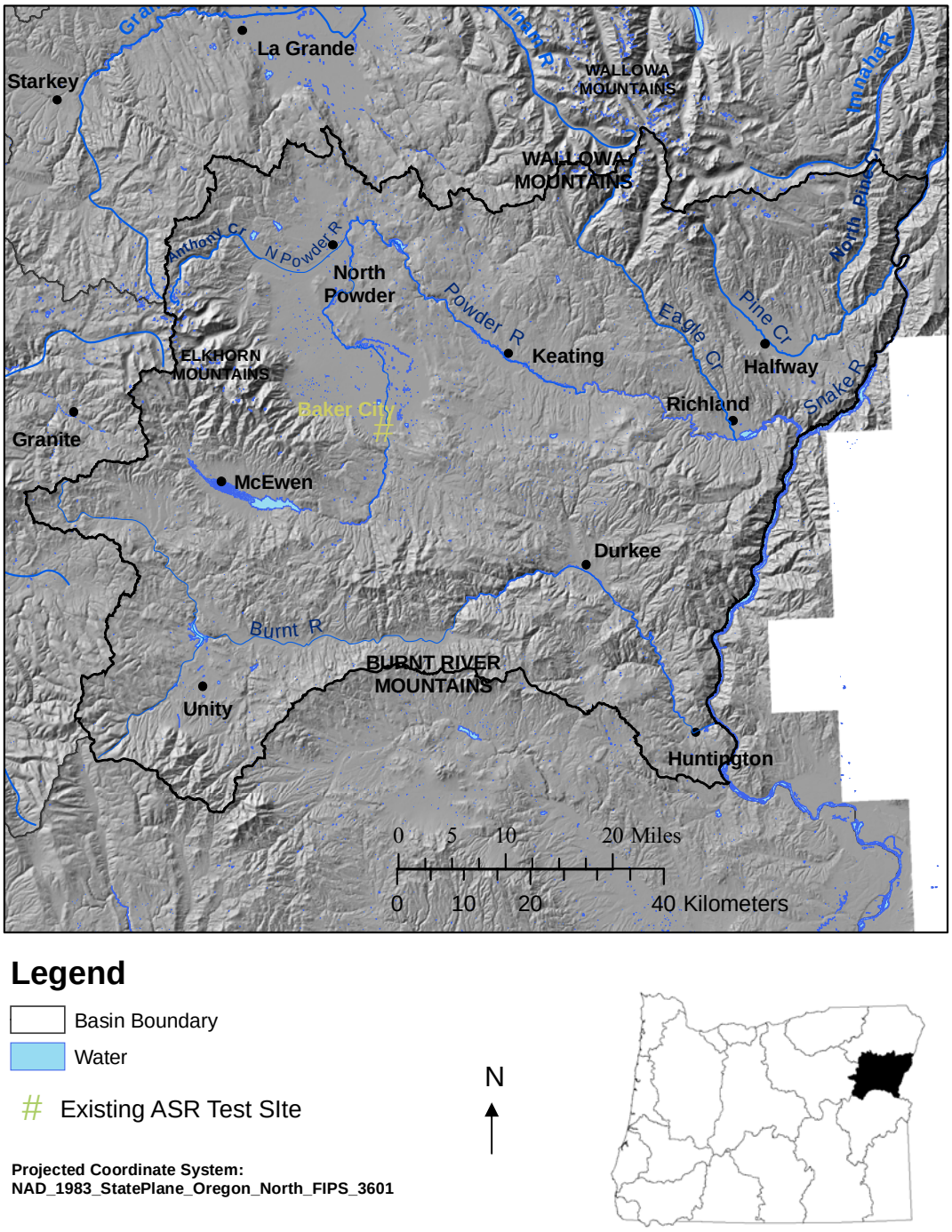
Hydrologic Description

The Powder Basin covers approximately 3,254 mi^2 (8,428 km^2), and is drained by Pine Creek the North Powder River, and the Burnt River, which originates in the Blue and Strawberry mountains and flows east to its confluence with the Snake River. Watershed divides delineating the basin are found to the south in the Burnt River Mountains, to the west in the Elkhorn Mountains, to the east at the Snake River, and to the north in the Wallowa Mountains.

The climate is high desert. Average annual precipitation ranges from approximately 10.64 in (270 mm) per year in Unity to 21.6 in (550 mm) in Halfway (Oregon Climate Service, 2007). The majority of groundwater recharge occurs by percolation of precipitation into unconfined sedimentary aquifers, with some flow of deep groundwater from the highlands of the Blue Mountains, Wallowa Mountains and Burnt River Mountains (Vaccarro, J.J., 1999; Price, 1967).

Physical Setting

There are two main types of topography in the basin (Figure 15-1). Valley plains surround Baker City, North Powder, and Halfway, and these valleys abruptly transition into canyons and mountainous uplands. Quaternary alluvium has a maximum thickness of 700 ft (213 m) near Baker City (Newcomb, 1960); alluvium is underlain by Tertiary basalts, Triassic metamorphosed sedimentary rocks and gabbros.



Legend

Basin Boundary

Water

Existing ASR Test SIte

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Projected Coordinate System:
NAD_1983_StatePlane_Oregon_North_FIPS_3601

Figure 15-1. Powder Basin location map. Location of topographic features, rivers and towns that are examined in this study (Data sources: Wright, 2006; Oregon Geospatial Data Clearinghouse, 2006).

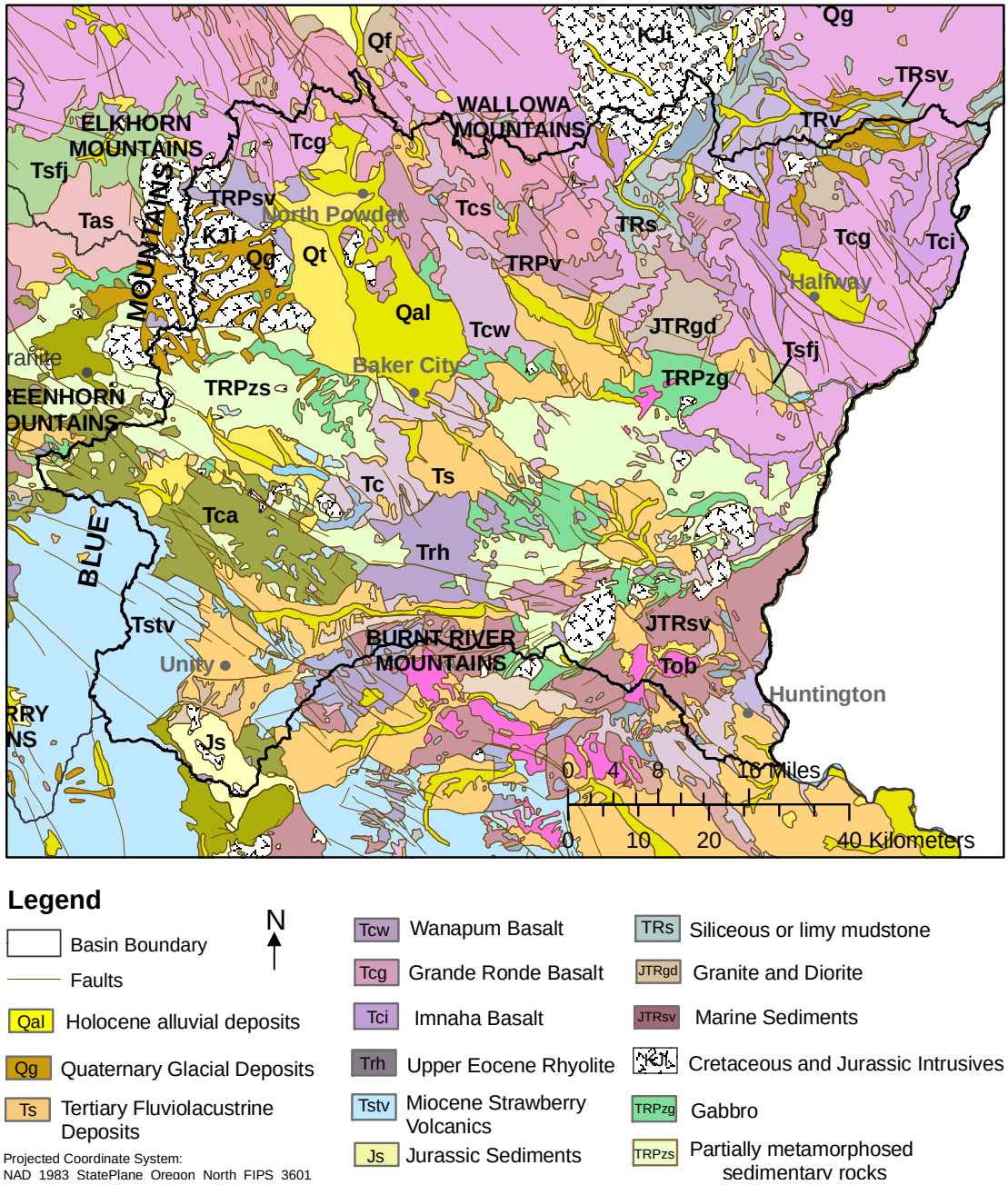


Figure 15-2. Powder Basin geology map. Geologic units of importance to future ASR include Tertiary basalts (Data sources: Walker and McLeod, 1991; Oregon Geospatial Data Clearinghouse, 2006).

Hydrogeologic Units

Major geologic units in the basin, from oldest to youngest include Pre-Tertiary metamorphic and igneous basement rocks (referred to as the Baker Terrane), Jurassic sedimentary rocks, Cretaceous intrusives, Miocene Columbia River Basalt, Tertiary and Quaternary sediments. Major geologic units are (Figure 15-2) discussed in relation to ASR in the following section.

Pre-Tertiary Basement Rocks

Predominately Triassic through Jurassic rocks include metamorphic and intrusive igneous rocks of the accreted Baker terrane, as shown in Figure 15-2 (TRs, JTRsv, JTRgd, TRPzg, TRPzs; Orr and Orr, 2000). Between North Powder and the Blue Mountains, a tonolitic pluton similar to the Wallowa batholith is exposed. Additional intrusives include quartz diorite and granodiorite, found in the southeastern corner of the basin. According to Hampton and Brown (1964), these units have low permeability, and therefore are generally not suitable for ASR or AR.

Columbia River Basalt

Miocene Columbia River Basalt flows (Tcw, Tcg, Tci, Tcs, Tc) overlie metamorphic and Pre-Tertiary sedimentary units as Grande Ronde Basalt (Tcg, 15.6-16.8 Ma), Wanapum Basalt (Tcw, 14.5- 15.2 Ma), and Saddle Mountains Basalt (Tcs, 0.6-14.5 Ma) (Beeson and Moran, 1979), as shown in Figure 15-2. Massive flows are separated by permeable interflow zones, which are important groundwater sources throughout the basin. This unit is exposed throughout the northern half of the basin, overlain by alluvial clay, sand and gravel sediments in the Baker City, North Powder, Unity, Huntington and Halfway valleys. Hydraulic conductivity varies from 1 to 10 ft/d (0.3 to 3 m/d); well specific capacity is 4 to 10 gpm/ft (72 to 179 m^2/d); transmissivity is estimated from 1,000 to 10,000 ft^2/d (304 to 3048 m^2/d) (Gonthier, 1985). Experience in Baker City utilizing Columbia River Basalt for ASR indicates a high probability of success storing water in this unit, given appropriate local transmissivity and source water volume.

However, according to Hampton and Brown (1964), basalt in mountainous uplands tends to be cut by canyons, and therefore groundwater in these units escapes to the surface easily. Basalts with interflow zones exposed to nearby canyons may not be suitable for ASR for this reason. Basalt underlying valley floors is more likely to be suitable.

Tertiary and Quaternary Sediments

Pleistocene glacial events and Pliocene through Holocene alluvial activity have created the unconsolidated sediments (Ts, Qg, Qal) found in the Powder, Pine Creek and Burnt River valleys. Hydraulic conductivity ranges from 25 to 30 ft/d (7.6 to 9.1 m/d); transmissivity ranges from less than 1,000 to 15,000 ft^2/d (93 to 14000 m^2/d) (Gonthier, 1985). ASR may be possible if stored water can be protected from access by other wells and groundwater flow rates are not so rapid that injected water flows outside a recoverable radius from the injection well. Unconfined sedimentary aquifers may be useful for AR in areas with suitable transmissivity and source water quality.

Tectonic Structure Influencing Groundwater Flow

The Blue Mountain Anticline trends northeast along the axis of the Blue Mountains, forming the western groundwater divide of the Powder Basin (Figure 15-2). Surface and groundwater flows east from the Elkhorn Mountains and south from the Wallowa Mountains, toward the cities of North Powder and Baker City. This is favorable for ASR operations, as stored water is not likely to flow rapidly away from the cities.

Northwest trending normal faults cut Tertiary units across the northeastern part of the basin, corresponding to the Olympic Wallowa Lineament. Faulting is concentrated in the northeastern and southwestern corners of the basin. Fault gouges are often characterized by low permeability clay that acts as a barrier to ground water flow. This means that faulting may compartmentalize basalt aquifers in these areas, and limit storage capacity, as found by Groundwater Solutions, Inc. (2003b) in Tualatin, Oregon. Faults can also act as escape routes for stored water to reach the surface, if fault zones are more

permeable than the surrounding aquifer. Local study of structural features' impact on groundwater flow is necessary.

ASR Assessment

The purpose of this section is to provide a general assessment of specific locations for their potential to employ ASR as a part of water supply systems. Site specific investigation is essential to determine if a recharge project is technically, economically, and environmentally feasible. Positive results from this study indicate local sites possess many of the necessary components for successful aquifer recharge.

Table 15-1: Summary of Analysis Methods. For more detail, see Chapter 3: Analysis Methods.

Method	Description	Result of Method
Volumetric Analysis	Mathematical comparison of aquifer storage capability to the volume of surface water available	If > 1, sufficient storage If = 1 marginal storage If < 1, insufficient storage
Brown's Site Rating System	Site is rated from 0 to 2 for each criteria such as distance to source water, water quality, groundwater flow rate, aquifer thickness	Produces % of ideal ASR parameters at a given site

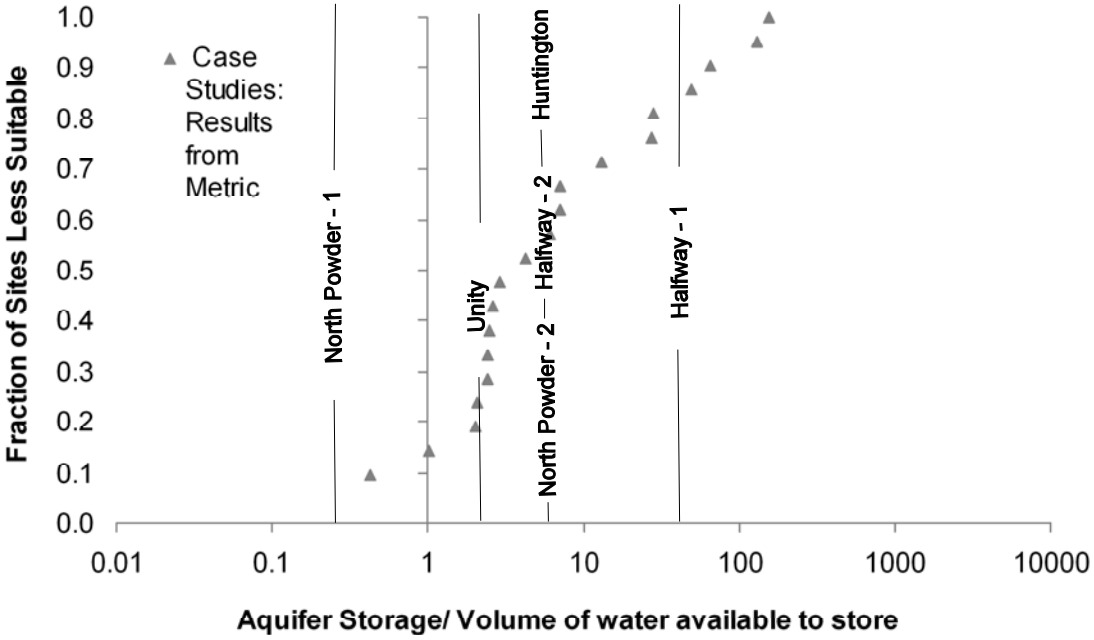


Figure 15-3: Powder Basin ASR metric results. Halfway, Huntington, North Powder-2 and Unity have sufficient aquifer storage for ASR. However, aquifer storage at North Powder-2 is not suitable. Data listed in Appendix B.

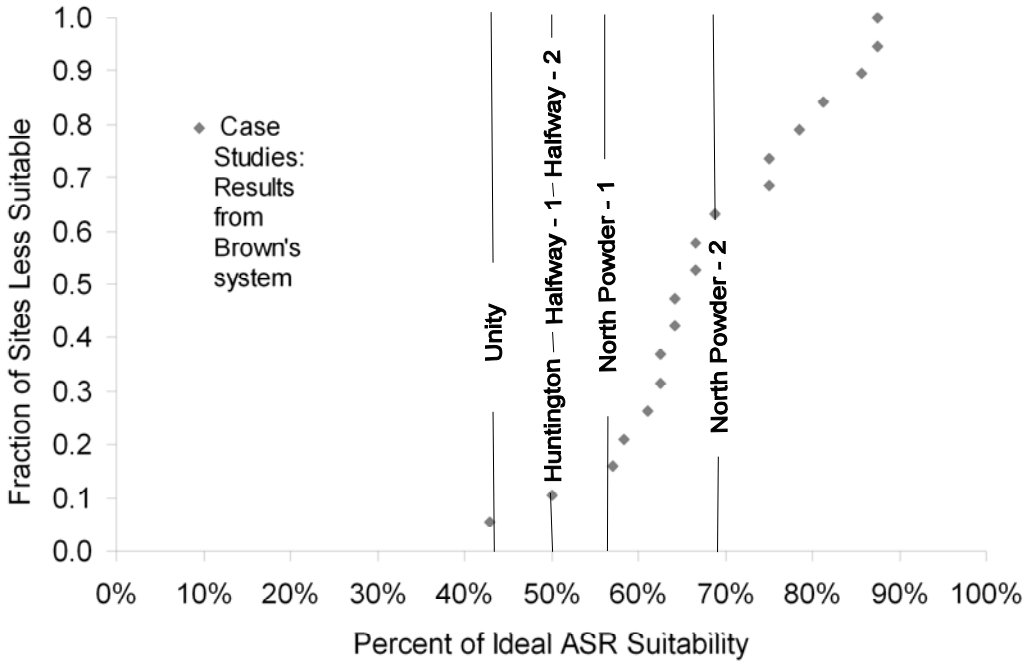


Figure 15-4: Powder Basin Brown's rating system results. Sites have from 43 % to 71% of ideal conditions. 60% of case studies' results is within the range of results for this basin. Data listed in Appendix C.

North Powder

North Powder is located in the northwestern part of the basin, 0.2 mi (0.3 km) from the North Powder River. Groundwater levels in an Quaternary unconfined sedimentary aquifer (Qal, Qt) have not changed significantly in the past decade (OWRD groundwater level database, accessed 2007). Since two of the municipal wells for North Powder access alluvial deposits, the aquifer may be experiencing similar stability in water levels. Population in the city of North Powder decreased slightly from 448 to 445 between 1990 and 2004 (U.S. Census, 2004). North Powder has no surface water rights at this time. Water from the North Powder River at the Mouth of Anthony Creek is available for allocation (OWRD WARS, 2007).

North Powder's Quaternary sedimentary (Qal, Qt) municipal wells (North Powder-1, UNIO 1537 and North Powder-2, UNIO 1542) are screened at depths ranging from approximately 150 to 490 ft below the surface (46 to 149 m). These wells have yields of 800 and 1,500 gpm (4,360 and 8,175 m^3/d), respectively. Transmissivity is estimated by this study is 3,300 and 12,900 ft^2/d (300 and 1,200 m^2/d) from specific capacity data.

Head space in North Powder-1 and North Powder-2 ranges from 0 to 4 ft (0 to 1.2 m), indicating the aquifer storage may not be sufficient for ASR. Water quality is also a concern; there have been reported algal blooms in the upstream Thief Valley reservoir and fecal contamination from agricultural runoff into the North Powder River and its tributaries. Due to water quality concerns, AR is also unlikely to be viable in this area, unless water treatment infrastructure is installed.

Volumetric analysis indicates aquifer storage is insufficient at North Powder-1 (UNIO 1537), which has low transmissivity and no head space at the well. However, North Powder-2 (UNIO 1342) accesses an aquifer with a higher transmissivity, and this compensates for the small head space in the well (Figure 15-3). According to Brown's site rating system, North Powder has 56 to 69% of ideal conditions for ASR (Figure 15-4).

Unity

Unity is located on Job Creek. The town sits in the middle of a 1.6 mi (2.6 km) wide Tertiary sediment filled basin. Population has increased from 87 in 1990 to 124 in 2004 (U.S. Census, 2004), while groundwater levels have remained stable in a nearby observation well. Depth to water was 45 ft (14 m); in both 1995 and 2005 (OWRD groundwater level database, accessed 2007). The city has no surface water rights, but it does have water rights to the Unity reservoir. The existing reservoir combined with the small population does not indicate an immediate need for water storage expansion for municipal uses. In the event of expanding water needs, there is water available for future allocation in the Burnt River.

A municipal well (MAHL 51426) has open intervals from approximately 37 to 209 ft (11 to 64 m) below the surface, accessing Tertiary fluvialacustrine sedimentary aquifers (Ts). Well yield is 15 gpm (82 m^3/d; OWRD well log database, accessed 2007). Transmissivity in the aquifer is estimated as 200 ft^2/d (20 m^2/d) from specific capacity data. This value is two orders of magnitude below the ideal range of 5,000 to 25,000 ft^2/d (465 to 2,323 m^2/d) for ASR.

Volumetric analysis indicates the aquifer's available storage is sufficient to inject 2 cfs (4,894 m^3/d) for 120 days (Figure 15-3). Unity has 43% of optimal ASR parameters in Brown's site rating system (Figure 15-4). The site lost points for low transmissivity and poor recharge water quality.

Halfway

Halfway is located in the eastern Powder Basin, on Pine Creek. Halfway sits in the southern end of a 2 mile wide Quaternary alluvium filled basin. The city has surface water rights to springs approximately 2 to 3 mi (3.2 to 3.8 km) west of the wells. Population and depth to water are stable in this area; census results report a population of 311 in 1995 and 319 in 2004 (U.S. Census, 2004), over the same time depth to water was stable at 10 ft below the surface.

Municipal wells Halfway-1 (BAKE 782) and Halfway -2 (BAKE 2063) access Quaternary sand and gravel aquifers (Qal) at depths of 78 to 403 ft (24 to 123 m) below

the surface, with well yields of 300 to 650 gpm respectively (1,635 to 3,543 m^3/d; OWRD well log database, 2007). Transmissivity estimated from well specific capacity is 4,500 and 3,700 ft^2/d (400 and 350 m^2/d). This is higher than Baker City's 1,000 ft^2/d (90m^2/d) (Groundwater Solutions, Inc., 2003a), suggesting ASR may be feasible in these sedimentary layers, if other factors are appropriate. However, these transmissivity values fall below the ideal range of 5,000 to 25,000 ft^2/d (465 to 2,323 m^2/d). The unconfined nature of the aquifer coupled with the 12 to 45 ft (3.7 to 14 m) to the water table indicate this aquifer has limited storage available without losing injected water to the surface.

Volumetric analysis indicates aquifer storage is suitable to inject 2 cfs (4,894 m^3/d) for 120 days (Figure 15-3). Brown's site rating system finds Halfway has 50% of optimal ASR parameters, losing points for low transmissivity and poor recharge water quality (Figure 15-4). AR may be feasible surficial gravel aquifers; it would also avoid the expense of installing a water treatment plant for an ASR project, assuming water quality is sufficient to meet AR standards.

Huntington

Huntington is located on the Burnt River. Population decreased from 522 residents in 1990 to 481 in 2004 (U.S Census, 2004). The City of Huntington has no surface water rights, but there is 3.33 cfs (8,149 m^3/d) available from the Burnt River at Huntington (OWRD WRIS, accessed 2007).

A municipal well (BAKE 1542) has open intervals from 330 to 550 ft (101 to 168 m) below the surface; water-bearing layers are interpreted as Columbia River Basalt (Tcw) with a yield of 520 gpm (2,834 m^3/d; OWRD well log database, 2007). According to Price (1967) Columbia River Basalts in the Huntington area are of limited extent, which limits storage capacity. Water quality issues include dredge trailings in the Burnt River and high Boron levels in groundwater (Price, 1967). These issues could preclude ASR operations, but local investigation is necessary.

Transmissivity estimated from specific capacity for the municipal well is 2,500 ft^2/d (230 m^2/d). This is less than the ideal range of 5,000 to 25,000 ft^2/d (465 to 2,323 m^2/d) for ASR (Brown et al., 2005). However, this is higher that Tigard (872 ft^2/d or 81

m^2/d; Golder Associates, 2001) and Baker City (977 ft^2/d or 90 m^2/d; Groundwater Solutions, 2003a). Volumetric analysis indicates Huntington's municipal well is suitable for ASR (Figure 15-3). Brown's site rating system finds Huntington has 50% of optimal ASR parameters (Figure 15-4). The site lost points for low transmissivity and poor recharge water quality. AR may be possible in overlying alluvial deposits, if infiltration rates and water quality are appropriate.

CHAPTER 16
ROGUE BASIN

Basin Hydrology

The Rogue Basin covers approximately 5,200 mi^2 (13,500 km^2) of southwest Oregon. Watershed divides delineating the basin are found at the crest of the Cascade Range to the east, in the Coast Range to the northwest, the Umpqua Mountains to the north and in the Klamath-Siskiyou Mountains to the south. It is drained by the Rogue River, which originates in the Cascades near Crater Lake and meanders through lowlands and rugged canyons to the Pacific Ocean. Major tributaries of the Rogue River include Little Butte Creek, Bear Creek, the Applegate River, and the Illinois River.

The basin varies from alpine conditions in the Cascade Range to moist, mild conditions in the Coast Range. Average annual precipitation ranges from approximately 65 in (1,680 mm) at Crater Lake, 20 in (510 mm) at Medford to 80 in (2,030 mm) at Gold Beach (Oregon Climate Service, 2007). Despite the low precipitation near Medford and Ashland, runoff from the damp Cascade and Coast Ranges feeds the perennial rivers of the basin. Groundwater recharge rates are unknown at this time. In the unconfined sedimentary aquifers of the lowlands, some recharge from stream loss may occur, as has been observed by Gannett et al. (2007) in the Klamath Basin to the east.

Physical Setting

The Rogue Basin has a unique and complex geology. Extending from near Ashland, west to the Oregon coast, and north to Roseburg, at least five exotic accreted terranes (pieces of island arcs and ocean crust that collided with the west coast and were subsequently deformed, subducted and “welded” onto the mainland) can be observed. These rocks are older than most rocks found in the basin (408 to 208 million years old, compared to the Western Cascades, which are approximately 40 million years old) and exhibit various metamorphic facies as a result of their history of folding, faulting and compression (Irwin and Wooden, 1999). Granitic plutons are exposed near Ashland and Medford .

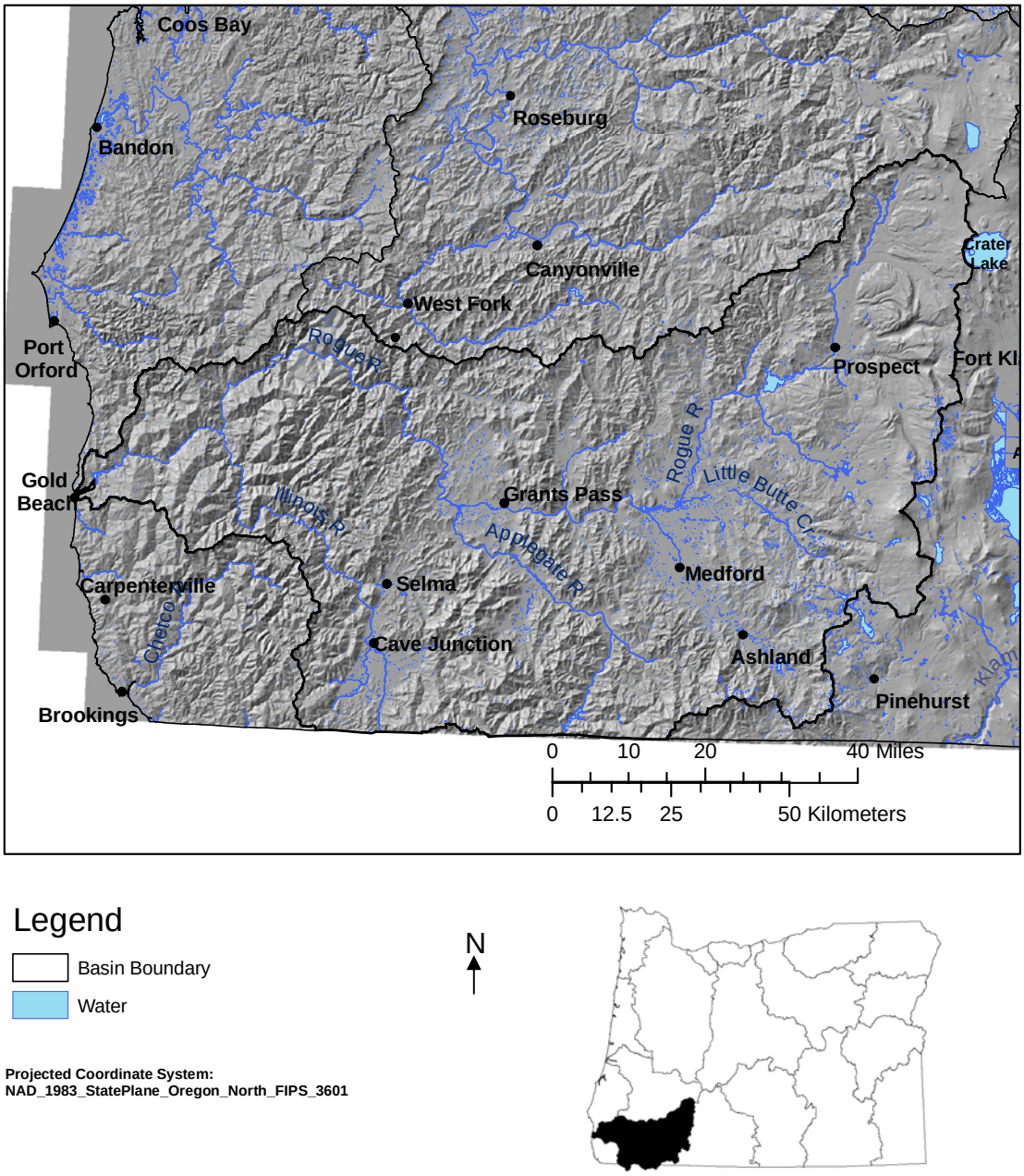


Figure 16-1. Rogue Basin location map. Location of topographic features, rivers and towns that are examined in this study (Data sources: Wright, 2006; Oregon Geospatial Data Clearinghouse, 2006).

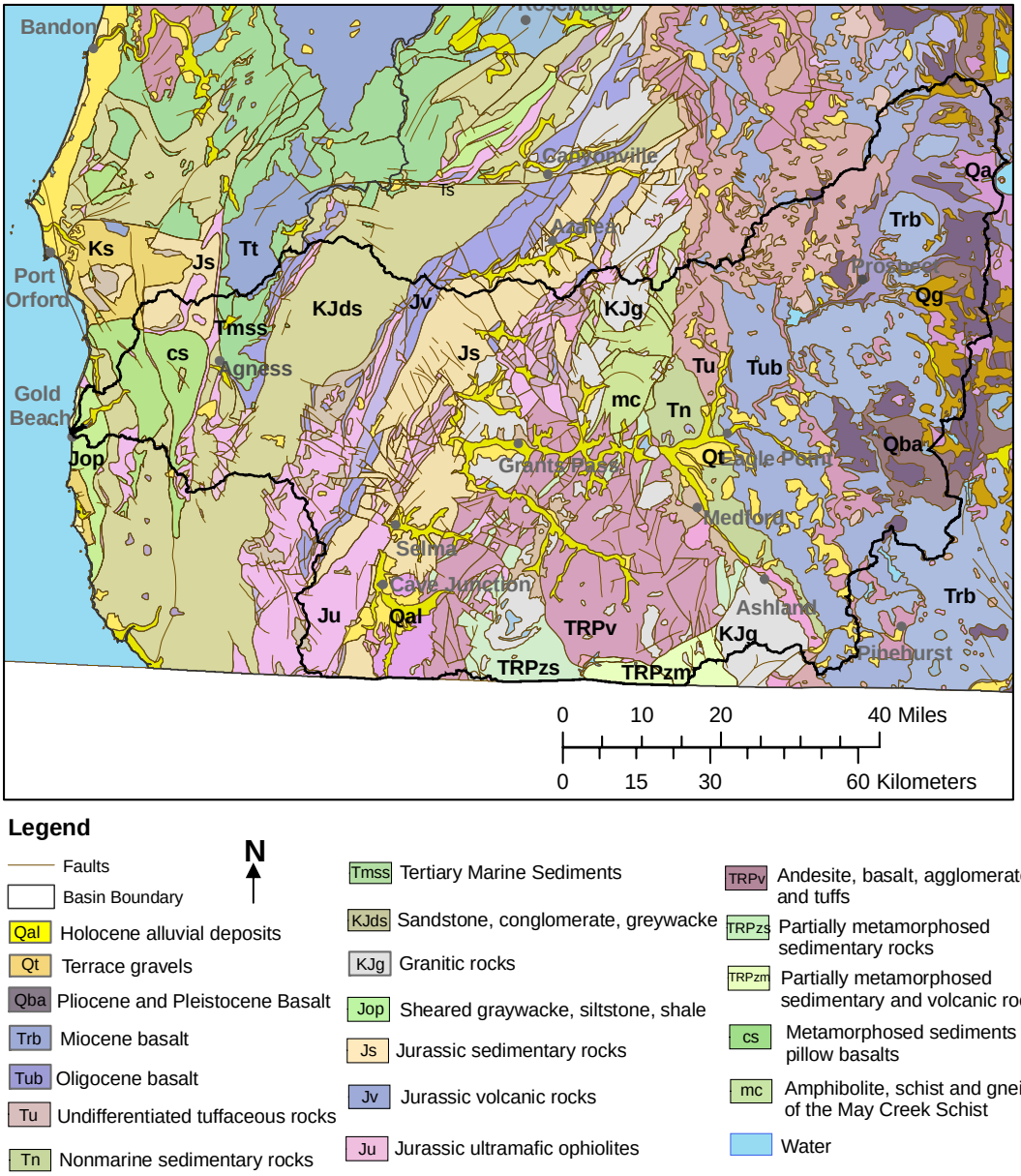


Figure 16-2. Rogue Basin geology map. Geologic formations of importance to future ASR include basin fill sediments (Data sources: Walker and McLeod, 1991; Oregon Geospatial Data Clearinghouse, 2006).

After the series of accretionary episodes that formed the Klamath Mountains, extrusive volcanic activity formed Western Cascade highlands to the east and later the High Cascades and Mt. Mazama (now Crater Lake). The Coast Range is a mixture of older accreted oceanic crust and younger volcanics and sediments.

The complexity of the Rogue Basin geology suggests a similarly intricate groundwater system, with local pockets of productive aquifers within generally unproductive aquifers. The following section discusses these variable units in detail and their potential for ASR or AR.

Hydrogeologic Units

Major geologic units in the basin, from oldest to youngest include Triassic metamorphics, Jurassic intrusives and sedimentary rocks, Cretaceous sedimentary rocks, Oligocene through Pliocene basalt, rhyolite and andesite, Miocene tuffs, and Pliocene through Holocene alluvial sediments. The units are illustrated in map form in Figure 9-2, grouped and discussed in relation to ASR in the following sections

Ophiolites and Metamorphic units

The oldest rocks in the Rogue Basin are accreted oceanic crust and island arc materials, many of which have been metamorphosed over time. Jurassic ophiolites (Ju), or ocean crustal series including ultramafics and gabbros, pillow basalts and deep sea clays, are exposed in the central and eastern mountains of the basin. Some components of the ophiolite series may be highly permeable, such as pillow basalts, while other parts have low permeability. Site specific investigation will determine where these rocks are productive aquifers, but they are generally not considered reliable water bearing units.

Permian through Jurassic metamorphic facies (TRPv, TRPzs, TRPzm, mc, cs, Jop) extend across the central portion of the basin, from Grants Pass to Ashland (Figure 16-2). These units have not only a complex stratigraphy due to their history of thrust faults and compression, but they also include both sedimentary and igneous rocks. They are generally of low permeability, and wells that access these units produce yields that

can support only small domestic needs. These low yields suggest generally low transmissivity which is unsuitable for ASR, although there may be local exceptions.

Intrusives

Jurassic through Cretaceous granitic intrusives are exposed southwest of Ashland, west of Grants Pass, and in smaller areas to the north and south. Wells in these areas draw water from granitic plutons (KJg), where water moves through secondary porosity features such as fractures and joints. West of Grants Pass is a band of Jurassic age granitic and gabbroic rocks (Jv) that are generally close-grained and yield little water (Hotz, 1971; OWRD, 1985). These units are not likely to support ASR or AR, due to their low permeability, although the more permeable weathered granites in Grants Pass may require further investigation to confirm this assumption.

Western Cascade Volcanics

Oligocene through Miocene basalt and andesite (Tb, Trb, Tu) of the Western Cascades are exposed in the headwaters of the Rogue River. These units generally have low permeability and have been observed as groundwater boundaries in neighboring Klamath Basin (Gannett et al., 2007). It is likely they serve the same function in the Rogue Basin. The basalts, rhyolites and tuffs tend to have low yielding wells, and are not a likely target for ASR or AR.

Quaternary volcanics of the High Cascades

Pleistocene volcanics (Qba, Qa) are exposed in the High Cascades at the eastern basin boundary. Although andesites and basalts in these groups are assumed to be highly permeable due to fracturing, they are not used for large capacity wells. Due to the rugged, steep terrain, the High Cascade volcanics are not likely candidates for ASR or AR.

Quaternary Sediments

Erosion of the region by rivers has created and deposited the unconsolidated Pleistocene through Holocene sediments (Qal, Qt) that fill valleys throughout the basin. Additionally, the eruption of Mt. Mazama (now Crater Lake) released high permeability air-fall materials including pumice and ash that were washed down the Rogue River valley and deposited in its flood plain. These units are widely accessed by shallow domestic and irrigation wells, and they represent the most productive aquifer in the basin. Unconfined sedimentary aquifers may be useful for ASR or AR in areas with suitable transmissivity, source water quality and availability.

Tectonic Structure Influencing Groundwater Flow

Most of the Rogue Basin is included in the Klamath Mountain geologic province, which is characterized by complex accreted terranes, extensive metamorphism and intricate thrust faulting. In some cases this history has benefited groundwater flow by fracturing tight grained units that would otherwise not conduct water. In other cases faults act as groundwater barriers. The western portion of the basin as less affected by faulting than the central area. Local investigation is necessary to determine the fault effects on groundwater flow relevant to specific ASR or AR sites.

ASR Assessment

The purpose of this section is to provide a general assessment of specific locations for their potential to employ ASR as a part of water supply systems. Site specific investigation is essential to determine if a recharge project is technically, economically, and environmentally feasible, but positive results from this study indicate the site possesses many of the necessary components for successful ASR.

Table 16-1: Summary of Analysis Methods. For more detail, see Chapter 3: Analysis Methods.

Method	Description	Result of Method
Volumetric Analysis	Mathematical comparison of aquifer storage capability to the volume of surface water available	If > 1, sufficient storage If = 1 marginal storage If < 1, insufficient storage
Brown's Site Rating System	Site is rated from 0 to 2 for each criteria such as distance to source water, water quality, groundwater flow rate, aquifer thickness	Produces % of ideal ASR parameters at a given site

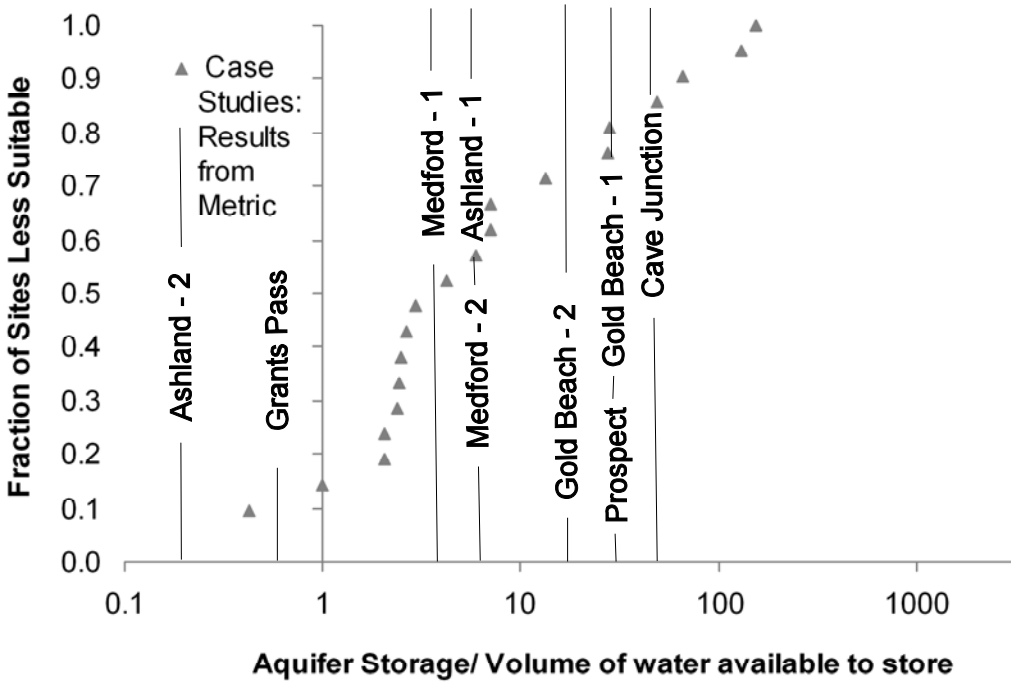


Figure 16-3: Rogue Basin ASR metric results. Cave Junction, Prospect, Gold Beach, Medford and Ashland-1 have sufficient aquifer storage for ASR. Results for Ashland-2 and Grants Pass indicate these sites have insufficient aquifer storage. Data listed in Appendix B.

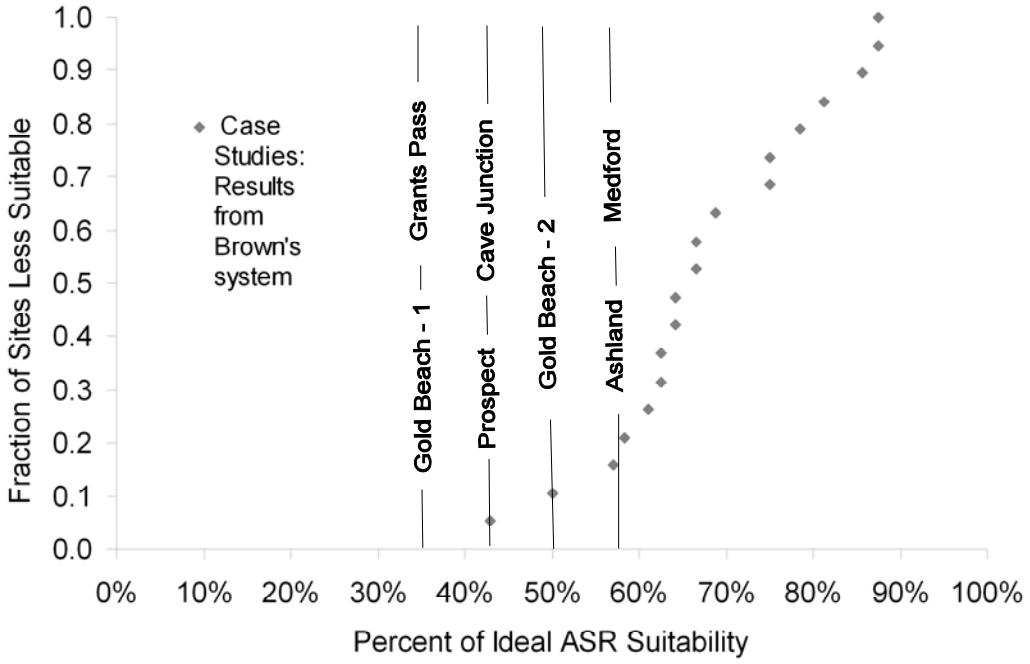


Figure 16-4: Rogue Basin Brown's rating system results. Sites have from 36 % to 57% of ideal conditions. 80% of case studies' results are greater than results for this basin. Data listed in Appendix C.

Medford

Medford is the largest town in the Rogue basin, located 8 mi (13 km) south of the Rogue River, in the Bear Creek Valley. The population is growing rapidly, from 46,951 to 70,147 residents between 1994 and 2004 (U.S. Census, 2004). Water is managed independently of city government by the Medford Water Commission. The city holds water rights to 67 cfs (163,950 m^3/d) from Big Butte Springs, which is the main source of municipal water. During times of high demand, additional water is acquired from the Rogue River at a maximum rate of 100 cfs (244,700 m^3/d) at Duff water treatment plant (the plant has a 45 MGD, or 170,325 m^3/d maximum capacity), near Touvelle State Park, in addition to water purchased from upstream reservoirs.

The most likely site for ASR is at the Duff treatment plant, which is located at the foot of Table Rock. Although there are no municipal wells in this area presently, a private well was selected to represent the local aquifer environment. A second well

owned by the city of Medford, but located in town was examined to explore the possibility of an ASR site that injects treated water from the municipal supply pipeline. Water could be stored in the winter, either at the treatment plant or at the municipal well in town, and then withdrawn during the summer months instead of purchasing water from reservoirs.

The well near Table Rock, Medford-2 (JACK 6852), penetrates Quaternary sedimentary units (Qal, Qt). It is screened at depths of approximately 24 to 400 ft (7 to 122 m) below the surface, and yielded 20 gpm (109 m^3/d) at the time of drilling. Transmissivity is estimated as 870 ft^2/d (80 m^2/d) from specific capacity data, which is below the ideal ASR range of 5,000 to 25,000 ft^2/d (465 to 2,323 m^2/d). Although these values are low for ASR, experience in Denver, CO and Green Bay, Wisconsin shows that similar transmissivity can in some places support ASR projects.

A larger capacity well, Medford-1 (JACK 6961), is owned by the City of Medford and was installed in town for industrial use. It extends to 165 ft (50 m) below the surface and draws 45 gpm (245 m^3/d) from a Quaternary gravel and tertiary shale aquifer (Qal, Tn). Transmissivity is similar to that found at the Duff treatment plant and low for ASR, estimated at 940 ft^2/d (90 m^2/d) by this study.

Volumetric analysis indicates that both wells access aquifers with sufficient storage to inject ½ of Medford's 45 MGD (170,325 m^3/d) treatment plant capacity for 120 days (Figure16-3). According to Brown's site rating system, Medford has 57% of ideal conditions for ASR (Figure 16-4). The town lost points for low transmissivity and the need to protect river flows for fish. However, the existing treatment plant and water pipelines provide high quality water for storage, which is advantageous for ASR. Marginal transmissivity is the largest barrier to ASR or AR in this area, and site specific examination will be important.

Grants Pass

Grants Pass is situated on the Rogue River, east of is confluence with the Applegate River. The town currently has surface water rights to 50 cfs (122,350 m^3/d) from the Rogue River (OWRD WRIS, accessed 2007), and a water treatment plant that

can process 20 MGD (75,700 m^3/d) for municipal use. Population increased from 17,488 to 28,882 between 1994 and 2004 (U.S. Census, 2004).

A municipal well (JOSE 18119) was examined for ASR suitability. It has open intervals from approximately 40 to 60 ft (12 to 18 m) below the surface, drawing water from a Cretaceous granite aquifer (KJg)(OWRD well log database, accessed 2007). Granite in this area is locally weathered to saprolite, which has a higher permeability than the surrounding, less decomposed granite (McFarland, 1983). Transmissivity is estimated at 1,100 ft^2/d (100 m^2/d) from specific capacity data. This value falls below the ideal range for ASR, but is similar to Windhoek, South Africa's fractured quartzite and schist ASR site which has a transmissivity of 646 ft^2/d (60 m^2/d).

Volumetric analysis (Figure 16-3) indicates the aquifer's available storage is insufficient to inject ½ the treatment plant capacity for 120 days. These results indicate that decreasing the injection rate will improve the volumetric suitability. Grants Pass has 36% of ideal conditions for ASR according to Brown's site rating system, with low scores on transmissivity, the presence of threatened species, and well density. AR may be feasible in Quaternary sediments of the Rogue River Valley, although the aquifer's connection to the river may limit this possibility.

Ashland

Located at the southeastern Rogue Basin, Ashland sits on a granitic intrusion of the Klamath Mountain geologic province. The City of Ashland currently has surface water rights to 15 cfs (36,705 m^3/d) from Reeder Reservoir on Mt. Ashland, where snowmelt is stored for the municipal water supply (OWRD WRIS, accessed 2007). Population increased from 16,234 to 20,829 between 1994 and 2004 (U.S. Census, 2004). No municipal wells well located by this study, so two domestic wells were chosen to represent local geologic environments.

Domestic well Ashland-1 (JACK 20656) utilizes a Cretaceous conglomerate aquifer (KJds), which likely represents the alluvial aquifer in the valley. Open intervals from depths of 40 to 203 ft (12 to 62 m) below the surface yielded 150 gpm (818 m^3/d) at the time of installation (OWRD well log database, 2007). Transmissivity estimated from

specific capacity is 1,000 ft^2/d (94 m^2/d). This is below the ideal range for ASR, although it is similar to transmissivity of a sand and sandstone aquifer used in Denver, Colorado for ASR. Local investigation is necessary.

A second well, which draws water from the granite aquifer, was also examined for ASR suitability. The domestic well Ashland-2 (JACK 35427) yields 5 gpm (27.3 m^3/d), and transmissivity estimated from specific capacity is 100 ft^2/d (9 m^2/d). This is below any known ASR site and is therefore not a likely location.

Volumetric analysis indicates aquifer storage is insufficient at Ashland-2 to inject ½ of the municipality's water treatment plant capacity for 120 days. Ashland-1 (JACK 20656, the conglomerate well) has sufficient aquifer storage due to its higher transmissivity (Figure 16-3). Brown's site rating system finds both wells have 57% of optimal ASR parameters (Figure 16-4). AR is not likely to succeed in surficial granite aquifers, although small alluvial aquifers north of town may be suitable depending infiltration rates.

Cave Junction

Cave Junction is located about 10 mi (16 km) north of the Oregon and California border on the Illinois River. The town has surface water rights to 3 cfs (7,341 m^3/d) from the Illinois River (OWRD WRIS, accessed June 2007), in addition to groundwater rights for shallow alluvial wells. The population increased from 1,126 residents in 1994 to 1,380 in 2004 (U.S. Census, 2004).

A municipal well (JOSE 6631) was selected as representative of local Quaternary alluvial and terrace deposit (Qal, Qt) community wells. This well is shallow, with open intervals from depths of 13 to 26 ft (4 to 8 m) below the surface and a well yield of 110 gpm (600 m^3/d; OWRD well log database, 2007). Transmissivity estimated from the well's specific capacity is 16,700 ft^2/d (1,550 m^2/d). This is within the target range for ASR.

Volumetric analysis (Figure 16-3) indicates the aquifer storage is sufficient to inject 1.5 cfs (3,671 m^3/d) for 120 days. According to Brown's site rating system, Cave Junction has 43% of optimal ASR parameters (Figure 16-4). The site lost points for high

well density, the presence of threatened fish species and aquifer thickness less than 25 ft (7.6 m). AR may be more feasible than ASR in this area, due to the shallow surficial sand and gravel aquifers, depending on local vertical permeability and water quality.

Prospect

Prospect is a small, unincorporated rural community located in the Western Cascades near the headwaters of the Rogue River. This location was chosen to examine the possibility of ASR in the mountainous eastern section of the basin. The town of Prospect has no surface water rights, but there is 1 cfs (2,447 m^3/d) available for storage from the Rogue River (OWRD WARS, accessed May 2007). Population in 2000 was stable with 530 residents (U.S. Census, 2004). Water is currently supplies by groundwater from domestic wells.

A domestic well (JACK 18740) draws water from Quaternary High Cascade basalt (Qba) at depths of 120 to 300 ft (37 to 91 m) below the surface, and yields 60 gpm (327 m^3/d; OWRD well log database, 2007). Transmissivity estimated from the well's specific capacity is 500 ft^2/d (50 m^2/d). This is below the ideal range for ASR.

Volumetric analysis indicates the aquifer storage is sufficient to inject 1 cfs (2,447 m^3/d) for 120 days (Figure 16-3). The small volume of water to be injected counteracts the low transmissivity in this case. Brown's site rating system finds Prospect has 43% of optimal ASR parameters (Figure 16-4). The site lost points for the presence of threatened species that may suffer from a decrease in river flow, low transmissivity, and high well density. AR may not be feasible in this area, due to the rugged topography, steep gradients, and depending on whether the water infiltrated into the aquifer will discharge into the nearby Rogue River before it can be recovered for municipal use.

Gold Beach

The town of Gold Beach is situated on the Oregon Coast, at the mouth of the Rogue River. Tourism is one of the main industries in the area, and visitors create an increased need for water during the time of lowest water supply, since most precipitation occurs during winter months. The town has surface water rights to 10 cfs (24,470 m^3/d)

from the Rogue River (OWRD WRIS, accessed June 2007), as well as groundwater rights to meet community water needs. Population increased from 1,546 to 1,930 between 1994 and 2004 (U.S. Census data, 2004).

A community well, Gold Beach-1 (CURR 236), was chosen to represent aquifer conditions in this area. It draws water from Quaternary terrace sand and gravel (Qt) at depths of 25 to 50 ft (8 to 15 m) below the surface, and yields 2,200 gpm (11,990 m^3/d). Transmissivity estimated from specific capacity is 107,000 ft^2/d (9,900 m^2/d), which is above the ideal range for ASR. This indicates water may flow away from the well too quickly to be recovered at the same site a few months after injection. There is also the potential that injected water may discharge into surface water before it can be recovered.

A second well was investigated to see if the transmissivity was more suitable. Gold Beach-2 (CURR 267) also draws water from Quaternary terrace sand and gravel (Qt), but has a lower estimated transmissivity of 8,350 ft^2/d (780 m^2/d). This falls within the target range for ASR, which illustrates the local aquifer is heterogeneous. Some sites may be suitable for ASR, while others will not be, even though they access a similar sand and gravel environment.

Injection at a rate of 5 cfs (12,235 m^3/d) for 120 days is feasible according to volumetric analysis of both wells (Figure 16-3). Brown's site rating system finds Gold Beach has 36 to 50% of optimal ASR parameters (Figure 16-4). The site lost points for high transmissivity at the large capacity well, the presence of threatened species that could be affected by decreased river flows and an aquifer thickness less than 25 ft (7.6 m). AR may be feasible in surficial alluvial aquifers, depending on vertical permeability and water quality.

CHAPTER 17
SANDY BASIN

Basin Hydrology

The Sandy Basin covers approximately 568 mi^2 (1471 km^2) and is drained by the Sandy River and its major tributaries: Bull Run River, Salmon River and Zigzag River from the east; and Beaver Creek from the south. Watershed divides delineating the basin are found to the east at the crest of Mt. Hood, to the west at the Sandy River and to the north at the Columbia River.

The climate transitions from snowy alpine and dense evergreen forest conditions at the crest of the High Cascades to wet, mild conditions in the valley at the center of the basin. In the High Cascades of the eastern Sandy Basin, average annual precipitation exceeds 100 in (2,540 mm), largely as snow, while at lowland elevations precipitation averages about 45 in (1,140 mm) (Woodward et al., 1998).

Physical Setting

The Sandy Basin includes topography ranging from alpine peaks to alluvial valleys (Figure 17-1). The eastern edge of the basin incorporates the younger High Cascades, while the more weathered Western Cascades make up the western Sandy Basin. The Cascades were formed by Miocene through Holocene basalt, andesite and tuff flows (Orr and Orr, 2000). Surface and groundwater are recharged in the High Cascades and flow west toward the Sandy River.

West of the Cascades lies the Sandy lowlands, characterized by the Pliocene Troutdale formation and Sandy River mudstone; they are underlain by the Pliocene and Miocene Sardine formation. This is underlain by Tertiary Columbia River Basalts, and basement confining units composed of Eocene Skamania volcanics.

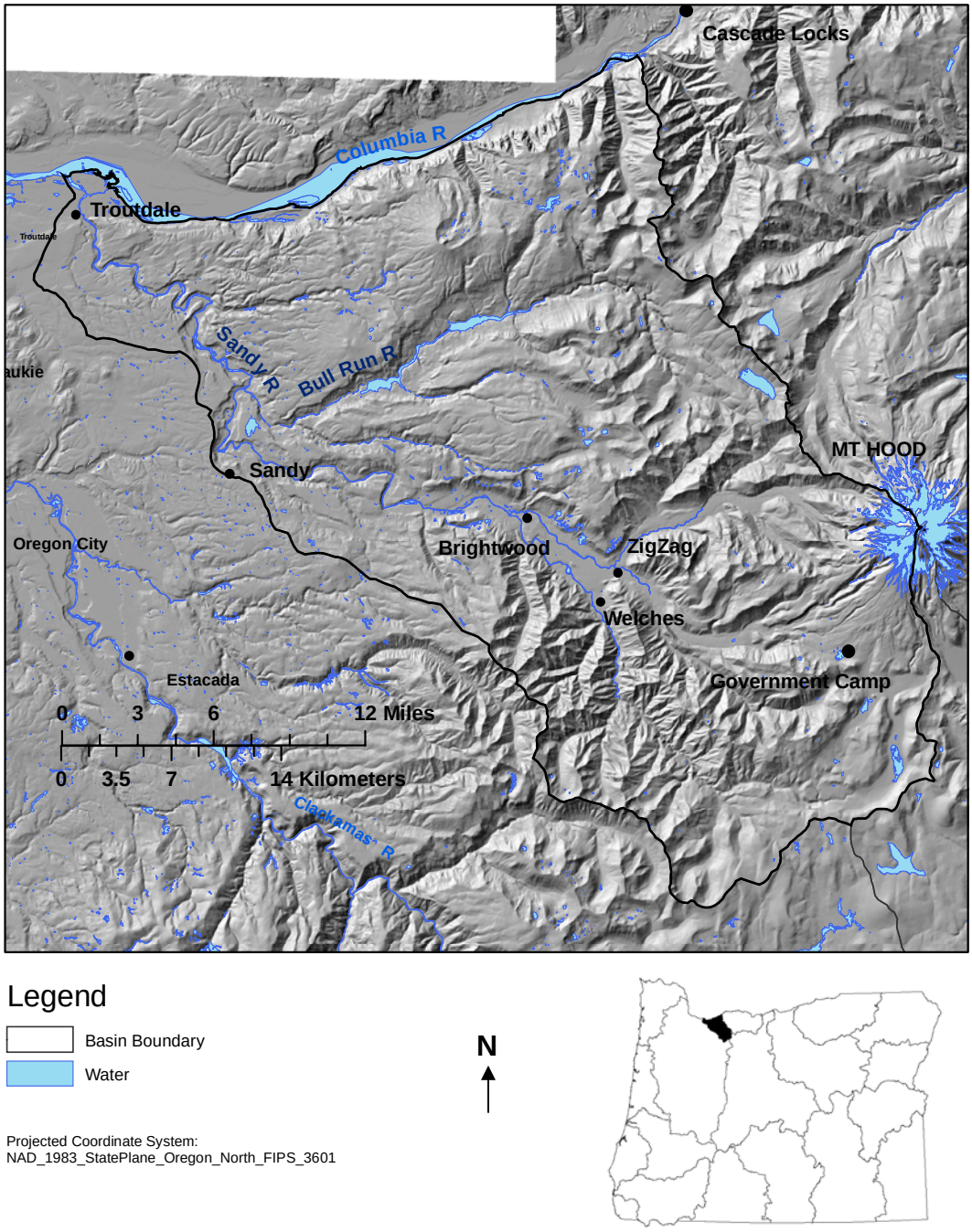


Figure 17-1. Sandy Basin location map. Topographic features, rivers and towns that are examined in this study (Data sources: Wright, 2006; Oregon Geospatial Data Clearinghouse, 2006).

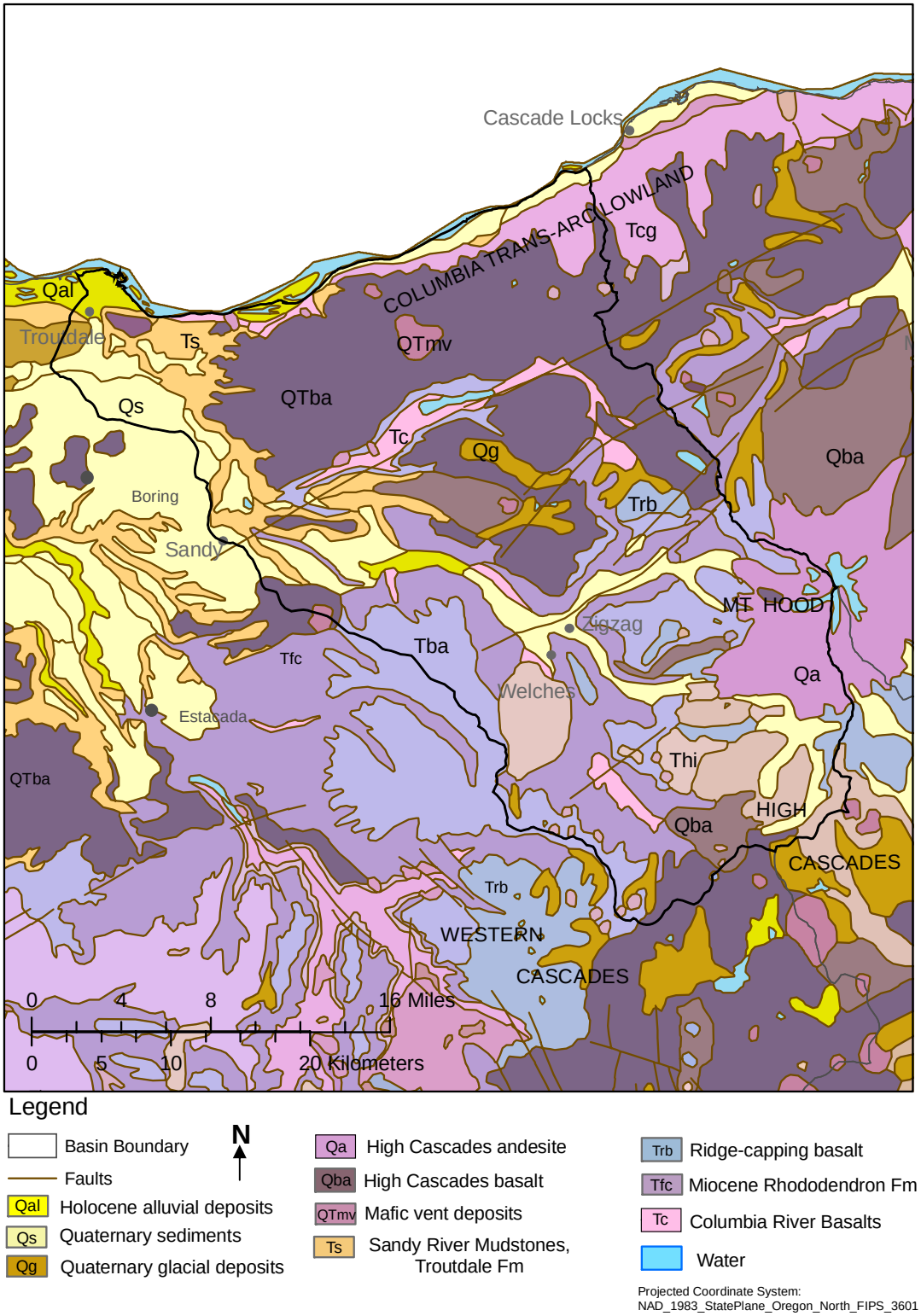


Figure 17-2. Sandy Basin geology map. Geologic formations of importance to future ASR include Tertiary and Quaternary basalts (Data sources: Walker and McLeod, 1991; Oregon Geospatial Data Clearinghouse, 2006).

Hydrogeologic Units

Geologic units (Figure 17-2) are discussed in relation to ASR in the following section.

Eagle Creek Formation

The Eagle Creek Formation represents the basement low permeability boundary to regional groundwater flow in the Hood River subbasin. It is characterized by poorly sorted volcanic sediments, conglomerates, tuffs, with some andesitic flow layers. It ranges from 0 to 4,200 ft (0 to 1,280 m) in thickness (Allen, 1960). According to Sceva (1966), a 200 ft (61 m) deep well at a U.S. Forest Service Ranger Station accessing this formation yielded 4 gpm, with 170 ft (52 m) of drawdown. This indicates low transmissivity which makes the Eagle Creek Formation unsuitable for ASR or AR projects.

Columbia River Basalt Group

The Miocene Columbia River Basalt Group (Tc, Tcg) consists of several layers of basalt flows, averaging a few hundred feet thick and ranging up to 1,000 ft (305 m) thick. This group extends from north of the Columbia River through the Sandy Basin. It is exposed along the Columbia River and on Mt. Hood near Brightwood. Massive flows are separated by permeable interflow zone aquifers which are important groundwater sources throughout the Sandy Basin (Leonard and Collins, 1983). The Columbia River Basalt's hydraulic conductivity ranges from 0.001 to 750 ft/day (0.0003 to 229 m/day); well specific capacity ranges from 0.01 to 100 gpm/ft (0.2 to 1,793 m^2/d) (McFarland, 1983). The Columbia River Basalt is currently used for most ASR projects in the Willamette Valley, and so is of interest to this study.

Rhododendron Formation

The Rhododendron Formation (Tfc) consists of volcanic mudflow deposits, andesite and tuff. It is estimated to be 600 ft (183 m) thick near Sandy, increasing in thickness to the east, and pinching out to the west where it interfingers with the Troutdale

Formation (Swansen et al., 1993). It is exposed along the Sandy and Zigzag Rivers. Hydraulic conductivity ranges from 0.1 to1 ft/d (0.03 to 0.3 m/d); well specific capacity in this formation ranges from 0.1 to 4 gpm/ft (1.8 to 72 m^2/d) (McFarland, 1983). Moderate permeability indicates that this aquifer is of importance locally, especially along the Highway 26 corridor (Leonard and Collins, 1983); however, it is mostly mudflow deposits and therefore not a likely target for ASR or AR projects.

Troutdale Formation and Sandy River Mudstone

The Pliocene Troutdale Formation (Ts, QTs) consists of sandstone, conglomerate and finer grained Sandy River Mudstone. It overlies the Rhododendron Formation and in places the Columbia River Basalt. The Troutdale Formation originates from Columbia River sediments and Cascade volcanic rocks. Both formations are exposed along the Sandy River, extending from the Columbia River floodplains south through the lowlands of the Willamette valley. Thickness ranges up to 720 ft (220 m) (Leonard and Collins, 1983). Hydraulic conductivities range from 7 to 16 ft/day (2 to 4.9 m/day; McFarland and Morgan, 1996), specific capacities of wells accessing this formation have a median value of 10 gpm/ft (179 m^2/d) (McFarland, 1983). This aquifer may be suitable for surface spreading AR operations, and of local interest for ASR projects. It should be noted that Portland tested ASR in this formation from 2002 to 2003 and subsequently discontinued the project (Groundwater Solutions, 2003). The Troutdale Formation is overlain by a very weathered Cascadian gravel deposit, so surface infiltration may be a problem for AR (Ken Lite, personal communication, 2007).

Boring and High Cascade Lavas

Pliocene and Pleistocene volcanic activity deposited the Boring and High Cascade lavas (QTba, Tba, Qa). They are exposed in the mountains between the Sandy River and the Cascade crest, near Government Camp. These units include both andesitic and basaltic rocks. Thickness varies with topography, ranging from 100 to 3000 ft (30 to 914 m) (Leonard and Collins, 1983). Hydraulic conductivity ranges from 0.0001 to 1,000 ft/d (0.00003 to 305 m/d). High Cascades units are not accessed by many wells in this

area. Their variable hydraulic conductivity indicates with they may be suitable for ASR locally, but generally the rugged, inaccessible terrain makes High Cascade lavas unlikely candidates for ASR or AR.

Tectonic Structure Influencing Groundwater Flow

Major tectonic structures of the Sandy Basin include dip-slip, strike-slip faults and compressional folds resulting in anticlines and synclines that form local groundwater divides and subbasins. Faults can potentially truncate aquifers by offsetting high permeability layers; previous studies by Tualatin Valley Water District found similar offset made some ASR projects infeasible (Groundwater Solutions, Inc., 2003b). Dip-slip faults have displaced interflow zones in the Columbia River Basalt, disconnecting high permeability flow zones and limiting storage capacity.

The northeast trending Columbia trans-arc lowland is a syncline that preceded the Columbia River Basalt flows. This syncline is thought to be part of the Yakima structural belt, a series of low-angle folds extending from central Washington to the Sherwood trough in the Willamette Valley (Figure 17-2). Northwest trending faults found throughout the basin may affect groundwater flow locally, and will require local investigation to determine the impact on ASR projects.

ASR Assessment

The purpose of this section is to provide a general assessment of specific locations for their potential to employ ASR as a part of water supply systems. Site specific investigation is essential to determine if a recharge project is technically, economically, and environmentally feasible, but positive results from this study indicate the site possesses many of the necessary components for successful aquifer recharge.

Table 17-1: Summary of Analysis Methods. For more detail, see Chapter 3: Analysis Methods.

Method	Description	Result of Method
Volumetric Analysis	Mathematical comparison of aquifer storage capability to the volume of surface water available	If > 1, sufficient storage If = 1 marginal storage If < 1, insufficient storage
Brown's Site Rating System	Site is rated from 0 to 2 for each criteria such as distance to source water, water quality, groundwater flow rate, aquifer thickness	Produces % of ideal ASR parameters at a given site

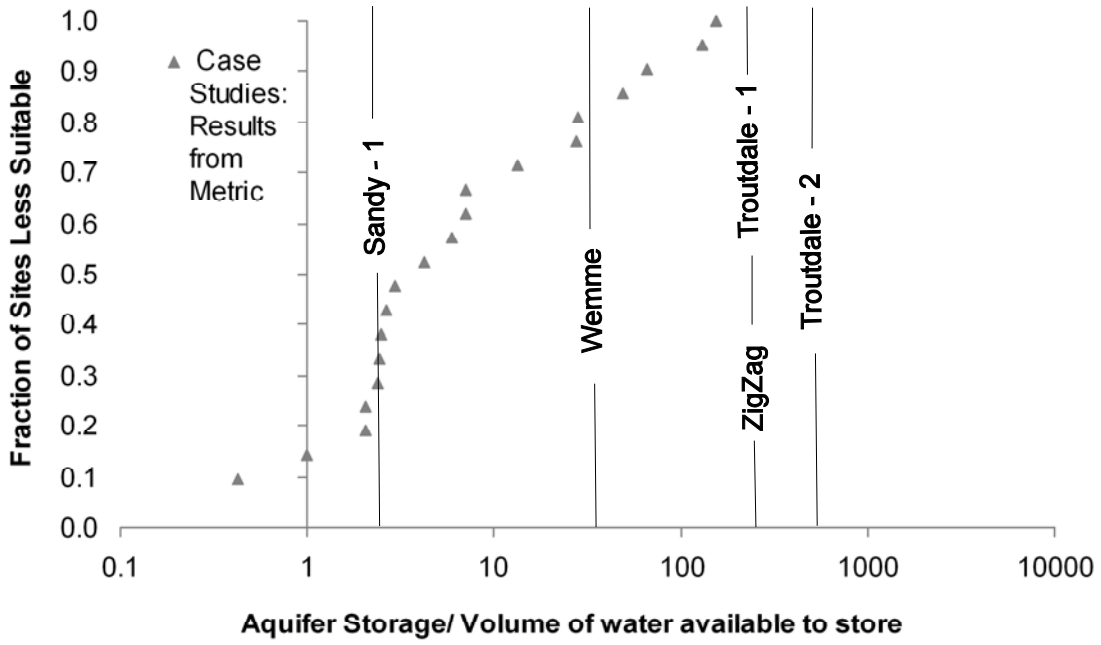


Figure 17-3: Sandy Basin ASR metric results. Aquifer storage is sufficient for ASR at all sites. Data listed in Appendix B.

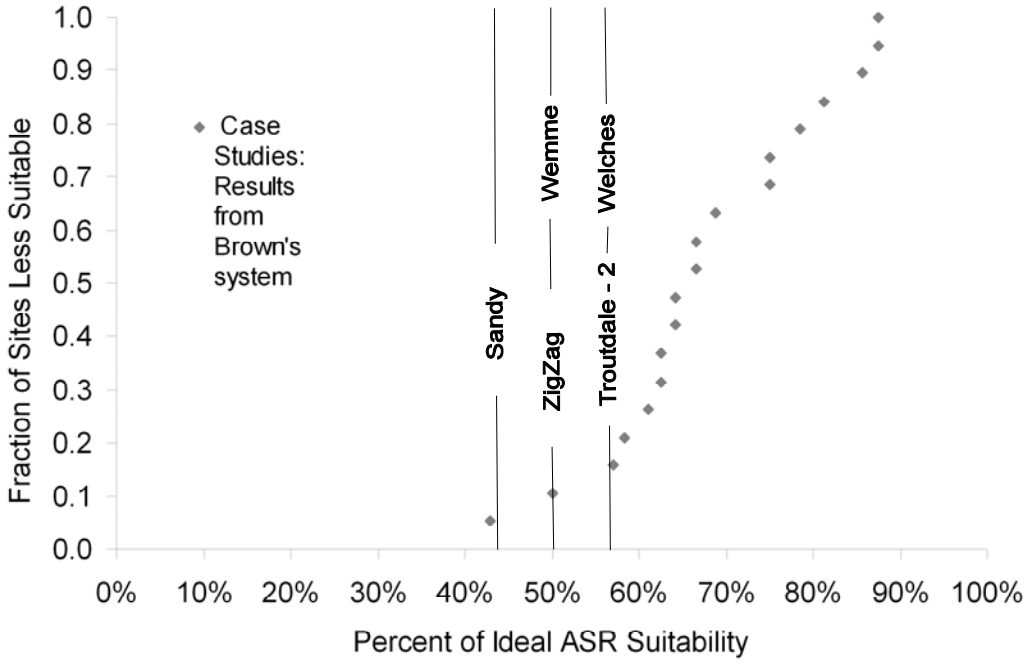


Figure 17-4: Sandy Basin Brown's rating system results. Sites have from 45 % to 57% of ideal conditions. 80% of case studies' results are greater than results for this basin. Data listed in Appendix C.

Sandy

Sandy is located in the northwestern border of the Sandy Basin. The City of Sandy currently has surface water rights to 16.3 cfs of the Salmon River that meet municipal water supply needs (OWRD WRIS, 2006). Surface water is available to the city from Alder Creek, where there is already a water treatment plant capable of processing 2.6 MGD (9,841 m^3/d). Groundwater levels in Sandy are not showing decline (OWRD water level database, accessed August 2006), but its population increased from 4,152 in 1990 to 7,871 in 2004 (U.S. Census, 2004). This moderate growth in population may increase water supply needs.

Wells in the Sandy area have open intervals in Tertiary to Quaternary cemented gravel (Ts, Qs) from 150 to 160 ft (45.7 to 49 m) below the surface; this is most likely the Sandy mudstone of the Troutdale formation (OWRD well log database, 2006). Wells are

also open to deeper aquifers from 500 to 600 ft (152 to 183 m) below the surface in the Columbia River Basalt or the Rhododendron Formation.

Previous studies have found median hydraulic conductivities for the Sandy River mudstone to be 1 ft/d (0.3 m) (McFarland and Morgan, 1996). Transmissivity of the Sandy mudstone in Sandy can be approximated as 3 ft^2/d (0.3 m^2/d). This transmissivity is several orders of magnitude lower than the ideal range for ASR Aquifer storage (Figure 17-3) in mudstone sand and gravel is marginally suitable for ASR. According to Brown's site rating system, Sandy has 44% of optimal ASR parameters (Figure 17-4). The site lost points for low transmissivity and aquifer thickness less than 25 ft (7.6 m). Therefore, ASR may not feasible in Sandy, although site specific investigation may identify local exceptions.

Troutdale

Troutdale is located at the confluence of the Sandy and Columbia Rivers, about 13 mi (21 km) east of Portland. The city has surface water rights to 0.22 cfs (538 m^3/d) of Troutdale spring year round, as well as groundwater rights (OWRD WRIS, 2006). Population has increased rapidly from 7,852 in 1990 to 14,898 in 2004 (U.S. Census, 2004). Population growth suggests an increasing pressure on water supplies, especially during seasons of drought.

Municipal wells have open intervals from 340 to 475 ft (104 to 145 m) below the surface, with yields of 300 to 1,000 gpm (1,635 to 244,700 m^3/d; OWRD well log database, 2006). They access the Troutdale Formation (Ts), including sand and gravel layers. Median hydraulic conductivity for this formation has been reported as 30 ft/day (9 m/day) (Hogenson and Foxworthy, 1965). Specific capacity at the municipal well is 3 to 25 gpm/ft (58 to 448 m^2/d) (OWRD well log database, 2006). Transmissivity estimated from specific capacity is 2,500 and 9,800 ft^2/d (200 and 900 m^2/d); the later is within the ideal range for ASR.

Volumetric analysis indicates the aquifer storage is sufficient to inject ½ of the treatment plant's capacity for 120 days (Figure 17-3). According to Brown's site rating system, Troutdale has 56% of optimal ASR parameters. Quaternary and Tertiary

sediments to the east and west of Troutdale may be suitable for surface spreading AR operations.

Welches, Wemme and Zigzag

Welches, Wemme and Zigzag are located on the southwestern slope of Mt. Hood, about 26 mi (42 km) southeast of Troutdale. Welches has surface water rights to 0.25 cfs (612 m^3/d) of a tributary of the Salmon River year round, as well as private wells for domestic use; Wemme and Zigzag presently have groundwater rights only.

Wells have open intervals varying from 104 to 116 ft (32 to 35 m) below the surface, with yields of 80 to 200 gpm (436 to 1,090 m^3/d; OWRD well log database, 2006). They access Quaternary sand and gravel aquifers (Qs). Transmissivity estimated from specific capacity for both Wemme is 2,000 ft^2/d, and Zigzag is 1,500 ft^2/d (200 and 140 m^2/d respectively). This is below the ideal range for ASR.

Volumetric analysis indicates the Welches, Wemme and Zigzag aquifers' storage is suitable for small scale ASR (Figure 17-3). Low transmissivity at Welches and Wemme does not make ASR infeasible because the volume to be injected (306 m^3 over 180 days) is quite small. However, a small project may not be economically efficient. Welches has 57% of optimal ASR parameters, while Wemme and Zigzag have 50% (Figure 17-4). Due to the steep mountainous terrain, AR is not likely to succeed in this area, and ASR will be difficult where groundwater gradients are also steep.

CHAPTER 18
SOUTH COAST BASIN

Basin Hydrology

The South Coast Basin covers approximately 2,950 mi^2 (7,640 km^2). Watershed divides delineating the basin are found at the crest of the Coast Range to the east and the Pacific Ocean to the west. The southern portion is drained by the Chetco River, while the northern portion is drained by the Elk, Coquille and Coos Rivers, in addition to many smaller streams that flow west off the Coast Range.

The basin varies from alpine conditions in the Cascade Range to mild, moist conditions in the Coast Range. Average annual precipitation ranges from approximately 70 in (1,780 mm) at Coos Bay, 90 in (2,290 mm) at Brookings, to120 in (3,050 mm) near the crest of the Coast Range (Oregon Climate Service, 2007). Most of the precipitation occurs between October and May, while June through September can be drier. This dry period coincides with the time of greatest water consumption in the area due to summer tourism.

Groundwater recharge rates are unknown at this time, although a decrease in aquifer recharge has been inferred as a result of drain tiles installed in the 1970's to create agricultural fields. Water that would have previously ponded and infiltrated into the aquifers now is channeled into streams by drain tiles, resulting in rapid streamflow response to rainfall events and a noted increase in stream down-cutting in recent decades (Lissner, 1977).

Physical Setting

The South Coast Basin has a complex geology. The basin includes portions of the Klamath Mountains, with their characteristic metamorphic accreted terranes, Coast Range marine sequences and younger beach deposit formations. This complexity suggests a similarly intricate groundwater system, with local pockets of productive aquifers within a generally unproductive groundwater environment. Faults, fractures and shear zones have created a secondary porosity in cemented sand and siltstones that represent localized productive groundwater sources.

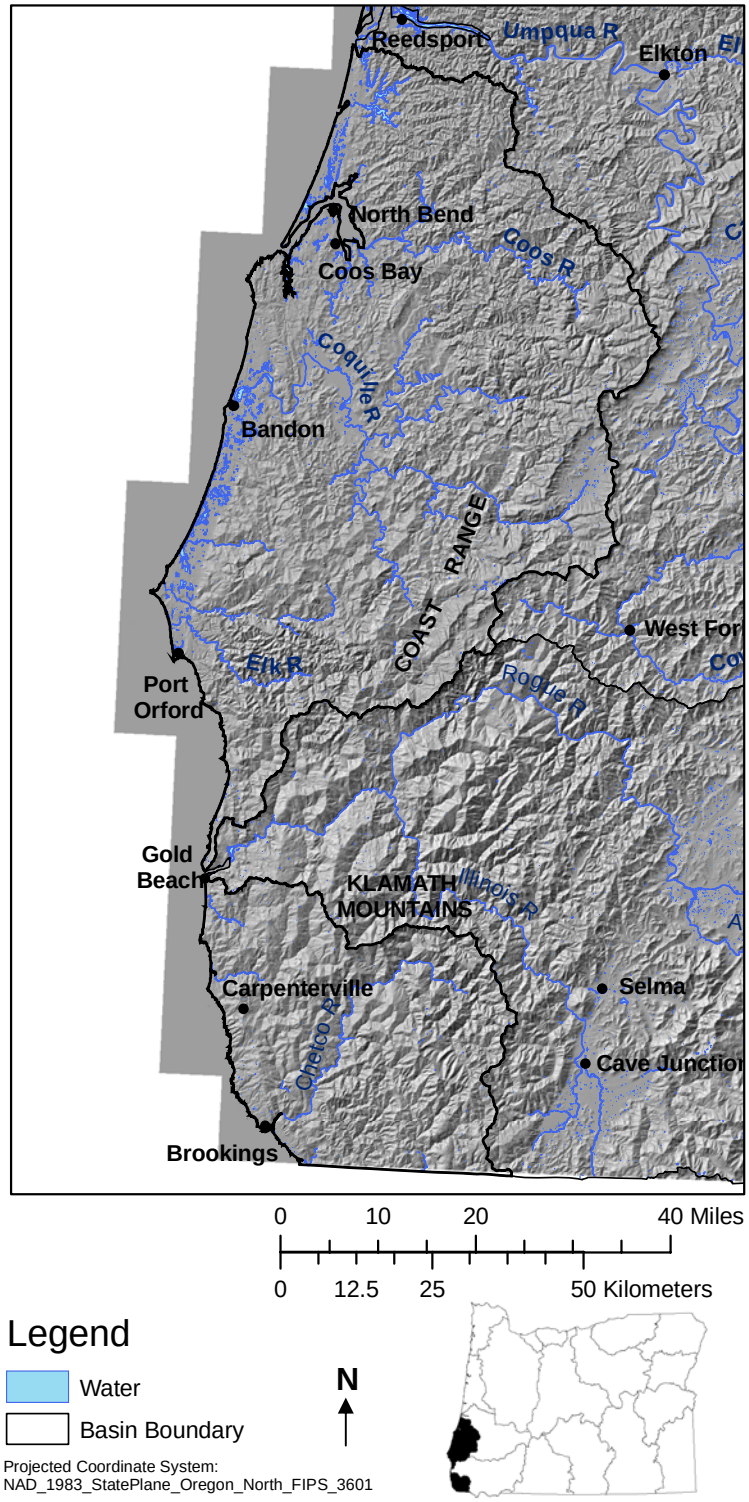
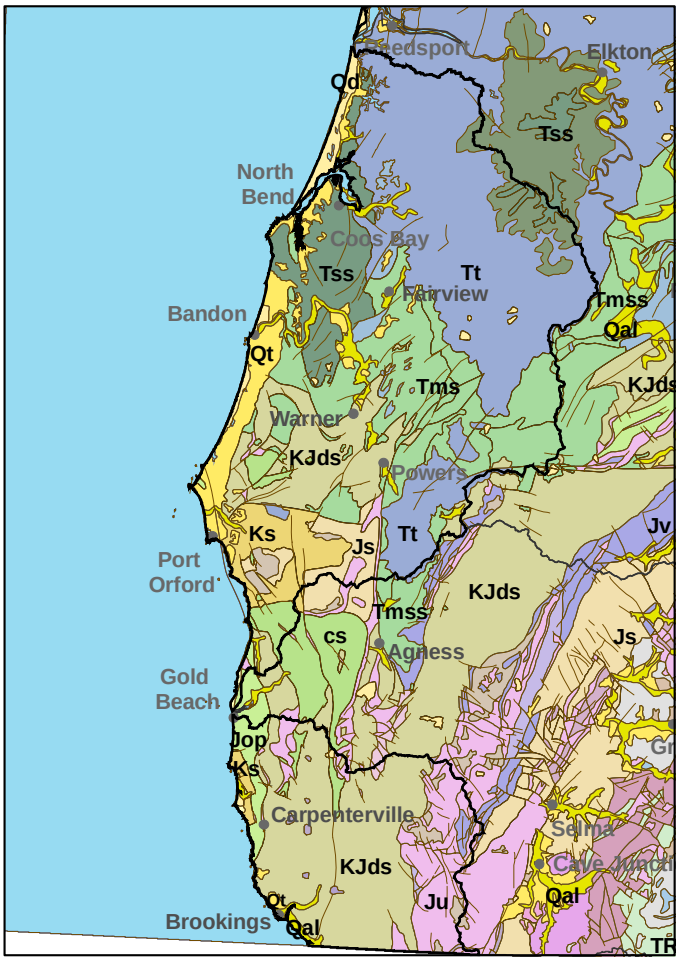


Figure 18-1. South Coast Basin location map. Location of topographic features, rivers and towns that are examined in this study (Data sources: Wright, 2006; Oregon Geospatial Data Clearinghouse, 2006).



0 10 20 40 Miles

0 15 30 60 Kilometers

Legend

N

- Faults
- Basin Boundary
- Qal — Holocene alluvial deposits
- Qd — Holocene dune sand
- Qt — Terrace deposits
- Tss — Tertiary marine siltstone
- Tsr — Eocene Siletz River volcanics
- Tt — Eocene marine siltstone
- Tms — Tertiary marine sediments
- KJds — Sandstone, conglomerate, greywacke
- Ks — Cretaceous sedimentary rocks
- Jop — Sheared graywacke, siltstone, shale
- Js — Jurassic sedimentary rocks
- Jv — Jurassic volcanic rocks
- Ju — Ophiolite sequences and mafic rocks
- Water

Figure 18-2. South Coast Basin geology map. Geologic formations of importance to future ASR include Quaternary sediments (Data sources: Walker and McLeod, 1991; Oregon Geospatial Data Clearinghouse, 2006).

Hydrogeologic Units

Major geologic units in the basin, from oldest to youngest, include Jurassic metamorphic and sedimentary rocks, Cretaceous sedimentary rocks, Tertiary marine volcanics and sediments, Tertiary and Quaternary alluvial and marine deposits. The units are (Figure 18-2) discussed in relation to ASR in the following sections

Ophiolites and Metamorphic units

The oldest rocks in the South Coast Basin are accreted oceanic crust and island arc materials, many of which have been metamorphosed over time. Jurassic ophiolites (Ju), or ocean crustal series including ultramafics and gabbros, pillow basalts and deep sea clays are exposed in the southeastern mountains of the basin. Some components of the ophiolite series may be highly permeable, such as pillow basalts, but they are generally not considered reliable water bearing units.

Minor exposures of Jurassic metamorphic units (cs, Jop) are found south of Gold Beach. These units have a complex stratigraphy due to their history of thrust faults and compression. They are generally of low permeability, and wells that access these units produce yields that can support domestic needs. These low yields suggest a generally low transmissivity which is unsuitable for ASR, although there may be local exceptions.

Jurassic and Cretaceous Units

Jurassic and Cretaceous sandstones, conglomerates, volcanics and greywacke (Jv, Js, Ks, KJds) are exposed in a broad northeast trending band between the Oregon-California border and Carpenterville. These cemented sediments and small bands of volcanics have low permeability, with secondary porosity formed by fractures and shearing (Lissner, 1977). While they may be suitable for ASR through wells that influence these fracture zones, these units are not likely to be targets for ASR.

Tertiary Marine Deposits

Eocene through early Miocene marine sequences (Tms, Tt, Tsr, Tss) include sandstone, siltstone and volcanics. These units are exposed throughout the Coast Range

and continue to the coastline. This unit yields enough water in some places for domestic use, but at depths greater than about 200 ft below the surface, native groundwater becomes increasingly saline, with median dissolved solids concentration of 300 mg/L and maximum reported concentration of 70,000 mg/L (McFarland, 1983). This water quality issue, combined with low hydraulic conductivity of 0.1 to 10 ft/d (0.035 to 3 m/d), indicates that marine sediments are not a preferred unit for ASR.

Quaternary Sediments

Erosion of the region by river and ocean activity has created and deposited unconsolidated Pleistocene through Holocene sediments (Qal, Qt, Qd) that line the coast of the basin. These units are widely accessed by shallow domestic and irrigation wells, and they represent the most productive aquifers in the basin. Unconfined to semi-confined sedimentary aquifers may be useful for ASR or AR in areas with suitable transmissivity, source water quality and availability.

Tectonic Structure Influencing Groundwater Flow

The South Coast Basin is influenced by north-south trending faults and fractures, resulting from the gradual up-warping of the Coast Range. In some cases this history has benefited groundwater flow by fracturing tight grained units that would otherwise not conduct water. In other cases faults act as groundwater barriers. Local investigation is necessary to determine the fault and fracture effects on groundwater flow relevant to specific ASR or AR sites.

ASR Assessment

The purpose of this section is to provide a general assessment of specific locations for their potential to employ ASR as a part of water supply systems. Site specific investigation is essential to determine if a recharge project is technically, economically, and environmentally feasible, but positive results from this study indicate the site possesses many of the necessary components for successful ASR.

Table 18-1: Summary of Analysis Methods. For more detail, see Chapter 3: Analysis Methods.

Method	Description	Result of Method
Volumetric Analysis	Mathematical comparison of aquifer storage capability to the volume of surface water available	If > 1, sufficient storage If = 1 marginal storage If < 1, insufficient storage
Brown's Site Rating System	Site is rated from 0 to 2 for each criteria such as distance to source water, water quality, groundwater flow rate, aquifer thickness	Produces % of ideal ASR parameters at a given site

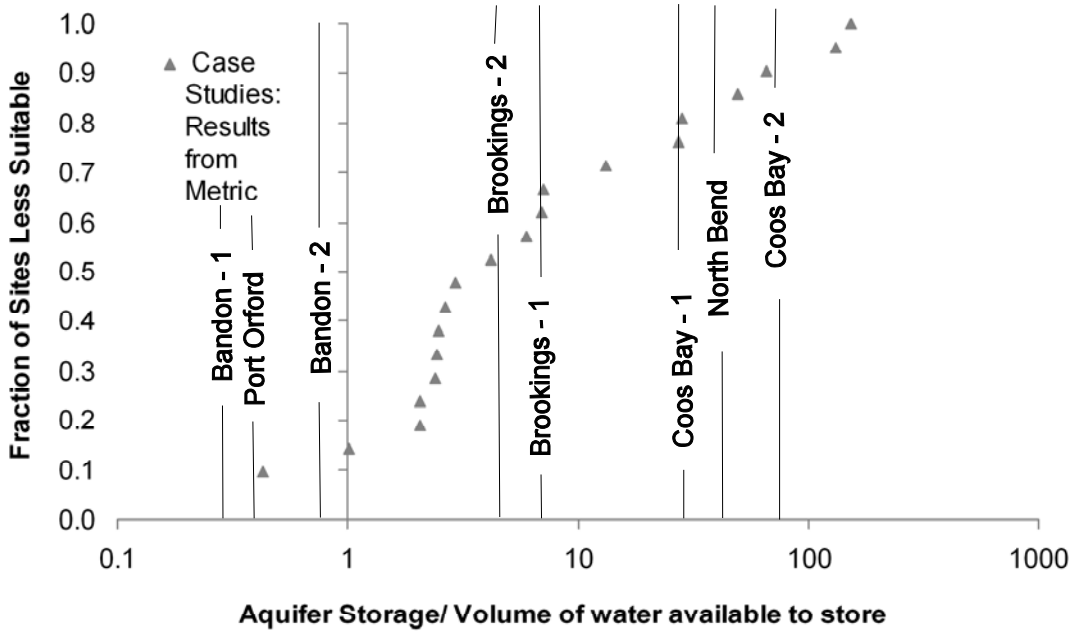


Figure 18-3: South Coast Basin ASR metric results. Coos Bay, North Bend and Brookings have sufficient aquifer storage for ASR. Results for Port Orford and Bandon indicate aquifer storage is unsuitable for ASR. Data listed in Appendix B.

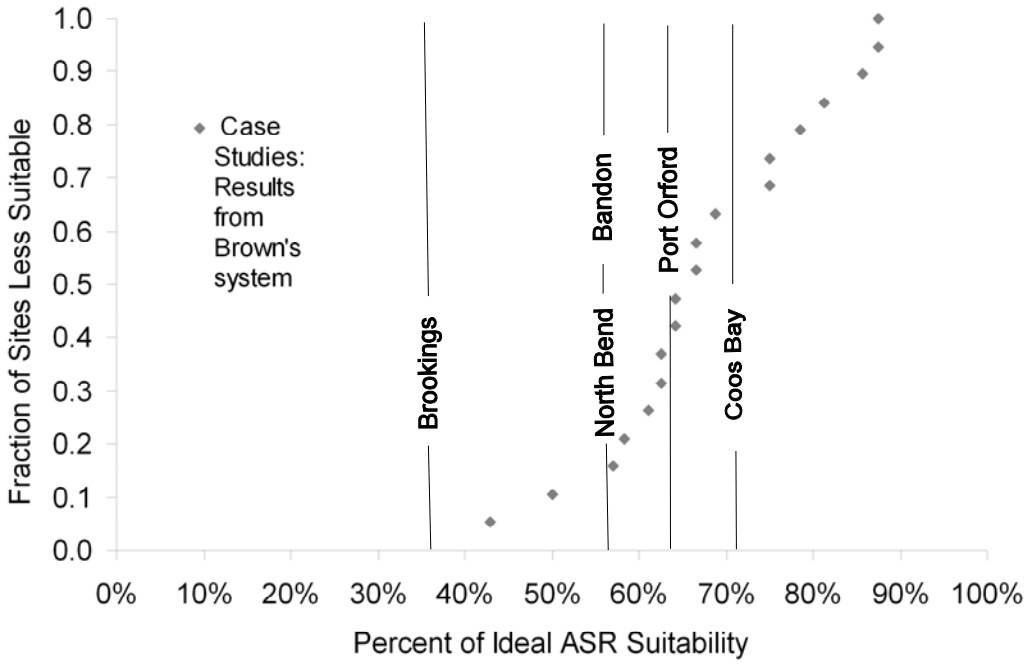


Figure 18-4: South Coast Basin Brown's rating system results indicate that sites have from 36 % to 71% of ideal conditions. 60% of case studies' results is within the range of results for this basin. Data listed in Appendix C.

Brookings

Brookings is located 3 mi (5 km) north of the Oregon-California border, at the mouth of the Chetco River. The population is growing rapidly, with 4,400 residents in 1990 and 6,344 in 2006 (U.S. Census, 2006). Water is managed by the city public works department. The city holds water rights to 10 cfs from the Chetco River, which is the main source of municipal water.

The most likely ASR site is at the City of Brookings water treatment plant on the Chetco River. Although there are no significant municipal wells in this, a private irrigation well was selected nearby for ASR suitability analysis. A second, large capacity well owned by Harbor Rural Water District was examined to explore the possibility of an ASR site that stores water in the dunes south of Brookings.

The irrigation well, Brookings-1 (CURR 124), penetrates Quaternary sedimentary units (Qal). It is screened at depths of approximately 18 to 30 ft (5 to 9 m) below the

surface, and yields 40 gpm (218 m^3/d). Pump tests (Lissner, 1977) found the transmissivity at this well to be 12,600 ft^2/d (1,170 m^2/d), which is within the ideal ASR range of 5,000 to 25,000 ft^2/d (465 to 2,323 m^2/d).

A larger capacity well, Brookings-2 (CURR 473), is owned by the Harbor Rural Water District as a part of their dune well field. It extends to 41 ft (12.5 m) below the surface and draws 1,500 gpm (8,175 m^3/d) from the Quaternary dune (Qd) aquifer. Transmissivity is estimated at approximately 60,400 ft^2/d (5,600 m^2/d) from specific capacity data. This is above the ideal range for ASR, so it will be important to determine if the aquifer boundaries can retain the injected water through the storage period.

Volumetric analysis indicates that both wells are using suitable aquifers to inject ½ of Brooking's surface water right for 120 days (Figure18-3). According to Brown's site rating system, Brookings has 36% of ideal conditions for ASR (Figure 18-4). The town lost points for well density greater than 5 wells per square mile, the presence of threatened fish species, high transmissivity and an aquifer thickness less than 25 ft (7.6 m). However, the existing treatment plant and water pipelines provide high quality water for storage, which is advantageous for ASR. The 4 to 22 ft (1.2 to 6.7 m) depth to water does not allow for much water level rise during injection. This water level rise could impact other wells in the area, or create new, undesirable springs.

Port Orford

Port Orford is situated south of the Elk River. The town currently has surface water rights to 3.25 cfs (7,953 m^3/d) from the Hubbard Creek (OWRD WRIS, accessed 2007), and a water treatment plant for municipal use. Wells owned by the city are shallow with relatively small capacities. Population increased from 1,025 to 1,164 between 1990 and 2006 (U.S. Census, 2006).

A domestic well (CURR 1684) was examined for ASR suitability, because is typical in depth, aquifer type and yield of wells in the area. It has open intervals from approximately 30 to 110 ft (9 to 34 m) below the surface, drawing water from a Cretaceous to Quaternary sandstone aquifer (Ks, Qt) (OWRD well log database, accessed 2007). Sandstone in this area is faulted and fractured, and these fractures are the main

flow paths for groundwater (Lissner, 1977). Transmissivity is estimated at 136 ft^2/d (13 m^2/d) from specific capacity data. This value falls below the ideal range of adequate transmissivity for ASR of 5,000 to 25,000 ft^2/d (465 to 2,323 m^2/d), and below any other ASR site found by this study.

Volumetric analysis (Figure 18-3) indicates the aquifer storage is insufficient to inject ½ the municipal water rights for 120 days. These results indicate this volume is at the high end of feasible injection rates at this site, and decreasing the rate will improve the volumetric results. Port Orford has 64% of ideal conditions for ASR according to Brown's site rating system, with a low score for transmissivity (Figure 18-4). AR may be feasible in Quaternary terrace deposits, although the aquifer's connection to the beach cliffs and small creeks may limit this possibility.

Bandon

Located at the mouth of the Coquille River, Bandon sits on Quaternary terrace deposits of the Oregon coast. The City of Bandon currently has surface water rights to 14 cfs (34,258 m^3/d) from Ferry Creek (OWRD WRIS, accessed 2007). Population increased from 2,215 to 2,900 between 1990 and 2006 (U.S. Census, 2006). No municipal well logs were located by this study, so two domestic wells were chosen to represent local hydrogeologic environments.

Domestic well Bandon-1 (COOS 51117) utilizes a Quaternary terrace deposit sandstone aquifer (Qt). Open intervals from depths of 30 to 95 ft (9 to 29 m) below the surface yield 47.5 gpm (259 m^3/d; OWRD well log database, 2007). Transmissivity estimated from specific capacity is 1,700 ft^2/d (160 m^2/d), which is below the ideal range for ASR, although it is similar to transmissivity of a sand and sandstone aquifer used in Denver, Colorado for ASR.

A second well, Bandon-2 (COOS 3921), draws water from a deeper interval in the sandstone aquifer and yields 37 gpm (202 m^3/d). Transmissivity estimated from specific capacity is 1,664 ft^2/d (155 m^2/d). This is below the ideal range for ASR.

Volumetric analysis indicates the aquifer storage is insufficient to inject ½ of the water treatment plant capacity for 120 days at both wells (Figure 18-3). Decreasing the

injection rate will improve volumetric results. Brown's site rating system finds both wells have 57% of optimal ASR parameters (Figure 18-4). The Bandon sites lost points for low transmissivity and the presence of threatened fish species. AR is not likely to succeed in this area.

Coos Bay

The town of Coos Bay sits on the southwest shore of Coos Bay near the mouth of the Coos River. Like most coastal towns in Oregon, the city experiences a population boom in the summer tourism months, which coincides with the driest portion of the year. The Coos Bay-North Bend Water Board jointly manages water treatment and distributions for the neighboring communities. The shared water treatment facilities currently have an 8 MGD (30,280 m^3/d) capacity. The population of Coos Bay increased from 15,076 residents in 1990 to 16,000 in 2006 (U.S. Census, 2006).

Municipal well Coos Bay-1 (COOS 1960) is part of the Quaternary dune (Qd) well field owned by the Coos Bay-North Bend Water Board. This well has open intervals from depths of 56 to 104 ft (17 to 32 m) below the surface and a well yield of 500 gpm (2,725 m^3/d; OWRD well log database, 2007). Transmissivity estimated from the well's specific capacity is 9,200 ft^2/d (900 m^2/d). This is within the target range of 5,000 to 25,000 ft^2/d (465 to 2,323 m^2/d) for ASR.

An industrial well Coos Bay-2 (COOS 2424) was also examined for ASR suitability. The well is open to a similar sandstone aquifer from the depth of 12 to 107 ft (3.6 to 33 m) below the surface, and yields 50 gpm (273 m^3/d). Transmissivity estimated from specific capacity is similar to the water board's well, at 9,840 ft^2/d (914 m^2/d).

Volumetric results indicate the aquifer storage is sufficient to inject 4 MGD (25,240 m^3/d) for 120 days (Figure 18-3). According to Brown's site rating system, Coos Bay has 71% of optimal ASR parameters (Figure 18-4). The site lost points for the presence of threatened fish species. AR may also be feasible in this area in the shallow surficial sand and gravel aquifers, depending on local vertical permeability and water quality.

North Bend

North Bend is located just north of the town of Coos Bay. The community shares the same surface water sources. Population in North Bend grew from 9,614 to 9,846 between 1990 and 2006 (U.S. Census, 2006). No municipal well logs were located by this study that provided sufficient information for ASR suitability analysis, so a similar domestic well was selected.

A domestic well (COOS 2350) draws water from Quaternary terrace sand and clay (Qt) at depths of 68 to 110 ft (21 to 34 m) below the surface. Well yield is 15 gpm (82 m^3/d) OWRD well log database, 2007). Transmissivity estimated from the well's specific capacity is 1,500 ft^2/d (140 m^2/d). This is below the ideal range for ASR, although it is similar to conditions found in Denver, Colorado where ASR has succeeded. This indicates that if all other conditions are favorable, the site may be suitable for ASR.

Volumetric analysis indicates the aquifer storage is sufficient to inject 4 MGD (15,140 m^3/d) for 120 days (Figure 16-3). Brown's site rating system finds North Bend has 57% of optimal ASR parameters (Figure 16-4). The site lost points for the presence of threatened species that may suffer from a decrease in river flow and low transmissivity. AR may be feasible in this area, depending on whether the water infiltrated into the aquifer will discharge into the nearby bay before it can be recovered for municipal use.

CHAPTER 19
UMATILLA BASIN

Basin Hydrology

The Umatilla administrative Basin covers approximately 4,503 mi^2 (11,663 km^2) and is drained by the Umatilla and Walla Walla Rivers, and Butter, Willow and Birch Creeks. Watershed divides delineating the basin are found in highlands to the south and to the north at the Columbia River. The northeastern corner of the basin is bounded by the Washington-Oregon border, not a hydrological boundary.

The climate is high desert. Average precipitation for the entire basin ranges from approximately 6.8 in (172 mm) per year at the northern end of the basin to 13.3 in (338 mm) at Pilot Rock. Precipitation in the higher elevations exceeds 30 in (762 mm) annually (Oregon Climate Service, 2007). The majority of groundwater recharge for the basin occurs in the Blue Mountains (Vaccarro, 1995).

Physical Setting

The Umatilla Basin is characterized by high desert of the Columbia Plateau, transitioning into more humid, forested mountains to the east and south. The basin is part of a synclinal trough extending from the Columbia Hills in Washington south to the Blue Mountains in Oregon. The southern high topographic boundary of the basin is the Blue Mountain Anticline, which continues to the northeast and to the southwest (Hogeson, 1964). Topographic features of the Umatilla basin are shown in Figure 19-1.

Groundwater Restricted Areas (Figure 19-1) in the Umatilla Basin are administrative regions designated by OWRD because they are experiencing long-term water level declines. Further allocation within these areas is currently suspended, and some existing water rights have been limited to protect the resource.

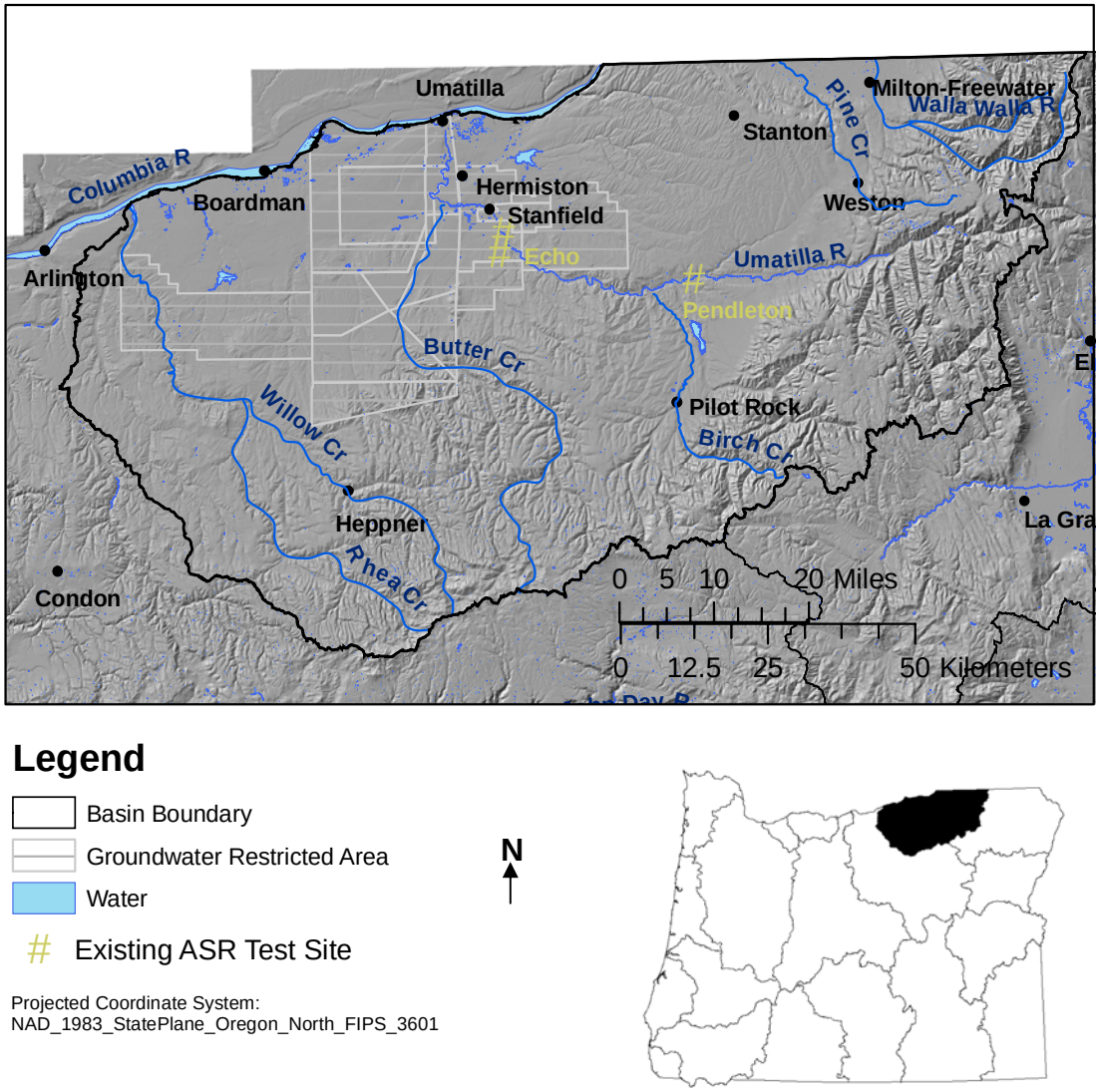


Figure 19-1. Umatilla Basin location map. Location of topographic features, rivers and towns that are examined in this study (Data sources: Wright, 2006; Oregon Geospatial Data Clearinghouse, 2006).

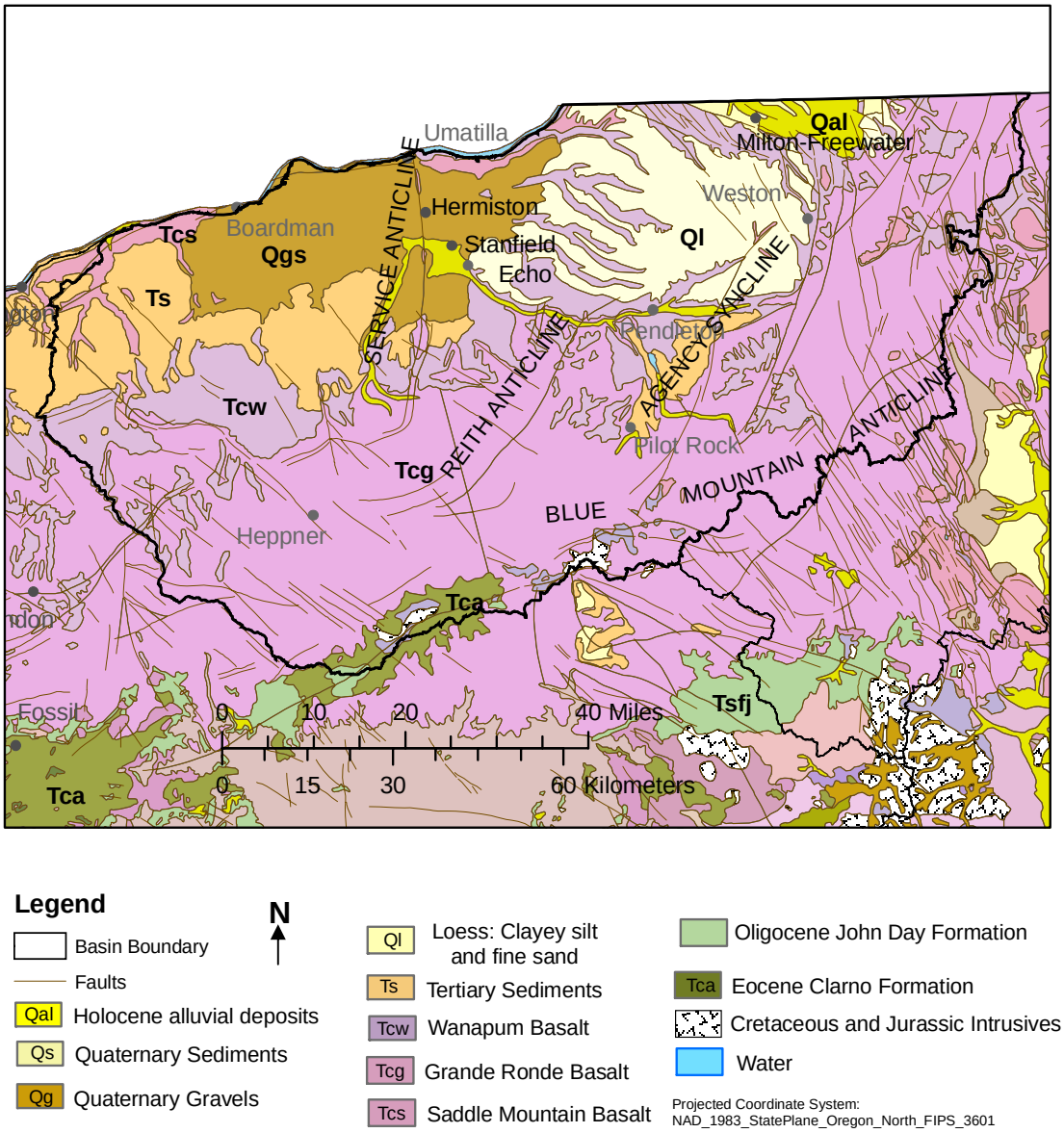


Figure 19-2. Umatilla Basin geology map. Geologic formations of importance to future ASR include Columbia River Basalt and Quaternary sediments (Data sources: Walker and McLeod, 1991; Oregon Geospatial Data Clearinghouse, 2006).

Hydrogeologic Units

Major geologic units in the basin, from oldest to youngest include the Columbia River Basalt Group, Pleistocene flood deposits, and Holocene alluvium. Geologic units (Figure 19-2) are discussed in detail in the following section.

Columbia River Basalt

Miocene Columbia River Basalt flows (Tcg, Tcw) cover most of the Umatilla Basin as Grande Ronde Basalt (Tcg, 15.6-16.8 Ma) and Wanapum Basalt (Tcw, 14.5-15.2 Ma) (Beeson and Moran, 1979). This unit appears from the Columbia River south to the range front of the Blue Mountains. Massive flows are separated by permeable interflow zones, which are an important groundwater source throughout the basin. Total thickness of the basalt may exceed 10,000 ft near the Columbia River, decreasing in thickness to the south (Wozniak, 1995). Hydraulic conductivity in the Columbia Plateau varies from 0.005 to 6,100 ft/d (0.001 to 1,859 m/d) with a median value of 5 ft/d (1.5 m/d; Whiteman et al., 1994); well specific capacity in this unit is 4 to 10 gpm/ft (72 to 179 m^2/d); transmissivity is estimated from 1,000 to 10,000 ft^2/d (304 to 3,048 m^2/d) (Gonthier, 1985). Pendleton, Oregon has an ASR test project that utilizes Columbia River Basalt for storage. Given appropriate local transmissivity and source water availability, this unit has potential for ASR use.

Pleistocene Flood Deposits

Pleistocene Missoula Flood Deposits (Qgs) appear in the lowlands of the Umatilla Basin, and constitute the major unconsolidated aquifer in the basin. Distribution is controlled by historic flood water elevation, which had a maximum of 1,150 ft (350 m) above sea level (Hogenson, 1964). Depending on the flood water's speed or degree of ponding, deposits range from coarse-grained sands to fine-grained sands and clays. Coarse-grained deposits are found throughout the basin at elevations less than 750 ft (229 m) with thickness up to 200 ft (61 m); fine-grained deposits are found at elevations between 750 ft (229 m) and 1,150 ft (350 m), and below 750 ft they underlie coarse-grained deposits. Thickness ranges up to 200 ft (61 m;Wozniak,1995).

Holocene Alluvium

Erosion of uplands, glacial deposits and alluvial activity created the Holocene Alluvium (Qal) found in the Umatilla River and Butter Creek valleys. These sediments are generally thin deposits of reworked flood deposits, loessal soils and basaltic gravels transported through stream drainages (Wozniak, 1995). Sedimentary deposits overlie Pleistocene flood deposit aquifers throughout the basin, but are not generally considered important aquifer sources. AR projects in the Walla Walla basin are successful in this aquifer (Bower, personal communication 2006).

Tectonic Structure Influencing Groundwater Flow

Major tectonic structures of the Umatilla Basin include anticlines and synclines which are the southern portion of the Yakima Fold belt. The Dalles-Umatilla westward plunging syncline forms the basin's topographic low between Umatilla and Arlington (Newcomb, 1969). The Horse Heaven Anticline in Washington and the northeast trending Blue Mountain Anticline to the south form the topographic highs. These large-scale structures affect Columbia River Basalt aquifer flow patterns, forcing water to flow away from uplands (Newcomb, 1969). Smaller, north-south trending folds of the Service and Reith Anticlines and the Agency Syncline are cut by the Umatilla River.

Faulting is centered in the eastern portion of the Basin, near the Blue Mountain Anticline. It is largely strike slip faulting with minor displacements in the north-south direction. There are also many feeder-dike complexes in the southeastern area which affect groundwater flow because they are roughly vertical or steeply dipping, and they crosscut older basalt flows (Whiteman et al., 1994). The low permeability of these dikes causes them to act as groundwater barriers.

Future ASR projects will require careful site specific evaluation to determine where faults and dikes may truncate storage zones or create hydraulic connection to other aquifers.

ASR Assessment

The purpose of this section is to provide a general assessment of specific locations for their potential to employ ASR as a part of water supply systems. Site specific investigation is essential to determine if a recharge project is technically, economically, and environmentally feasible. Positive results from this study indicate the site possesses many of the necessary components for successful aquifer recharge.

Table 19-1: Summary of Analysis Methods. For more detail, see Chapter 3: Analysis Methods.

Method	Description	Result of Method
Volumetric Analysis	Mathematical comparison of aquifer storage capability to the volume of surface water available	If > 1, sufficient storage If = 1 marginal storage If < 1, insufficient storage
Brown's Site Rating System	Site is rated from 0 to 2 for each criteria such as distance to source water, water quality, groundwater flow rate, aquifer thickness	Produces % of ideal ASR parameters at a given site

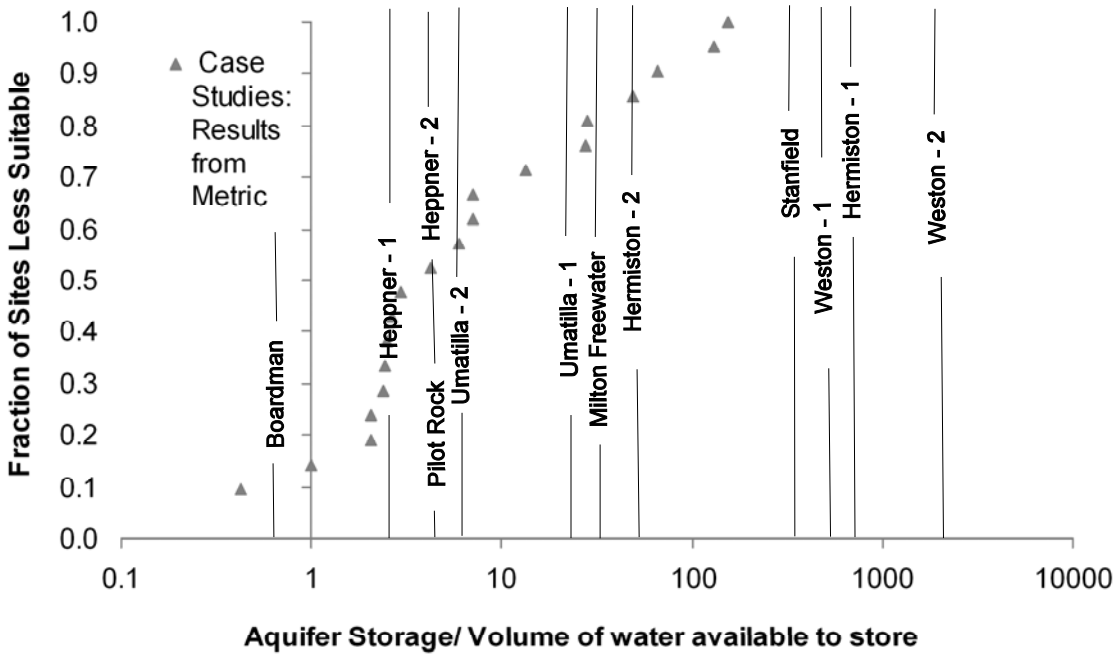


Figure 19-3: Umatilla Basin ASR metric results. Aquifer storage is sufficient for ASR, except at Boardman. Data listed in Appendix B.

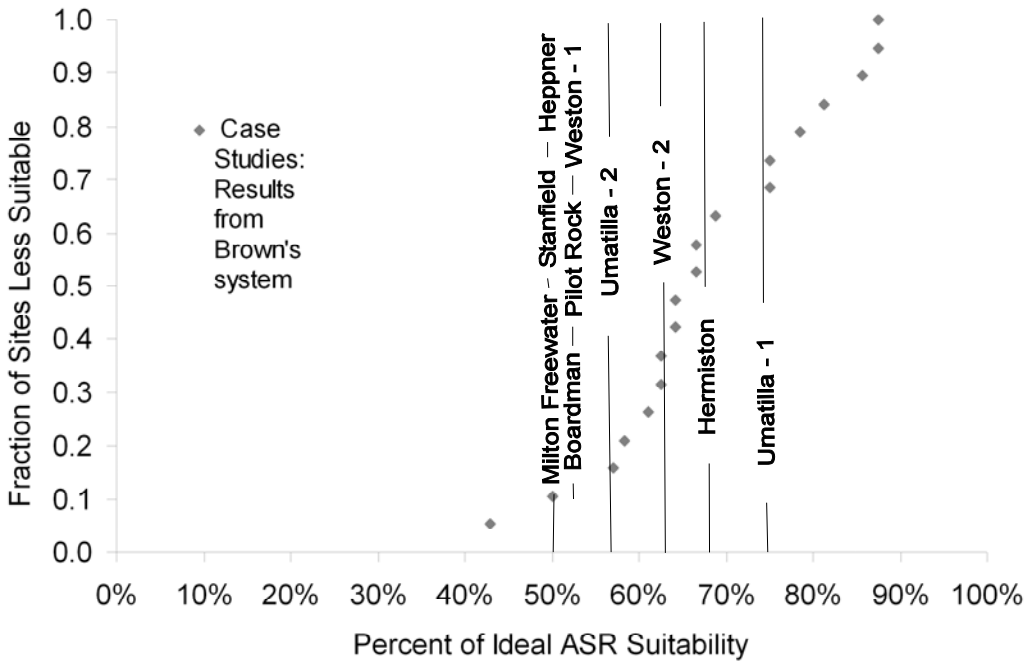


Figure 19-4: Umatilla Basin Brown's rating system results indicate that Umatilla Basin sites have from 50 % to 75% of ideal conditions. 30% of case studies' results are greater than the range of results for this basin. Data listed in Appendix C.

Umatilla

Umatilla is located at the northern border of the Basin, where the Umatilla joins the Columbia River. While Umatilla groundwater levels have not shown significant decline in the past decade (OWRD groundwater level database, accessed 2007), groundwater in some gravel and basalt aquifers of the basin has experienced serious declines in the last 50 years. The City of Umatilla has water rights to 23 cfs (56,281 m^3/d) of water from the Columbia River. Population in the City of Umatilla increased from 3,046 in 1990 to 6,306 in 2004 (U.S Census, 2004). Additional, expected growth will increase water demand in the future.

Umatilla's municipal wells (Umatilla-1, UMAT 3361 and Umatilla-2, UMAT 3347) are screened at depths ranging from approximately 500 to 1100 ft (152 to 335 m) below the surface, drawing water from Columbia River Basalt aquifers (Tcw, Tcs). These wells have yields ranging from 1,245 to 2,500 gpm (6,785 to 13,625 m^3/d; OWRD

well log database, 2007). Transmissivity in the basalts is estimated at 2,800 to 5,550 ft^2/day (260 to 500 m^2/day) from specific capacity data.

Volumetric analysis aquifer storage is sufficient to inject ½ the surface water right for 120 days. (Figure 19-3). According to Brown's site rating system, Umatilla has 56 to 75% of ideal conditions for ASR, with low scores for transmissivity and hydraulic gradient at the less suitable well (Figure 19-4).

There is potential for AR through surface spreading in the Umatilla area due to the low relief topography; infiltrated water should not flow away too quickly to be recovered at the same location. AR projects by the County Line Water Improvement District, the Butter Creek AR project and Echo Meadows Winter AR Project have been authorized. The County Line project has been operating since 1976, using a leaky canal to recharge the alluvial aquifer. The purpose is both to recharge the aquifer for irrigation and dilute or flush nitrate from the aquifer (Oregon Department of Environmental Quality, 2006). The longevity of this project indicates suitable aquifer permeability in the alluvial aquifer for AR.

Hermiston

Hermiston is located approximately 1 mi (1.6 km) east of the Umatilla River. The city has surface water rights to a total of 7 cfs (17,129 m^3/d) from springs that are tributaries to the Umatilla River. Population has increased from 13,154 in 2000 to 14,657 in 2005 (U.S Census, 2006), while groundwater levels have shown some decline in municipal wells. Municipal well UMAT 2061 is also an OWRD observation well, and records show that between 1995 to 2005, depth to water increased from 60 to 90 ft (18 to 27.4 m) below the surface (OWRD groundwater level database, 2007). These factors suggest an increasing pressure on limited water supplies, as well as available storage in the aquifer due to water-level decline.

Municipal wells Hermiston-2 (UMAT 2061) and Hermiston-1 (UMAT 5450) have open intervals from approximately 310 to 1500 ft (94 to 457 m) below the surface. Both wells access Columbia River Basalt interflow zone aquifers (Tcw). Both wells yield 2,500 gpm (13,625 m^3/d; OWRD well log database, 2007). Transmissivity in the

basalts is estimated by this study as 5,300 to 17,600 ft^2/day (490 to 1,600 m^2/day) from specific capacity data. These values are within the ideal range of 5,000 to 25,000 ft^2/day (465 to 2,323 m^2/d) for ASR.

Volumetric analysis indicates aquifer storage is sufficient to inject ½ the city's surface water rights for 120 days (Figure 19-3). The drop in water level over the past 10 years has created additional storage in the aquifer for ASR. According to Brown's site rating system, Hermiston has 69% of optimal ASR parameters (Figure 19-4). The site received low scores for a hydraulic gradient greater than 0.001 and proximity to source water greater than 1 mile (1.6 km).

Heppner

Heppner is located in the southern Umatilla Basin, on Willow Creek. The city has surface water rights to a total of 16 cfs (39,152 m^3/d) from the Columbia River, Heppner Creek, and East Fork Willow Creek year round, as well as groundwater rights. Population has increased slightly from 1,412 in 1990 to 1,438 in 2004 (U.S. Census, 2004), while groundwater levels have shown some decline in municipal wells. Depth to water in 1964 was 0 ft; in 1980 it was 35 ft (11 m) (OWRD groundwater level database, 2007). These factors suggest available storage in the aquifer due to water-level decline.

Municipal wells (Heppner-1, MORR 304 and Heppner-2, MORR 1750) have open intervals from approximately 30 to 200 ft (10 to 61 m) below the surface; they access Columbia River Basalt interflow zone aquifers (Tcg, Tcw). Well yields range from 350 to 460 gpm (1,908 to 2,507 m^3/d; OWRD well log data). Transmissivity is estimated by this study as 2,200 to 2,400 ft^2/day (200 to 220 m^2/day) from specific capacity data. This is below the optimal range of 5,000 to 25,000 ft^2/day (465 to 2,323 m^2/d).

Volumetric analysis indicates the aquifer storage is sufficient to inject ½ the city's surface water rights (Figure 19-3). According to Brown's site rating system, Heppner has 50% of optimal ASR parameters with low scores for transmissivity and groundwater gradient (Figure 19-4).

Boardman

The City of Boardman is located west of Umatilla on the south bank the Columbia River. Boardman has water rights to 36 cfs (88,092 m^3/d) from the Columbia River. Population increased from 1,387 to 3,051 between 1990 and 2004 (U.S. Census, 2004)

A municipal well (MORR 745) taps Columbia River Basalt interflow zones (Tcs), yielding 490 gpm (2,671 m^3/d; OWRD well log database, 2007). Estimated transmissivity from specific capacity is 1,600 ft^2/d (150 m^2/day). This is higher that Tigard's 900 ft^2/d (81 m^2/day) (Golder Associates, 2001) and Baker City's 1,000 ft^2/d (90 m^2/day) (Groundwater Solutions, 2003a). This suggests ASR may be feasible in these basalt layers based on transmissivity, despite falling below the optimal 5,000 to 25,000 ft^2/d (465 to 2,323 m^2/d) range set forth by Brown et al.(2005).

Volumetric analysis of this site indicates the aquifer storage is sufficient to inject ½ of the city's surface water rights for 120 days (Figure 19-3). Brown's site rating system finds Boardman has 50% of optimal ASR parameters, with low scores for transmissivity and hydraulic gradient (Figure 19-4). AR may be feasible in surficial gravel aquifers; it would also avoid the expense of installing a water treatment plant for an ASR project, if water quality is sufficient to meet AR needs.

Pilot Rock

Pilot Rock is located about 19 mi (31 km) south of Pendleton on Birch Creek. The population is relatively stable with 1,478 residents in 1990 increasing to 1,525 in 2004 (U.S. Census, 2004). Pilot Rock has water rights to a 3.2 cfs (7,830 $m^{3/}$d) from Birch Creek. Groundwater levels have fallen in the past decade; depth to water in 1995 was 0 ft, in 2005 it was 20 ft (6 m) (OWRD groundwater level database, 2007).

A municipal well (UMAT 89) has open intervals from 100 to 486 ft below the surface (30 to 148 m); water-bearing layers are reported to be Columbia River Basalts (Tcg) with a yield of 450 gpm (2,453 m^3/d; OWRD well log database, 2007). Transmissivity estimated from specific capacity for the municipal well is 2,000 ft^2/day (190 m^2/day). This is higher that Tigard's 870 ft^2/d (81 m^2/day; Golder Associates,

2001) and Baker City's 1,000 ft^2/d (90 m^2/day; Groundwater Solutions, 2003a), suggesting ASR may be feasible in these basalt layers.

Volumetric analysis indicates the Columbia River Basalt aquifer has sufficient storage to inject ½ of the city surface water right for 120 days (Figure 19-3). Brown's site rating system finds Pilot Rock contains 50% of optimal ASR parameters, with low scores for transmissivity and hydraulic gradient (Figure 19-4). AR may be possible in surficial sediments, if infiltration rates are appropriate in nearby alluvial deposits.

Weston

The City of Weston is located 45 mi (71 km) east of Umatilla. Weston has water rights to 0.2 cfs (489 m^3/d) from Pine Creek. The population is relatively stable, increasing from 606 to 714 between 1990 and 2004 (U.S. Census, 2004). Two municipal wells were selected to represent the local hydrogeologic environment.

Municipal well Weston-1 (UMAT 3089) draws water from Columbia River Basalt interflow zones (Tcw), with a well yield of 450 gpm (2,453 m^3/d; OWRD well log database, 2006). Transmissivity estimated from specific capacity is 800 ft^2/d (80 m^2/day). This is below the ideal range for ASR, although other ASR sites in Oregon utilize aquifers with similar, less than ideal transmissivity.

Weston-2 (UMAT 3083) accesses Columbia River Basalt interflow zones, and yields from 300 gpm (1,635 m^3/d;OWRD well log database, 2007). Transmissivity estimated from well specific capacity is 8,900 ft^2/d (820 m^2/day). This is within the ideal range for ASR, suggesting ASR may be feasible in these basalt layers.

Volumetric analysis of this site indicates the aquifer storage is sufficient to inject ½ of the city's surface water rights at both wells (Figure 19-3). It should be noted the city has a small surface water right of 0.2 cfs (489 m^3/d), which creates a relationship of a large amount of storage compared to the available water injection rate. Brown's site rating system finds Weston has 50 to 63% of optimal ASR parameters, with low scores for transmissivity and hydraulic gradient (Figure 19-4). AR could recharge surficial gravel aquifers given adequate vertical permeability; it would also avoid the expense of installing a water treatment plant for an ASR project.

Milton-Freewater

Located on the Walla Walla River, the town of Milton-Freewater currently has no surface water rights. However, there is 1 cfs (2,447 m^3/d) available for allocation in the winter months from the Walla Walla River (OWRD WRIS, accessed 2007). The population increased from 5,533 to 6,402 between 1990 and 2006 (U.S. Census, 2006). According to observation well data, water levels have dropped from 250 to 275 ft (76 to 84 m) below the surface between 1990 and 2005.

A well owned by the city of Milton-Freewater (UMAT 5065) was selected to examine the local Quaternary sand and gravel aquifer (Qal, Ql) for ASR suitability. It yields 45 gpm (245 m^3/d) and transmissivity estimated from specific capacity is 900 ft^2/d (84 m^2/d). This is below the ideal range of 5,000 to 25,000 ft^2/day (465 to 2,323 m^2/d) for ASR.

Volumetric analysis indicates aquifer storage is sufficient to inject ½ of the city's potential surface water rights for 120 days (Figure 19-3). According to Brown's site rating system, Milton-Freewater has 50% of ideal parameters for ASR, with low scores for low transmissivity and high well density (Figure 19-4).

Stanfield

Situated on the Umatilla River, the City of Stanfield has surface water rights to 11.5 cfs (28,141 m^3/d) from the river (OWRD WRIS, accessed 2007). The population increased from 1,568 to 1,966 between 1990 and 2006 (U.S. Census, 2006). Water levels are stable in the basalt aquifer, according to observation well data.

A large capacity municipal well (UMAT 2962) was selected to investigate the Columbia River Basalt's (Tcw) ASR suitability. It draws water from 156 to 1,161 ft (48 to 354 m) below the surface. Transmissivity estimated from specific capacity is 4,000 ft^2/d (380 m^2/d), which is slightly below the target range for ASR.

Volumetric analysis indicates the aquifer has sufficient storage to inject ½ of Stanfield's surface water right for 120 days (Figure 19-3). Brown's site rating system finds Stanfield has 50% of ideal parameters for ASR, with low scores for high well density and transmissivity below the target range (Figure 19-4).

CHAPTER 20
UMPQUA BASIN

Basin Hydrology

The Umpqua Basin covers approximately 4,660 mi^2 (12,070 km^2) of southwest Oregon. Watershed divides delineating the basin are found at the crest of the Cascade Range to the east, in the Coast Range to the northwest, and the Umpqua Mountains to the south. It is drained by the Umpqua River, which originates in the Cascades near Diamond Lake and meanders through the basin lowlands to the Pacific Ocean. Major tributaries include Cow Creek from the south and Calapooya Creek from the east.

The basin varies from alpine conditions in the Cascade Range to extremely moist rainforest-type conditions in the Coast Range. Average annual precipitation ranges from approximately 50 in (1,270 mm) at Diamond Lake, 34 in (860 mm) at Roseburg, to 80 in (2,030 mm) at Reedsport (Oregon Climate Service, 2007). Runoff from the Cascade and Coast Ranges feeds the rivers of the basin year round. Groundwater recharge rates are unknown at this time.

Physical Setting

The Umpqua Basin is located at the convergence of the Western and High Cascades, the Coast Range and the Klamath Mountain geologic provinces. Coast Range marine sedimentary and volcanic formations of Tertiary age extend from Reedsport east to Sutherlin. Older, Klamath Mountain province Jurassic and Cretaceous sedimentary and metamorphic units extend across the central basin. Granitic plutons displaying varying degrees of weathering are exposed near Myrtle Creek and Azalea. Western and High Cascades volcanics extend from Glide east to the basin boundary.

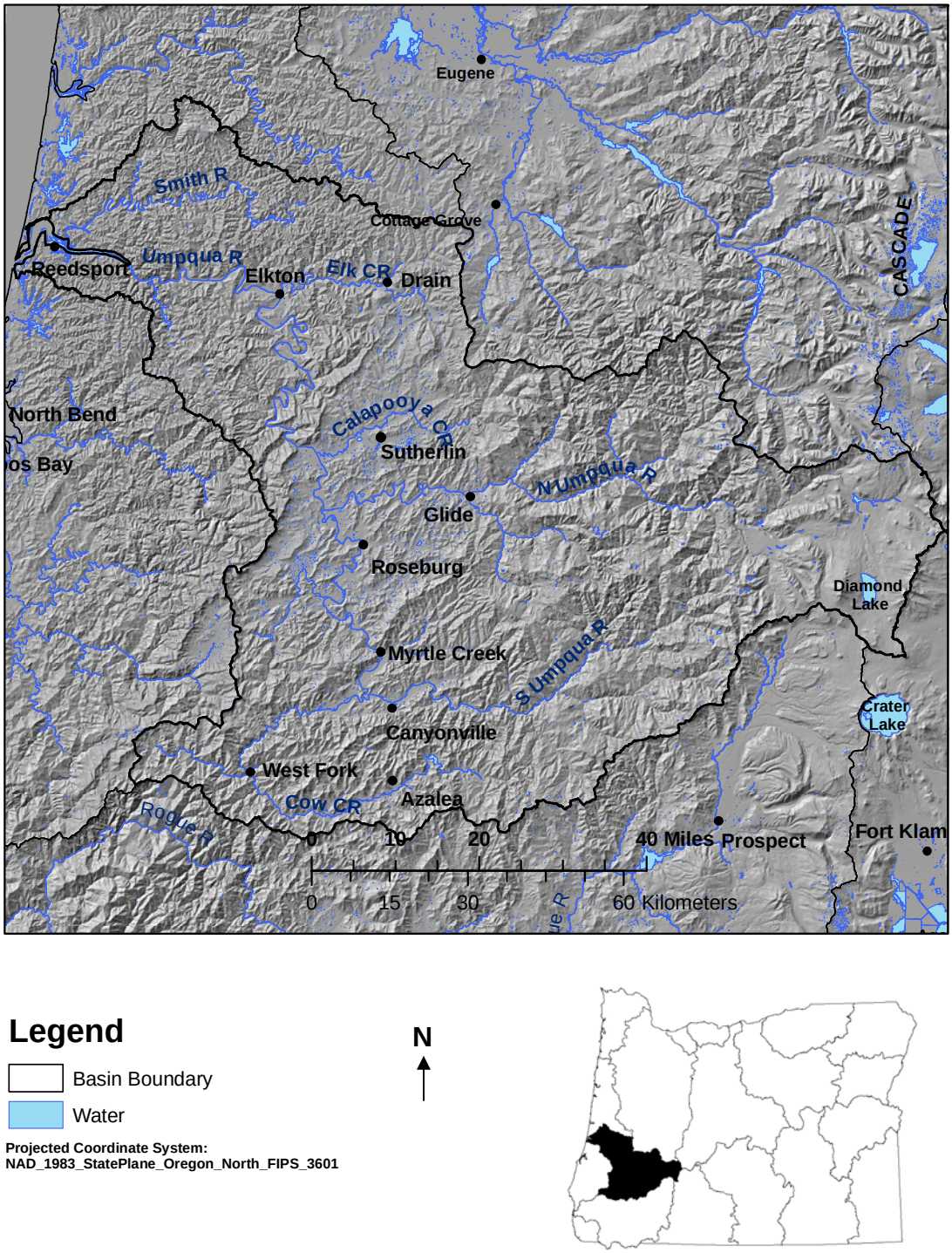


Figure 20-1. Umpqua Basin location map. Location of topographic features, rivers and towns that are examined in this study (Data sources: Wright, 2006; Oregon Geospatial Data Clearinghouse, 2006).

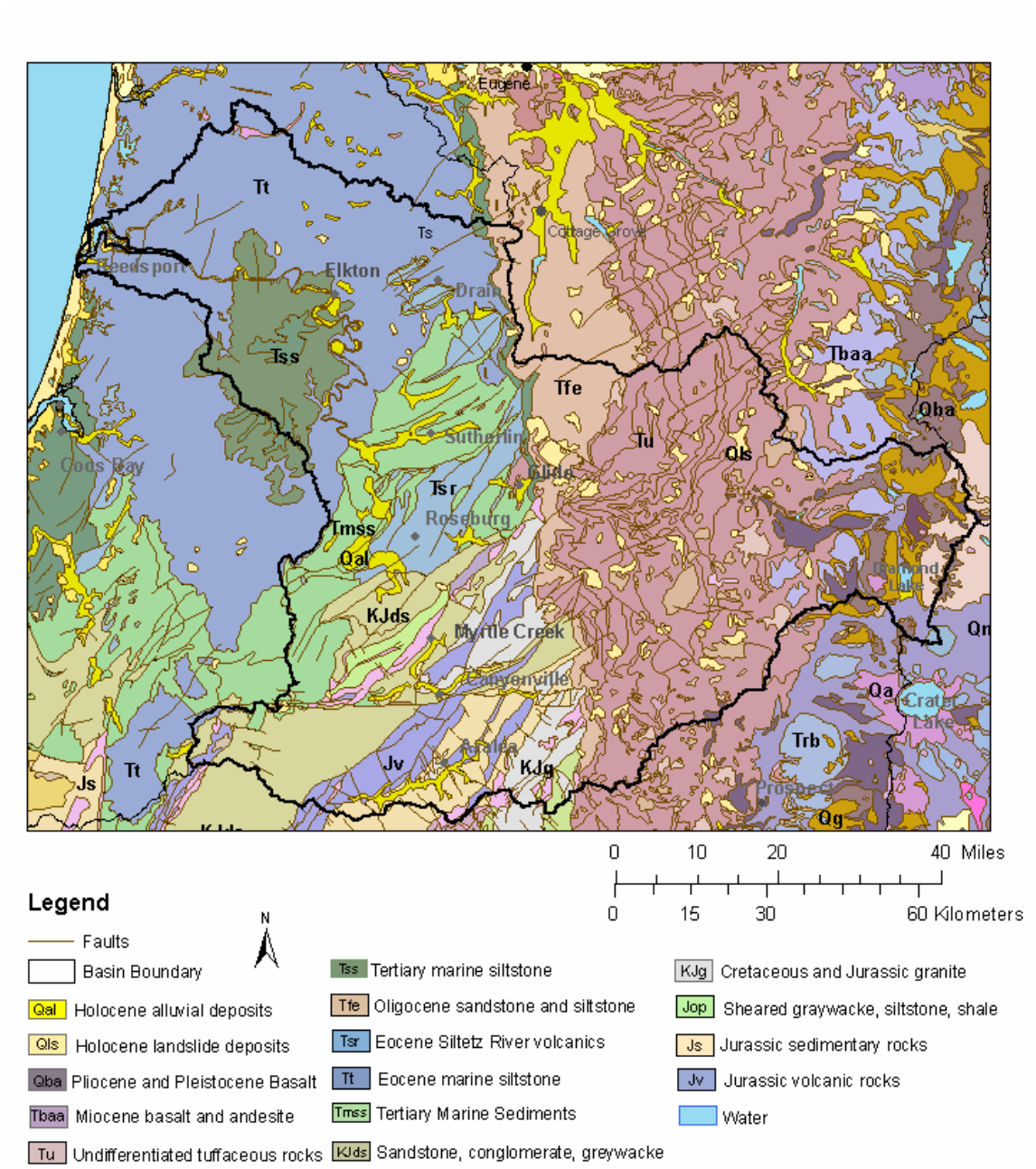


Figure 20-2. Umpqua Basin geology map. Geologic units of importance to future ASR include Quaternary sediments (Data sources: Walker and McLeod, 1991; Oregon Geospatial Data Clearinghouse, 2006).

Hydrogeologic Units

Major geologic units exposed in the basin, from oldest to youngest include Jurassic intrusive, metamorphic and sedimentary rocks, Cretaceous sedimentary rocks, Tertiary basalt and andesite, Tertiary tuffs, and Quaternary alluvial and landslide sediments. The complexity of the Umpqua Basin geology suggests a similarly intricate groundwater system, with local pockets of productive aquifers within generally unproductive aquifers. The units are (Figure 20-2) grouped and discussed in relation to ASR in the following sections.

Cretaceous and Jurassic units

The oldest rocks exposed in the Umpqua Basin are Jurassic marine sequences (Jv, Js), which include metamorphic, volcanic and sedimentary units. Metamorphic and sedimentary series (Jop, KJds) of shale, conglomerate, sandstone and greywacke extend in a northeast trending band west of Myrtle Creek. These units are generally of low permeability, and wells that access these layers produce yields that can support small domestic needs. ASR and AR are not likely in this series of rocks.

Granitic plutons (KJg) are exposed east of Myrtle Creek and Azalea. Water moves through secondary porosity features such as fractures and joints in this unit. The granitic intrusions are not likely to support ASR or AR, due to their low permeability, although local testing may reveal small, exceptionally permeable areas.

Western Cascade Volcanics

Oligocene through Miocene volcanics (Tbaa, Tu) of the Western Cascades are exposed in the headwaters of the Umpqua River, extending through the eastern third of the basin. These units generally have low permeability, hydraulic conductivity ranges from 0.1 to 10 ft/d (0.03 to 3 m/d; McFarland, 1983). The basalts, andesites and tuffs tend to have low yielding wells, and are not a likely target for ASR or AR.

Tertiary Marine Sediments

The Coast Range in this area is composed of Paleocene through Miocene marine sequences (Tss, Tsr, Tt, Tmss, Tfe). These units range from thinly to thickly bedded, and include micaceous and arkosic sandstone, volcanic air fall debris, deep sea fan deposits and marine basalts. The marine sediments range up to 15,000 ft (4,572 m^3/d) thick (McFarland, 1983). Wells in these units are capable of supplying domestic or livestock water, but are not widely used for large scale municipal or irrigation needs. They are unlikely to support ASR or AR for these reasons.

Quaternary Sediments

Erosion of the region by energetic rivers has transported and deposited the unconsolidated Holocene sediments (Qal) that fill narrow valleys of the basin. Quaternary alluvium units are widely accessed by shallow domestic and irrigation wells, and they represent the most productive aquifer in the basin. Hydraulic conductivity ranges from 20 to 600 ft/d (6 to 183 m/d) in the alluvial aquifers (McFarland, 1983). Unconfined alluvial aquifers may be useful for ASR or AR in areas with suitable transmissivity, source water quality and availability. Well density (the number of wells using the same aquifer that may be close enough to withdraw stored water) will need to be examined to evaluate the security of stored water, in addition to the aquifer's likelihood to discharge into surface water.

Holocene landslide activity in the steep hillsides that dominate the basin topography has produced pockets of poorly sorted sediments (Qls). Landslide deposits are not a likely storage unit, due to their location on steep hillsides.

Tectonic Structure Influencing Groundwater Flow

Broad tectonic structures in the Umpqua Basin include the Coast Range up-warp, where the marine sedimentary sequences have gradually buckled upward in response to the coastal subduction zone. This feature may affect groundwater recharge in the valleys, channeling infiltrated Coast Range precipitation down dip, toward inland lowlands and coastal valleys.

Faulting the in the central part of the basin may result in unpredictable groundwater flow patterns, especially between Azalea and Roseburg. Thin bands of Jurassic through Cretaceous age metamorphic and sedimentary rocks are truncated by thrust faults and secondary fractures. Faults and fractures may function as boundaries in some areas and provide preferential flow paths in other situations. Careful site specific investigation is important to determine if these structures will support or deter ASR or AR.

ASR Assessment

The purpose of this section is to provide a general assessment of specific locations for their potential to employ ASR as a part of water supply systems. Site specific investigation is essential to determine if a recharge project is technically, economically, and environmentally feasible, but positive results from this study indicate the site possesses many of the necessary components for successful ASR.

Table 20-1: Summary of Analysis Methods. For more detail, see Chapter 3: Analysis Methods.

Method	Description	Result of Method
Volumetric Analysis	Mathematical method that compares aquifer storage capability to the volume of surface water available for storage	If > 1, water will "fit" If = 1 water "barely fits" If < 1, water will not "fit"
Brown's Site Rating System	Site is rated from 0 to 2 for each criteria such as distance to source water, water quality, groundwater flow rate, aquifer thickness	Produces % of ideal ASR parameters at a given site

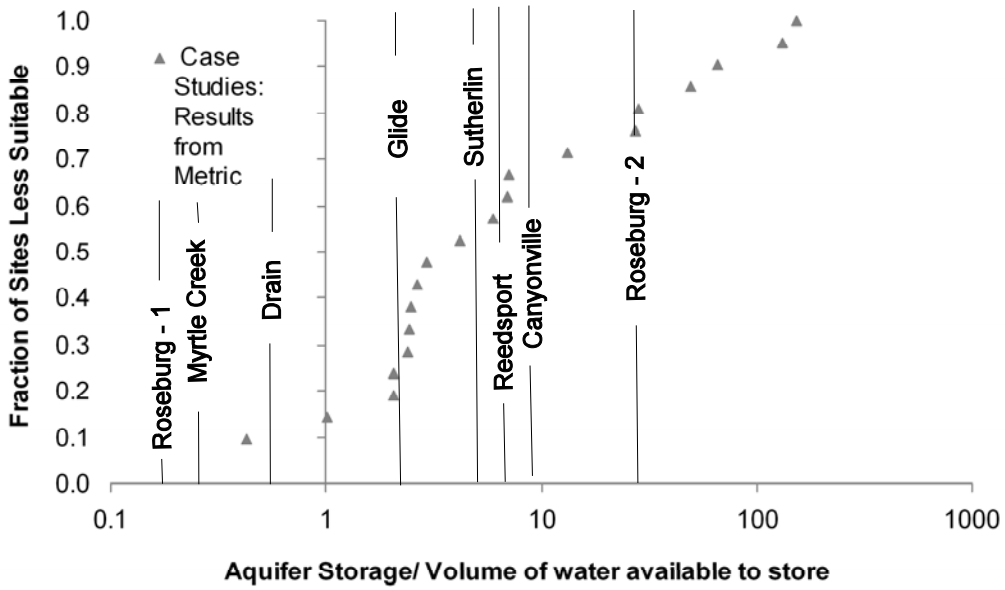


Figure 20-3: Umpqua Basin ASR metric results. Glide, Reedsport, Sutherlin, Canyonville and Roseburg-2 (basalt) have aquifer storage sufficient for ASR. Aquifer storage at Drain, Myrtle Creek and Roseburg-1 (sandstone) is not suitable for ASR. Data listed in Appendix B.

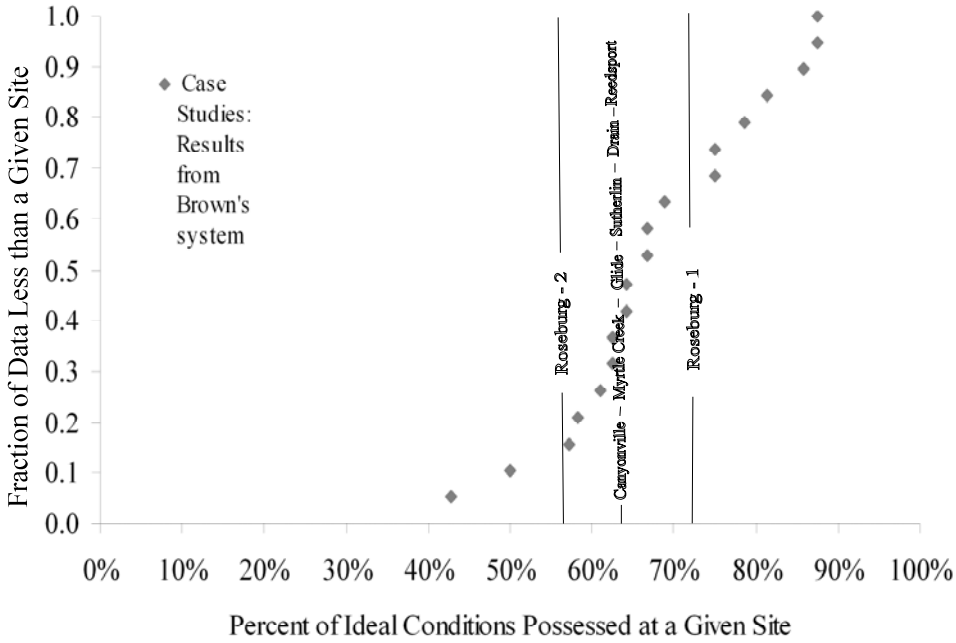


Figure 20-5: Umpqua Basin Brown's rating system results indicate Umpqua Basin sites have from 57 % to 71% of ideal conditions. 50% of case studies' results are within the same range as the results for this basin. Data listed in Appendix C.

Reedsport

Reedsport is the largest coastal town in the basin, situated on the Umpqua River. The population has decreased slightly, from 4,796 to 4,361 residents between 1994 and 2004 (U.S. Census, 2004). The city holds water rights to 35 cfs (85,645 m^3/d) from Clear Lake, which is the main source of municipal water.

A large capacity domestic well was selected to represent the local aquifer's suitability for ASR. It draws water from a Quaternary sand and gravel aquifer (Qal) from depths of 139 to 142 ft (42 to 43 m) below the surface, and yields 1,800 gpm (9,810 m^3/d; OWRD well log database, accessed 2007). Of all the wells examined in this basin, this one indicated the area of highest aquifer permeability. Transmissivity estimated from specific capacity is 23,200 ft^2/day (2,600 m^2/day), which is within the ideal range of 5,000 to 25,000 ft^2/day (465 to 2,323 m^2/d) for ASR.

Volumetric analysis indicates aquifer storage is sufficient to inject ½ of Reedsport's 35 MGD (132,475 m^3/d) treatment plant capacity for 120 days (Figure 20-3). The results from this analysis would improve if the rate of injection was decreased. According to Brown's site rating system, the town has 64% of ideal conditions for ASR (Figure 20-4). The site lost points for an aquifer thickness less than 25 ft (6.7 m), but otherwise scored well. Because the town is located on the Umpqua River, the largest barrier to ASR may be the discharge of stored water into surface water before it can be withdrawn for municipal use. This hydraulic connection between groundwater and surface water would have to be carefully examined.

Drain

Drain is a historic timber community situated on Elk Creek, east of its confluence with the main stem of the Umpqua River. The city currently has surface water rights to 5 cfs (12,235 m^3/d) from the Bear Creek Reservoir (OWRD WRIS, accessed 2007). Population is stable, increasing slightly from 1,011 to 1,039 between 1994 and 2004 (U.S. Census, 2004).

A low-yield well owned by the city was examined for ASR suitability. The well has open intervals from approximately 26 to 195 ft (8 to 60 m) below the surface,

drawing water from a Tertiary marine sandstone aquifer (Tt) (OWRD well log database, accessed 2007). Transmissivity is estimated at 130 ft^2/d (12 m^2/day) from specific capacity data. This value falls far below the ideal range of adequate transmissivity for ASR, and below that found at any known ASR sites. This indicates ASR may be not possible at this location.

Volumetric analysis (Figure 20-3) indicate the aquifer's available storage is insufficient to inject ½ the city's surface water rights for 120 days. Drain has 64% of ideal conditions for ASR according to Brown's site rating system, with a low score only on transmissivity (Figure 20-4). This may be misleading, because a high score on all the other factors will be negated by low aquifer transmissivity. AR is not likely in this area, because the surficial marine sediment geology has generally low vertical permeability (McFarland, 1983).

Sutherlin

Located in the north-central Umpqua Basin between the Cascades and the Coast Range, the historic logging town of Sutherlin sits south of Calapooya Creek. Low permeability Tertiary marine sediments underlie the town, which currently uses surface water for municipal supply. The City of Sutherlin has surface water rights to 4 cfs (9,788 m^3/d) from Calapooya Creek (OWRD WRIS, accessed 2007). Population increased from 5,020 to 7,281 between 1994 and 2004 (U.S. Census, 2004). No municipal wells were located by this study, so a domestic well was selected to represent the local geologic environment.

A domestic well (DOUG 4606) utilizes a Tertiary marine clay and sandstone aquifer (Tmss, Tt), and likely represents the marine sediment aquifer that extends through the valley. Open intervals from depths of 19 to 185 ft (6 to 56 m) below the surface yields 14 gpm (76 m^3/d; OWRD well log database, 2007). Transmissivity estimated from specific capacity is 200 ft^2/d (20 m^2/day). This is below the ideal range of 5,000 to 25,000 ft^2/d (465 to 2,323 m^2/d) for ASR, and below any known ASR site. This indicates the aquifer may be unsuitable for ASR.

Volumetric analysis indicates the aquifer has sufficient storage to inject ½ of the municipality's surface water right for 120 days (Figure 20-3). Brown's site rating system finds the site has 64% of optimal ASR parameters. Although the site scores well for most factors, the low transmissivity may negate other suitable parameters (Figure 20-4). AR is not likely to succeed in surficial marine sediment aquifers, although small alluvial aquifers along Calapooya Creek may be suitable depending on vertical permeability and hydraulic connection to surface water.

Roseburg

Roseburg is the largest community in the Umpqua Basin, located on the South Umpqua River. The city has surface water rights and a water treatment plant with a 12 MGD (45,420 m^3/d) capacity (City of Roseburg website, accessed July 2007). The population grew from 17,032 to 20,727 between 1994 and 2004 (U.S. Census, 2004). Municipal water is supplied from surface water, so domestic wells were selected to investigate the local hydrogeologic environment.

A domestic well Roseburg-1 (DOUG 6487) draws water from Tertiary marine sandstone and basalt (Tmss, Tsr) at depths of 19 to 150 ft (6 to 46 m) below the surface. The well yield at the time of installation was 120 gpm (654 m^3/d; OWRD well log database, 2007). Transmissivity estimated from the well's specific capacity is 1,000 ft^2/d (90 m^2/day). This is below the ideal range for ASR, although it is similar to the values found at Tigard, Oregon's basalt ASR site, which has a transmissivity of 870 ft^2/d (81 m^2/day; Golder Associates 2001).

A deeper domestic well, Roseburg-2 (DOUG 6679), was also examined. This well accesses Eocene marine basalt (Tsr) from 38 to 350 ft (12 to 107 m) below the surface, and yields 4 gpm (21.8 m^3/d; OWRD well log data, accessed July 2007). However, transmissivity estimated from specific capacity is 13,500 ft^2/d (1,250 m^2/day), which is much higher than the other Roseburg well because there was almost no drawdown in the well during the pump test. This value is within the ideal range for ASR, indicating a locally suitable area for ASR, given other appropriate parameters.

Volumetric analysis indicates aquifer storage is sufficient to inject ½ the treatment plant's capacity for 120 days at the deeper basalt well, Roseburg-2 (DOUG 6679). Storage is not sufficient at Roseburg-1 (DOUG 6487). The higher transmissivity at Roseburg-2 makes it more suitable for ASR (Figure 20-3). Brown's site rating system finds Roseburg has 57% of optimal ASR parameters at the shallow well, and 71% at the deeper basalt well (Figure 20-4). The sites lost points for the high well density, meaning that the water stored might be accessible to other wells that use the same geologic layer for water. AR may not be feasible in this area, due to generally low permeability of the marine volcanics that underlie the town.

Myrtle Creek

The town of Myrtle Creek is situated south of Roseburg, on the South Umpqua River. Originally founded during the gold rush of the 1940's, the town soon transformed into a timber community. Myrtle Creek has surface water rights to 20 cfs (48,940 m^3/d) from springs that are tributaries to the Umpqua River (OWRD WRIS, accessed 2007). Population increased from 3,063 to 3,528 between 1994 and 2004 (U.S. Census data, 2004).

The city of Myrtle Creek does not own municipal wells, so a domestic well was selected. A domestic well (DOUG 8475) draws water from Cretaceous and Jurassic granite (KJg) at depths from 17 to 100 ft (5 to 30 m) below the surface. When installed, the well yielded 1.5 gpm. Transmissivity estimated from specific capacity is 300 ft^2/d (30 m^2/day), which is below the ideal range for ASR. This value is also below any existing ASR site found by this study, which implies that Myrtle Creek may not be a likely site for ASR based on this parameter.

Volumetric analysis indicates aquifer storage is insufficient to inject at a rate of 1.5 cfs (3,671 m^3/d) for 120 days (Figure 20-3). Brown's site rating system finds Myrtle Creek has 64% of optimal ASR parameters (Figure 20-4). The site scored poorly for low transmissivity. Like other sites evaluated in this basin, the low transmissivity of the aquifer may negate other favorable parameters. AR may be feasible in surficial alluvial

aquifers, depending on vertical permeability and hydraulic connection to surface water, but the alluvial aquifer has limited extent in this area.

Canyonville

Located near the southern edge of the Umpqua Basin, the historic settlement of Canyonville sits at the confluence of Canyon Creek and the South Umpqua River. The town was a resting place for settlers moving in wagons north from Azalea, Oregon, and later served as a supply for gold miners and packers. The town currently has surface water rights to 3 cfs (7,341 m^3/d) from Canyon Creek (OWRD WRIS, accessed 2007), and domestic wells provide local water supply. Population decreased from 1,397 to 1,219 between 1994 and 2004 (U.S. Census, 2004). No municipal wells were located by this study.

A domestic well (DOUG 875) utilizes a decomposed Cretaceous and Jurassic granite aquifer (KJg), and most likely represents the local granite weathered to saprolite, which has a higher permeability than the surrounding, less decomposed granite (McFarland, 1983). Open intervals from depths of 57 to 97 ft (17 to 30 m) below the surface yields 5 gpm (27 m^3/d; OWRD well log database, 2007). Transmissivity estimated from specific capacity is 300 ft^2/d (30 m^2/day). This is far below the ideal range of 5,000 to 25,000 ft^2/d (465 to 2,323 m^2/d) for ASR, and indicates the aquifer may be unsuitable for ASR.

Volumetric analysis indicates the aquifer storage is sufficient to inject ½ of the municipality's surface water right for 120 days (Figure 20-3). Brown's site rating system finds Canyonville has 64% of optimal ASR parameters (Figure 20-4). Although the site scores well for most factors, the low transmissivity may negate other good results. AR is not likely to succeed in surficial marine sediment aquifers, although small alluvial aquifers along Canyon Creek may be suitable depending on vertical permeability, water quality, and hydraulic connection to surface water.

CHAPTER 21
WILLAMETTE BASIN

Basin Hydrology

The Willamette Basin covers approximately 11,470 mi^2 (29,707 km^2). It is drained by the Willamette River and its major tributaries: the Santiam, McKenzie and Middle Fork Willamette from the east; Coast Fork, Tualatin and Yamhill Rivers from the west. Watershed divides delineating the basin are found to the east at the crest of the High Cascades, to the west at the crest of the Coast Range and to the north at the Columbia River.

The basin transitions from alpine and dense evergreen forest conditions at the crest of the High Cascades to wet, mild conditions in the valley at the center of the basin. The Coast Range consists of densely forested, mountainous uplands. Elevation ranges from 96 to 400 ft (29 to 122 m) in the valley, up to 3,000 ft (914 m) in the Coast Range and up to 11,200 ft (3,413 m) in the High Cascades. Average groundwater recharge through infiltration for the entire basin is estimated to be 22 in (559 mm; Conlon et al., 2005). In the High Cascades of the eastern Willamette Basin, average annual precipitation exceeds 100 in (2,540 mm), largely as snow, while at lowland elevations precipitation averages about 45 in (1,140 mm) as rain (Woodward et al., 1998).

Physical Setting

The Willamette Basin ranges from steep alpine peaks to broad alluvial valleys (Figure 21-1). The eastern edge, incorporating the older Western Cascades and the younger High Cascades, constitutes the oldest part of the basin. The Cascades are formed of Miocene through Holocene basalt, andesite and tuffs. Surface and groundwater are recharged at this high point and flow west off the Cascades toward the Willamette River.

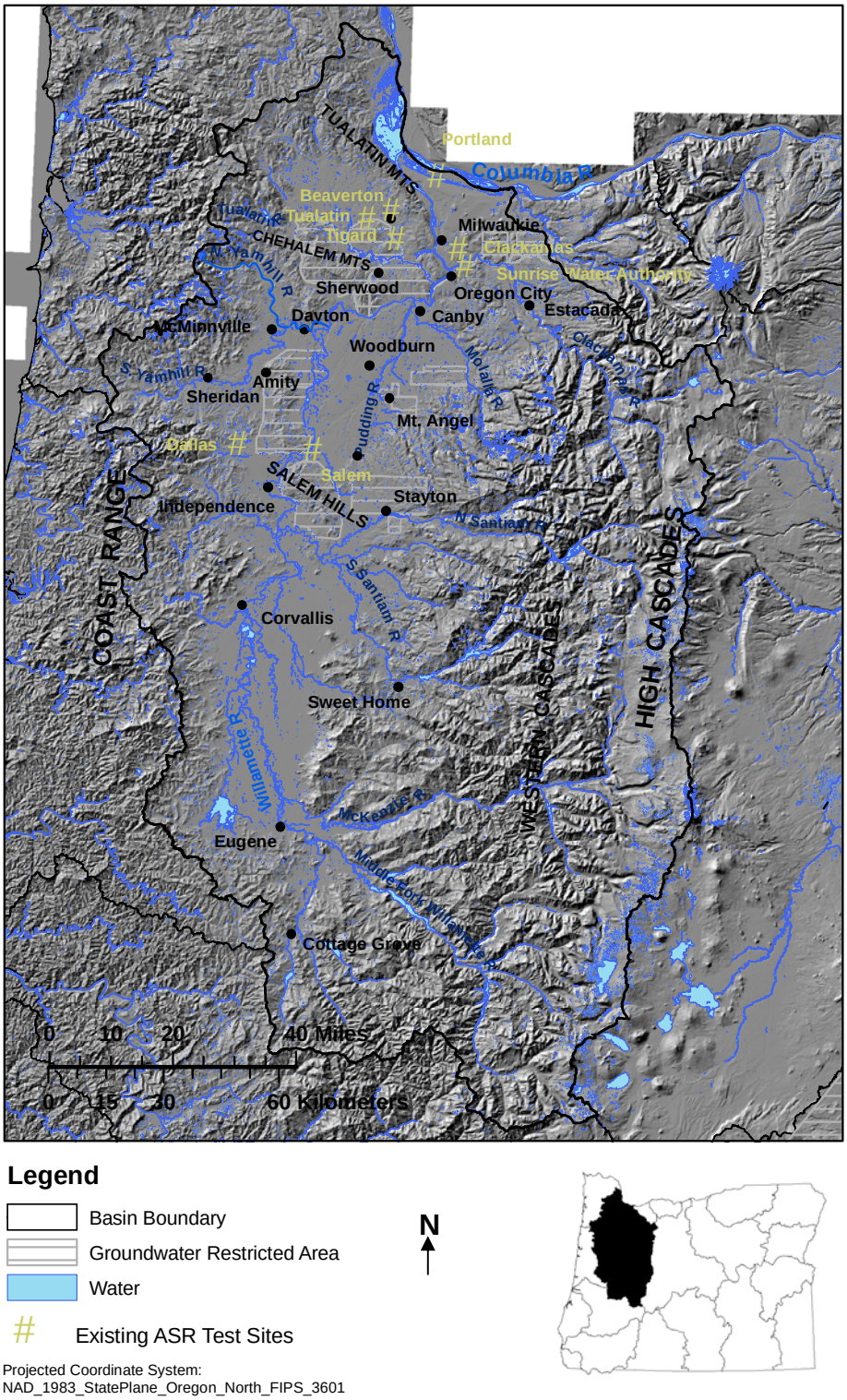


Figure 21-1. Willamette Basin location map. Location of topographic features that are examined in this study (Data sources: Wright, 2006; Oregon Geospatial Data Clearinghouse, 2006).

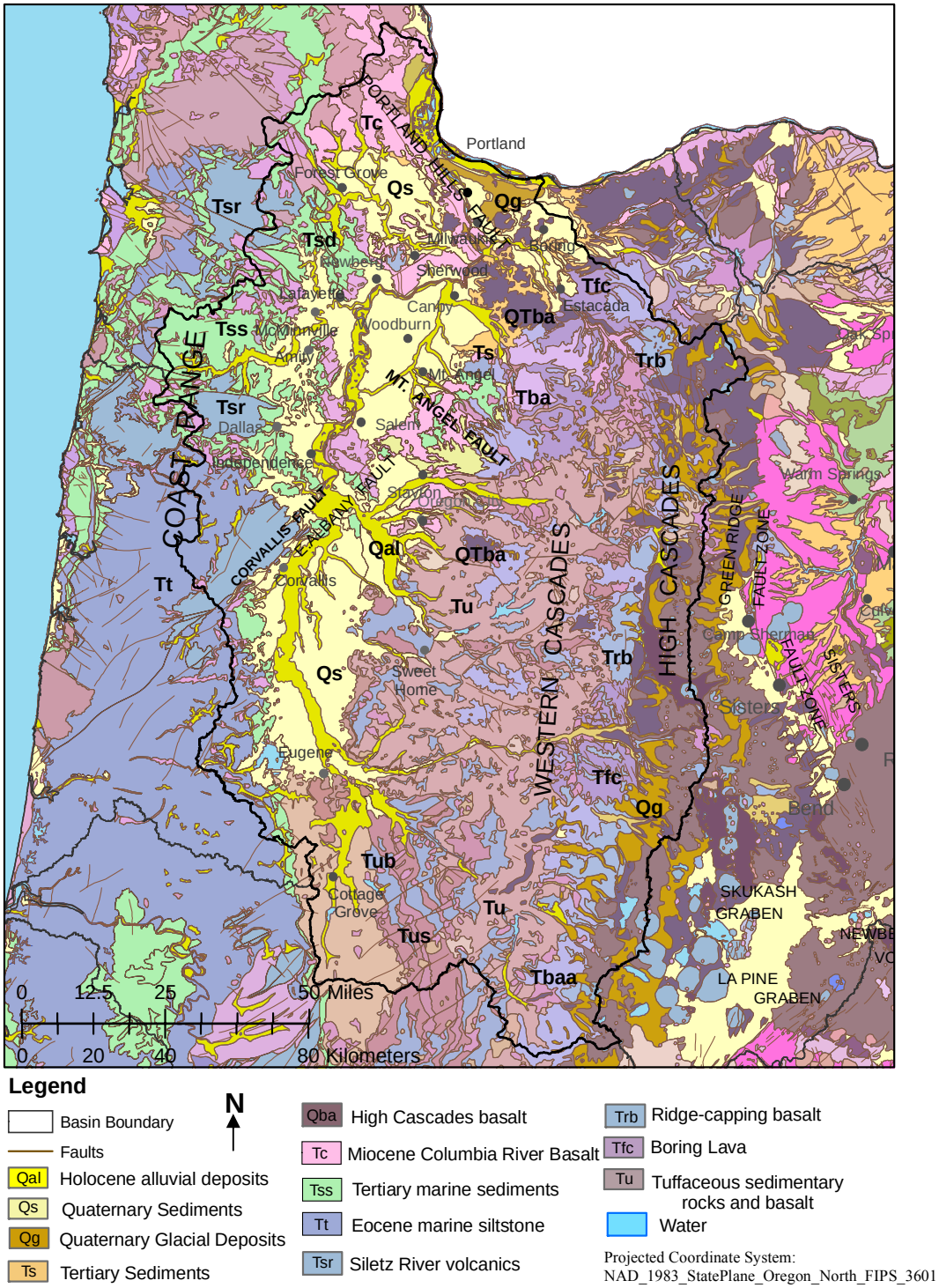


Figure 21-2. Willamette Basin geology map. Geologic formations of importance to future ASR include Columbia River Basalt and Quaternary sediments (Data source: Walker and McLeod, 1991; Oregon Geospatial Data Clearinghouse, 2006).

West of the Cascades lies the Willamette lowland, characterized by Quaternary alluvial and Pleistocene glacial flood deposits; they are underlain by Tertiary Columbia River Basalts from the Columbia River south to the Santiam River area, and basement confining units composed of Tertiary continental shelf marine sediments and Eocene volcanics. The western edge of the Willamette Basin is delineated by the north-south trending Coast Range. The Coast Range originated as a volcanic island arc, which collided with the North American plate during the early Eocene (Orr and Orr, 2000). Subduction induced volcanic activity through the Eocene was followed by uplift and erosion that continues to the present.

Groundwater Restricted Areas (Figure 21-1) are administrative regions designated by OWRD because they are experiencing long-term groundwater level declines. Further allocation within these areas is currently suspended, and some existing water rights have been limited to protect the resource.

Hydrogeologic Units

Geologic units (Figure 21-2) are discussed in relation to ASR and AR in the following section.

Tertiary Marine Sediments and Western Cascade Volcanics

Eocene through Oligocene marine sediments (Ts) and Oligocene through Miocene Western Cascade volcanics (Tu, Trb, Tfc, Tba) make up the basement confining unit throughout the Willamette Basin. From the Columbia River south to the Santiam River they are overlain by Columbia River Basalt (Tc), the Willamette confining unit, Willamette Aquifer, and Willamette Silt (Woodward et al. 1998). The Willamette units are included in the Quaternary sediments (Qs). This basement confining unit has a thickness ranging from 0 to greater than 10,000 ft (3,048 m); median hydraulic conductivity is estimated at 0.8 ft/d (0.24 m/d) and specific capacity ranges from 0.1 to 3 gpm/ft (1.8 to 54 m^2/d) (McFarland, 1983). Although marine sediments are locally important aquifers for domestic wells, this low permeability unit is generally unsuitable for ASR or AR projects.

Columbia River Basalt

The Columbia River Basalt Group (Tc) consists of layered basalt flows, averaging a few hundred feet thick and ranging up to 1,000 ft (305 m) thick. Basalt extends from the Columbia River to the North Santiam River. It is exposed in the Tualatin and Chehalem Mountains, the Salem Hills and north of the Stayton subbasin. Massive flows are separated by permeable interflow zone aquifers which are important groundwater sources throughout the northern and central Willamette Valley (Woodward et al., 1998). According to Conlon et al. (2005) the Columbia River Basalt's hydraulic conductivity ranges from 0.001 to 1,100 ft/d (0.0003 to 335 m/d); specific capacity ranges from 0.01 to 100 gpm/ft (0.2 to 1,793 m^2/d) (McFarland, 1983). The Columbia River Basalt is currently targeted for most ASR projects in Oregon, and so is of paramount interest to this study.

Quaternary Alluvium: Willamette Confining Unit

The Willamette confining unit (Qs) consists of fine-grained distal alluvial fan deposits of low permeability clay. It is 0 to 1,600 ft (0 to 488 m) thick in the Willamette Basin, extending from the Columbia River south throughout the lowlands of the basin (Conlon et al., 2005). It is exposed in the Tualatin subbasin and around the Willamette River near Newberg. Elsewhere in the basin it is overlain by Quaternary Willamette silt and alluvium. Hydraulic conductivity ranges from 0.01 to 90 ft/d (0.003 to 27 m/d) with a median estimate of 5 ft/d (1.5 m/d); specific capacity ranges from 7 to 40 gpm/ft (125 to 717 m^2/d) (Woodward et al., 1998). Low permeability indicates that although this aquifer may be of some importance locally, it is not the main aquifer of the region, nor is it a primary target for ASR or AR projects.

Quaternary Alluvium: Willamette Aquifer

Coarse-grained Quaternary alluvium (Qal, Qs) constitute the main Willamette aquifer, extending from the Columbia River floodplains south through the lowlands of the Willamette valley. This aquifer is semi-confined through most of the basin, overlain in some areas by the Willamette silt. Thickness ranges from 20 to 600 ft (6 to 183 m)

(Woodward et al., 1998). Hydraulic conductivities have a median value of 10 ft/d (3 m/d) in the Portland Basin and 19 ft/d (6 m/d) in the central Willamette Valley (Morgan and McFarland, 1996). Specific capacity for wells with open intervals in the Willamette Aquifer ranges from 40 to 300 gpm/ft (12 to 91 m^2/d) (Woodward et al., 1998). This aquifer may be suitable for surface spreading AR operations.

Quaternary Alluvium: Willamette Silt

Late Pleistocene glacial outburst floods deposited the Willamette silt unit (Qs), a fine-grained layer extending from the Molalla River south to Salem, through the Yamhill River floodplain, and from the South Santiam River southwest to the Long Tom River. It overlies the Willamette Aquifer. The Willamette Silt is thickest between the Molalla and Willamette Rivers, ranging from 20 to 120 feet (6 to 37 m). Hydraulic conductivity ranges from 0.01 to 8 ft/d (0.003 to 2.4 m/d; Conlon et al., 2005). The Willamette silt is an unconfined unit, and due to its low permeability is not a likely candidate for ASR or AR.

Tectonic Structure Influencing Groundwater Flow

Major tectonic structures of the Willamette Basin include dip-slip, strike-slip faults and compressional folds resulting in anticlines and synclines that form local groundwater divides and subbasins. Faults can potentially truncate aquifers by offsetting high permeability layers; it appears from previous studies in Tualatin that this has made some ASR projects infeasible (Groundwater Solutions, 2003b). Conversely, faults can also create hydraulic connection between previously unconnected aquifers. Dip-slip faults have displaced interflow zones in the Columbia River Basalt, disconnecting high permeability flow zones and limiting storage capacity. According to CH2M Hill (1997), faults have also created connection between previously confined aquifers and the surface.

The northwest trending Portland Hills fault zone appears northwest of Portland, continuing southeast toward Estacada and transitioning into the northwest trending Clackamas River lineament and the Brothers fault zone of the Deschutes Basin. Movement is primarily along strike-slip faults, and penetrates Tertiary basalt as well as

Quaternary alluvium. There is some indication of dip-slip movement, with a minimum offset of the Columbia River Basalt of 503 ft (50 m) in the Canby area (Blakely et al., 2001). The Mt. Angel fault runs parallel to the Portland Hills fault, extending from Woodburn through Mt. Angel (Yeats, et al., 1991). The central Willamette Basin is characterized by a series of north-south folds, with faults parallel to the anticlines, including the Corvallis and East Albany faults. The unconsolidated alluvial aquifers experience less hydraulic disconnection due to faulting when compared to basalt interflow zones, because flow within these aquifers is not limited to horizons as it is in the basalts.

ASR Assessment

The purpose of this section is to provide a general assessment of specific locations for their potential to employ ASR as a part of water supply systems. Site specific investigation is essential to determine if a recharge project is technically, economically, and environmentally feasible, but positive results from this study indicate the site possesses many of the necessary components for successful aquifer recharge.

Table 21-1: Summary of Analysis Methods. For more detail, see Chapter 3: Analysis Methods.

Method	Description	Result of Method
Volumetric Analysis	Mathematical comparison of aquifer storage capability to the volume of surface water available	If > 1, sufficient storage If = 1 marginal storage If < 1, insufficient storage
Brown's Site Rating System	Site is rated from 0 to 2 for each criteria such as distance to source water, water quality, groundwater flow rate, aquifer thickness	Produces % of ideal ASR parameters at a given site

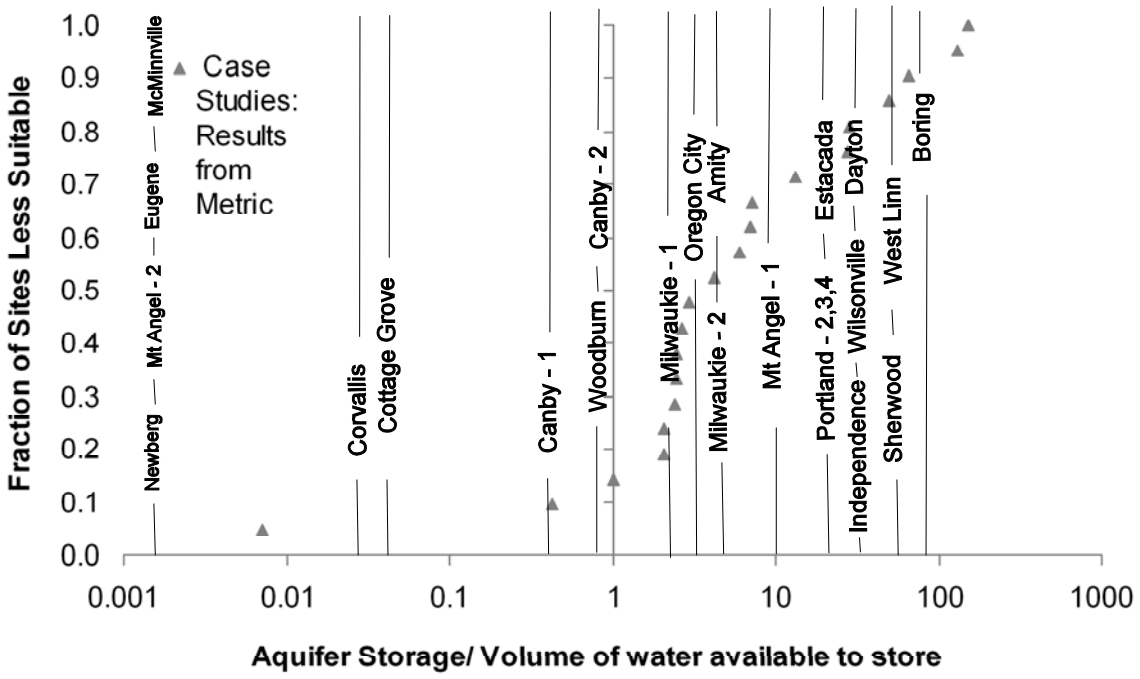


Figure 21-3. Willamette Basin ASR metric results. Newberg, Mt. Angel-2, Eugene, McMinnville, Corvallis, Cottage Grove, Canby-1, Woodburn and Canby-2 wells indicate aquifer storage is insufficient and therefore these sites are not suitable for ASR. Other selected sites are volumetrically suitable for ASR. Data listed in Appendix B.

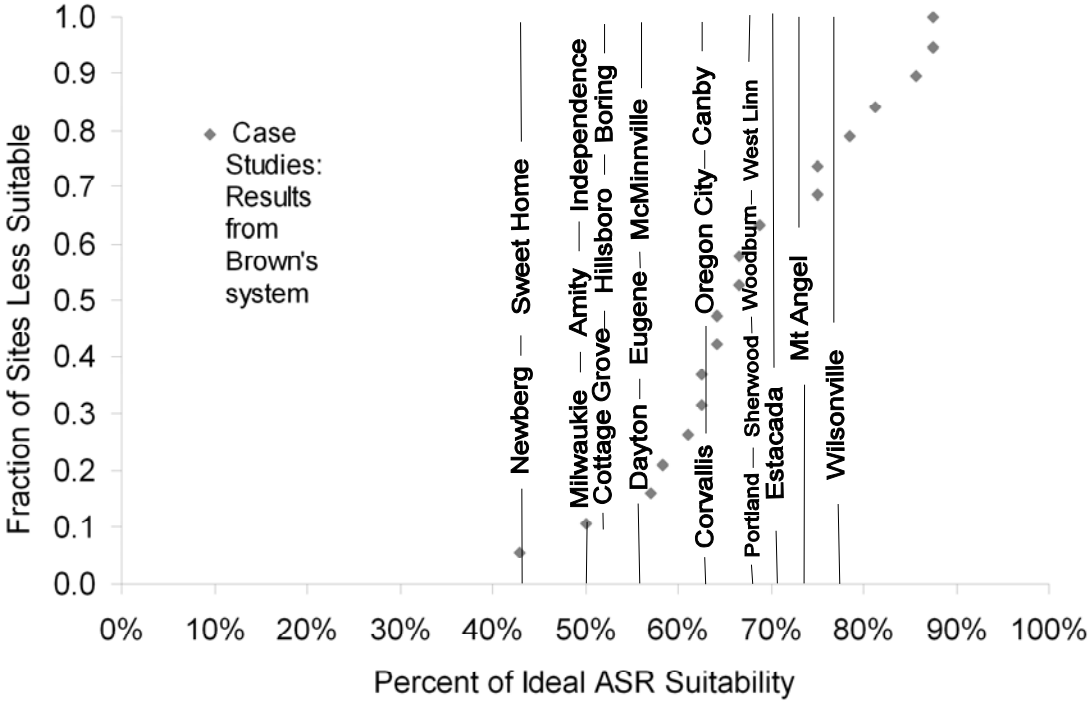


Figure 21-4: Willamette Basin Brown's rating system results indicate that Willamette Basin sites have from 43 % to 79% of ideal conditions. 80% of case studies' results are within the same range as the results for this basin. Data listed in Appendix C.

Milwaukie

Milwaukie is located in the northern part of the Willamette Basin, approximately 6 mi (9.6 km) south of downtown Portland. The City of Milwaukie currently has only groundwater rights (OWRD WRIS, 2006). While groundwater levels in the northern Willamette aquifer are not showing decline (1955 depth to water was reported 15 ft (4.5 m), while 1989 was 16 ft (4.9 m) (Woodward et al., 1998)), its population increased from 18,692 in 1990 to 20,755 in 2004 (U.S Census, 2004). This moderate growth in population may increase water supply needs.

Municipal wells have open intervals in sand, gravel and conglomerates from approximately 170 to 350 ft (52 to 107 m) below ground surface. This is most likely the unconfined Willamette aquifer (Qs; Woodward et al., 1998). Previous studies have found a wide range of hydraulic conductivities for the Willamette aquifer. Iverson (2002)

conducted pump tests in the middle sedimentary unit near Mt. Angel and found an average hydraulic conductivity of 20 ft/d (6 m/d). Assuming the aquifer thickness is equal to the well's open intervals, transmissivity in Milwaukie is approximately 2,140 ft^2/d (199 m^2/d). Transmissivity estimated from specific capacity is 4,600 to 4,700 ft^2/d (430 to 440 m^2/d). This is similar to transmissivity values found at Seattle's ASR project in glacial sand and gravel with transmissivity of 3,000 ft^2/d (279 m^2/d) (Brown et al., 2005). However, this falls slightly below the target range of 5,000 to 25,000 ft^2/d (465 to 2,323 m^2/d) for ASR.

Although faults have not been mapped at the surface in Milwaukie (Yeats et al., 1991), the Portland Hills fault trends southeast through the Milwaukie area to join the Clackamas River lineament. It continues through central Oregon as Brother's fault zone. This suggests faults may affect groundwater flow in the Milwaukie area, and local investigation is necessary to evaluate this potential limitation on aquifer continuity.

Volumetric analysis indicates aquifer storage is sufficient for ASR (Figure 21-3). Brown's site rating system finds Milwaukie has 50% of optimal ASR parameters (Figure 21-4).

There is a potential for AR through surface spreading in the Milwaukie area in the unconfined aquifer. The hydraulic gradient of 0.009 (Woodward et al., 1998) indicates that infiltrated water could be recoverable at a nearby location after 4 to 6 months of storage.

Oregon City

Oregon City is located in the northern Willamette Basin, on the banks of the Willamette River. The city has surface water rights to 40 cfs of the Clackamas River year round, as well as groundwater supplies to meet its needs. Population has increased rapidly from 14,698 in 1990 to 29,767 in 2004 (U.S. Census, 2004). This suggests an increasing pressure on water supplies, especially during seasons of drought when irrigation must be increased.

The municipal well (CLAC 4396) has open intervals between 300 to 560 ft (92 to 171 m) below the surface, and it yields 300 gpm (1,635 m^3/d; OWRD well log database,

2006). It accesses the Columbia River Basalt (Tc) interflow zones. Hydraulic conductivity for basalts in Oregon City has been measured at 85 ft/day (26 m/day), and transmissivity is reported as 22,000 ft^2/day (2,043 m^2/day) (Conlon et al., 2005). This is within the target range of 5,000 to 25,000 ft^2/day (465 to 2,323 m^2/d) (Brown et al., 2005).

Volumetric analysis indicates aquifer storage is sufficient to inject the available surface water (Figure 21-3). According to Brown's site rating system, Oregon City has 63% of optimal ASR parameters, with moderate scores for all parameters (Figure 21-4).

Quaternary and Tertiary sediments to the north and east of Oregon City may be suitable for surface spreading AR operations, if vertical permeability is sufficiently high. The hydraulic gradient is 0.004 (Woodward et al., 1998), which supports the recovery of water infiltrated into surficial aquifers.

Estacada

Estacada is located in the northeastern Willamette Basin, on the banks of the Clackamas River. The city has surface water rights to 4 cfs of the Clackamas River year-round, as well as groundwater rights. Population has increased moderately from 2,016 in 1990 to 2,416 in 2004 (U.S Census, 2004).

A municipal well (CLAC 57766) has open intervals varying from 630 to 840 ft (192 to 256 m) below the surface, yielding 120 gpm (654 m^3/d; OWRD well log database, 2006). It accesses the Boring Lavas or Columbia River Basalts (Tfc, Tc), including confined basalt interflow zones, pyroclastic, sand and gravel layers. Hydraulic conductivity for similar basalts in Oregon City has been measured at 85 ft/day (26 m/day), transmissivity 22,000 ft^2/day (2,043 m^2/day) (Woodward et al., 1998). Specific capacity at the Estacada well has been measured at 30 gpm/ft (538 m^2/d; OWRD well log database, 2006).

Transmissivity is estimated from specific capacity at 11,100 ft^2/day (1,000 m^2/day). Both the measured and estimated transmissivity fall within the target range of for ASR. Volumetric analysis indicates the aquifer storage is sufficient to inject ½

surface water rights for 120 days (Figure 21-3). Brown's ASR site rating system finds Estacada has 71% of optimal ASR parameters (Figure 21-4).

Quaternary and Tertiary sediments to the north and east of Estacada may be suitable for surface spreading AR operations, if the groundwater gradient and vertical permeability are suitable.

Canby

The City of Canby is located west of Estacada, near the confluence of the Molalla and Willamette Rivers. Canby has water rights to 15 cfs (36,705 m^3/d) of the Molalla River, and a water treatment plant on the banks of the river. Population increased from 8,983 to 14,715 between 1994 and 2004 (U.S. Census, 2004).

Municipal wells access Willamette Aquifer sands and gravels (Qal, Qs), and yield 400 gpm (2,180 m^3/d; OWRD well log database, 2006). Transmissivity estimated from specific capacity (at CLAC 12027 and CLAC 12025) is 2,800 and 6,100 ft^2/d (260 and 570 m^2/day), respectively.

Volumetric analysis finds aquifer storage is insufficient to inject ½ the surface water right for 120 days (Figure 21-3). Brown's site assessment system finds Canby has 63% of optimal ASR parameters (Figure 21-4).

Surficial alluvial aquifers may be suitable for infiltration basins for AR; the local hydraulic gradient is relatively low at 0.003 (Woodward et al., 1998). However, the close proximity of Canby to both the Molalla and Willamette Rivers may make AR less feasible than ASR, as surficial aquifers most likely are strongly connected to the rivers. Deeper aquifers may be more "secure" water storage zones for this reason.

Woodburn

Woodburn is located about 11 mi (17.6 km) southwest of Canby. It is growing rapidly with a population of 13,404 in 1990 increasing to 22,147 in 2004 (U.S. Census, 2004). The City of Woodburn has water rights to 12.5 cfs (30,588 m^3/d) of Mill Creek flow, but uses groundwater for most municipal needs. Groundwater levels appear to be

stable in the area; depth to water in 1965 was 42 ft (13 m), in 1989 it was 48 ft (14 m) (Woodward et al., 1998).

Municipal wells range in depth of open interval from 106 to 210 ft (32 to 64 m); water-bearing layers are reported to be sands and gravels of the Willamette aquifer (Qs; OWRD well log database, 2006). A pump test at an irrigation well was recorded by Conlon et al. (2005) in Woodburn. Transmissivity reported in the study is 6,300 ft^2/d (28 m^2/d), and specific capacity is 16 gpm/ft (287 m^2/d). This is within the target range for ASR sites (Brown et al., 2005).

Volumetric analysis indicates Woodburn municipal wells access an aquifer with slightly more storage than potential injection volume (Figure 21-3). Brown's site rating system finds Woodburn has 69% of optimal ASR parameters, with moderate scores for all parameters (Figure 21-4).

The Gales Creek-Mt. Angel structural zone may truncate potential storage zones, depending on the location of future ASR projects, because it extends directly through Woodburn (Conlon et al., 2005). This would need to be investigated before undertaking a large-scale ASR project in Woodburn. AR may be feasible in Woodburn's surficial Tertiary sediments, due to the low hydraulic gradient of 0.008 (Woodward et al., 1998).

Mt. Angel

Mt. Angel is located about 6 mi (9.6 km) southeast of Woodburn. It is a growing community with a population of 2,778 in 1990 which increased to 3,339 in 2004 (U.S. Census, 2004). The City of Mt. Angel has no surface water rights, because it does posses groundwater rights.

Open intervals in local wells range from 160 to 640 ft (49 to 195 m) below the surface. Water-bearing layers are reported to be interflow zones of the Columbia River Basalt (Tc), overlain by the Willamette Aquifer (Qs; OWRD well log database, 2006).

A pump test at an irrigation well was recorded by Conlon et al. (2005) in Mt. Angel. Transmissivity was estimated at 18,000 ft^2/d (1,672 m^2/d); specific capacity for the well was measured at 51 gpm/ft (914 m^2/d). This is within the target range of 5,000 to 25,000 ft^2/d (465 to 2,323 m^2/d; Brown et al., 2005) for ASR.

Volumetric analysis indicates aquifer storage is suitable for ASR (Figure 21-3). Brown's site rating system finds Mt. Angel has 75% of optimal ASR parameters (Figure 21-4).

The Gales Creek-Mt. Angel structural zone may truncate potential storage zones, depending on the location of future ASR projects, because it extends directly through Mt. Angel (Conlon et al., 2005). Aquifer truncation is suspected from recent rapid drawdown and pump test response (Malia Kupillas, personal communication, 2006). This would need to be investigated before pursuing an ASR project. AR may be feasible in Mt. Angel's surficial Tertiary sediments, due to the low hydraulic gradient of 0.004 (Woodward et al., 1998).

Sherwood

Sherwood is located about 10 mi (16 km) northwest of Canby, in the Tualatin subbasin. It is growing rapidly with a population of 3,093 in 1990 increasing to 14,540 in 2004 (U.S. Census, 2004). The City of Sherwood has water rights to 1.8 cfs (4,405 m^3/d) of Clear Creek flow, but uses groundwater for most municipal needs. Groundwater levels are declining in the area; depth to water in 1960 was 70 ft (21 m), in 1989 it was 95 ft (29 m) (Woodward et al., 1998).

A municipal well (WASH 51903) has open intervals from 400 to 860 ft (43 to 244 m) below the surface, and yields 500 gpm (2,725 m^3/d; OWRD well log database, 2006). Columbia River Basalts (Tc) at this well have transmissivity of 33,100 ft^2/d (3,100 m^2/d) (Woodward et al., 1998). This is above the ideal range for ASR. Other projects in the Tualatin subbasin have had mixed results. Beaverton, which uses the Columbia River Basalt for ASR, has been successful in recovering stored water, as discussed in Chapter 2. However, Tualatin Valley Water District curtailed ASR testing when a surface seep developed during injection in 2000 (Groundwater Solutions, 2001).

Volumetric analysis finds the aquifer has sufficient storage for the potential injection volume (Figure 21-3). Brown's site rating system finds Sherwood has 69% of optimal ASR parameters (Figure 21-4).

The Sherwood fault may truncate potential storage zones, depending on the location of future ASR projects. Further field testing is necessary to determine the extent of the influence of faults on local aquifers. AR may be feasible in Sherwood's surficial Tertiary sediments, due to the low hydraulic gradient of 0.002 (Woodward et al., 1998).

McMinnville

McMinnville is located about 17 mi (27 km) northwest of Woodburn. It is growing rapidly with a population of 17,894 in 1990 increasing to 28,973 in 2004 (U.S. Census, 2004). The City of McMinnville has water rights to 410 cfs (1,003,270 m^3/d) of Haskins Creek Reservoir. Groundwater levels appear to be stable in the area; depth to water in 1961 was 14 ft (4.3 m), in 1990 it was 18 ft (5.5 m) (Woodward et al., 1998).

McMinnville Water and Light wells (YAMH 5917 and 51032) have open intervals from 54 to 160 ft (16 to 49 m) below the surface. Water-bearing layers are reported to be mudstone, sandstone and clay of the Willamette silt (Qs) (OWRD well log data, 2006). Transmissivity is estimated at 660 ft^2/d (60 m^2/d) (Woodward et al., 1998), which is below the target range for ASR (Brown et al., 2005).

Volumetric analysis indicates aquifer storage is suitable for ASR (Figure 21-3). Brown's site rating system finds McMinnville has 56% of optimal ASR parameters (Figure 21-4). Hydraulic gradient in this area is low, 0.003 (Woodward et al., 1998), indicating AR may be feasible; however, the low vertical hydraulic conductivity of the Willamette silt may nullify this advantage. Iverson (2002) estimates vertical hydraulic conductivity at 0.008 ft/d.

Amity

Amity is located about 17 mi (27 km) west of Woodburn. The City of Amity has water rights to 0.475 cfs (1,162 m^3/d) of South Yamhill River flow. Groundwater levels appear to be stable in the area; depth to water in 1960 and 1989 was 18 ft (5.5 m) (Woodward et al., 1998). Population increased from 1,175 to 1,464 between 1994 nd 2004 (U.S. Census, 2006).

Municipal wells have depth to open intervals from 67 to 77 ft (20 to 23 m); water bearing layers are reported to be sand and gravel of the Willamette aquifer (Qs) (OWRD well log database, 2006). Transmissivity at Amity has been reported to be 1,700 ft^2/d (160 m^2/d) (Woodward et al., 1998). This is below the target range for ASR.

Volumetric analysis indicates aquifer storage is sufficient to inject the available rate of surface water (Figure 21-3). Brown's site rating system finds Amity has 50% of optimal ASR parameters (Figure 21-4). The site lost points for an aquifer less than 25 ft (7.6 m) thick and a groundwater gradient greater than 0.01 ft/ft.

Faults 0.8 mi (1.3 km) northeast of Amity may truncate potential storage zones, depending on the location of future ASR projects. Site specific testing is necessary to determine the influence of faults on groundwater flow in this area. AR may be infeasible in Amity's surficial Tertiary sediments, due to the hydraulic gradient of 0.03 (Woodward et al., 1998), which may cause stored water to flow away too quickly to be recovered 4 to 6 months later.

Independence

Independence is located on the west bank of the Willamette River, about 10 mi (16 km) southwest of Salem. The City of Independence has water rights to 1 cfs (2,447 m^3/d) from the South Fork of Ash Creek. Population increased from 4,425 to 8,764 between 1990 and 2006 (U.S. Census, 2006).

The municipal well (POLK 420) selected to represent the local aquifer has open intervals from 55 to 74 ft (17 to 23 m) below the surface. Water-bearing layers are sand and gravel of the Willamette Aquifer (Qs) (OWRD well log database, 2006). Transmissivity estimated from specific capacity is 17,700 ft^2/d (1,650 m^2/d), which is within the target range for ASR (Brown et al., 2005). The transmissivity values for sedimentary aquifers in Independence are similar to values reported for sand aquifers used for ASR in El Paso, Texas (13,363 ft^2/d or 1,242 m^2/d) (Sheng, 2005) and Aurora, Nebraska (12,589 ft^2/d or 1,170 m^2/d) (Lichtler et al., 1980).

Volumetric analysis indicates Independence's municipal well is suitable for ASR (Figure 21-3). Brown's site rating system finds Independence has 50% of optimal ASR

parameters (Figure 21-4). The site lost points for an aquifer less than 25 ft (7.6 m) thick, with moderate scores for all other parameters.

AR may be feasible in Independence's surficial Quaternary sediments, due to the hydraulic gradient of 0.006 (Woodward et al., 1998).

Corvallis

Corvallis is located west of the Willamette River, and holds water rights to 90 cfs (220,230 m^3/d) from its flow. Groundwater levels appear to be stable in the area; depth to water in both 1965 and 1989 was 16 ft (5 m) (Woodward et al., 1998). Population increased from 44,757 to 50,380 between 1990 and 2006 (U.S. Census, 2006).

Municipal wells (BENT 5264 and 51479) were selected to investigate the aquifer's feasibility for ASR use. Wells have an open interval from 30 to 120 ft (9 to 37 m) below the surface and produce 80 to 370 gpm (436 to 2,017 m^3/d). Water-bearing layers are interpreted to be sands and gravels of the Willamette Aquifer (Qal, Qs) (OWRD well log database, 2006). Transmissivity estimated from specific capacity is 3,600 ft^2/d (300 m^2/d) (Woodward et al., 1998). This is below the target range for ASR (Brown et al., 2005).

Volumetric analysis indicates aquifer storage at Corvallis municipal wells is not sufficient to inject the available surface water (Figure 21-3). The shallow water table contributes to this low suitability. Brown's site rating system finds Corvallis has 63% of optimal ASR parameters, with a low score on transmissivity (Figure 21-4).

AR may be feasible in Corvallis surficial Tertiary sediments, due to the hydraulic gradient of 0.006 (Woodward et al.,1998); however, the Willamette aquifer is overlain by Willamette silt, a low permeability unit which may prevent effective infiltration through surface spreading.

Sweet Home

Sweet Home is located about 28 mi (45 km) east of Corvallis. The City has water rights to 13.1 cfs (32,056 m^3/d) from the South Santiam River. Population increased from 6,850 to 8,576 between 1990 and 2006 (U.S. Census, 2006). Groundwater levels

appear to be stable in the area; depth to water in 1965 was 9 ft (2.7 m), in 1989 it was 9.5 ft (2.9 m) (Woodward et al., 1998).

A domestic well (LINN 12855) was selected in Sweet Home to represent the local aquifer environment. This well has open intervals in sandstone of the tuffaceous Western Cascade volcanics (Tu) from 20 to 335 ft (6 to 102 m) below the surface. Transmissivity estimated from specific capacity is 700 ft^2/d (65 m^2/d), which is below the ideal range for ASR.

Volumetric analysis indicates aquifer storage is not suitable for ASR, due to the shallow water table and low transmissivity (Figure 21-3). Brown's site rating system finds Sweet Home has 44% of optimal ASR parameters, with low scores for transmissivity and aquifer thickness less than 25 ft (7.6 m) (Figure 21-4).

AR may be feasible in Sweet Home surficial sediments, due to the hydraulic gradient of 0.003 (Woodward et al., 1998). However, the Willamette aquifer in this area is overlain by Willamette silt, a low permeability unit with may prevent effective infiltration through surface spreading.

Eugene

Eugene is located about 36 mi (58 km) south of Corvallis. The City has water rights to 3,592 cfs from the McKenzie River. Groundwater levels are variable in this area; depth to water in 1965 was 6 ft (1.8 m), in 1989 it was 12 ft (3.7 m) (Woodward et al., 1998). Population increased from 112,669 to 142,681 between 1990 and 2004 (U.S. Census, 2004).

Municipal wells have open intervals from 15 to 235 ft (5 to 72 m) below the surface. Water-bearing layers are interpreted to be sands and gravels of the Willamette aquifer (Qs) and tuffaceous Western Cascade volcanics (Tu) (OWRD well log data, 2006). Transmissivity in the sediments is reported as 2,700 to 78,000 ft^2/d (250 to 7246 m^2/d) (Woodward et al., 1998). Transmissivity estimated by this study from specific capacity data is 3,215 to 3,974 ft^2/d (299 to 370 m^2/d) (OWRD well log database, accessed 2006). This is below the target range for ASR, but it is similar to values

reported for sand aquifers used for ASR in Seattle, WA 3,000 ft^2/d (279 m^2/d), Washoe County, Nevada 2,991 ft^2/d (278 m^2/d), and Lancaster, California 2496 ft^2/d (232 m^2/d).

Volumetric analysis indicates aquifer storage is not suitable for ASR (Figure 21-3). This is partly due to the large injection volume, although the shallow water table also precludes ASR. Brown's site rating system finds Eugene has 56% of optimal ASR parameters, with a low score for transmissivity (Figure 21-4).

AR may be feasible in Eugene surficial sediments, due to the hydraulic gradient of 0.003 (Woodward et al., 1998). However, the Willamette aquifer is overlain by Willamette silt, a low permeability unit which may prevent effective infiltration through surface spreading.

Cottage Grove

Cottage Grove is located about 18 mi (29 km) south of Eugene. The City of Cottage Grove has water rights to 6.2 cfs (15,171 m^3/d) from the Row River. Population increased from 7,402 to 8,859 between 1990 and 2006 (U.S. Census, 2006).

A domestic well (LANE 58776) was chosen to examine the local aquifer's suitability for ASR. The well has an open interval from 59 to 190 ft (18 to 58 m) below the surface. Water-bearing layers are interpreted to be Tertiary marine sandstone (Tss) (OWRD well log database, 2006). Transmissivity was estimated by this study from specific capacity as 550 ft^2/d (50 m^2/d), which is below the target range for ASR.

Volumetric analysis indicates aquifer storage is insufficient for ASR (Figure 21-3). The shallow water table allows only 12 ft (4 m) of head space in the well for water to rise during injection. Water could be injected under pressure to accommodate this problem, but the low transmissivity can only be remedied by intentional hydraulic fracturing of the existing aquifer. Brown's site screening system finds Cottage Grove has 50% of optimal ASR parameters, with low scores for transmissivity and aquifer thickness less than 25 ft (7.6 m) (Figure 21-4).

AR may be feasible in Cottage Grove surficial sediments, due to the low hydraulic gradient of 0.0008 (Woodward et al., 1998).

CHAPTER 22
SUMMARY AND CONCLUSIONS

Summary

The results from both Brown's site rating system and the Aquifer Storage and Recovery (ASR) metric assessment methods show variable suitability across the state of Oregon (Figure 22-1, 22-2, 22-3, Appendix D). In summary, the ASR metric compares the aquifer's storage capacity to the desired injection rate. A result greater than one indicates the aquifer has sufficient storage for ASR (see Chapter 3). Because the ASR metric examines only the physical capability of the aquifer to accept water at a certain rate, the only way to improve a low rating is to decrease the injection rate or artificially increase hydraulic conductivity by artificial stimulation of the aquifer. On the other hand, Brown's rating system evaluates eight parameters, including aquifer characteristics, infrastructure and environmental constraints, and produces a result as the percentage of ideal parameters for ASR (see Chapter 3). Some of these factors may be improved by economic investment. This indicates that a low score in Brown's rating system can in some cases be improved, while a low ASR Metric may not be as flexible.

The aquifer parameters in Brown's system were also evaluated separately from the other factors to test the level of agreement between the two systems (Appendix D). When a favorable site is defined as receiving an ASR Metric greater than 1 and greater than 50% of ideal aquifer parameters in Brown's site rating system, the systems agree on 64% of the data. In some cases, more than one aquifer was investigated for ASR suitability; the color symbols in Figure 22-1 and 22-2 represent the best results for each site.

In general, poor ASR metric results correspond with terrace deposits on the South Coast, volcanic ash deposits of the Western Cascades, and the Deschutes Formation in Central Oregon (Figure 22-3). Suitable ASR metric results correlate with Columbia River Basalts, basin-fill and alluvial deposits, and North Coast dune deposits.

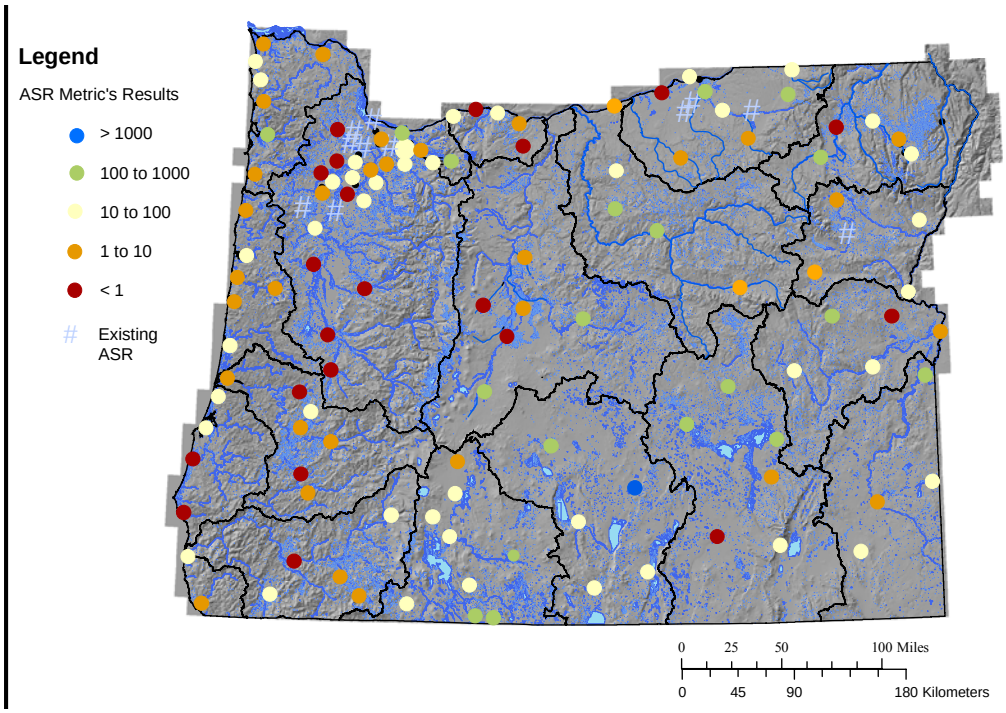


Figure 22-1. ASR metric results. The ASR metric finds more suitable sites in eastern Oregon than in western Oregon. Data listed in Appendix B and D.

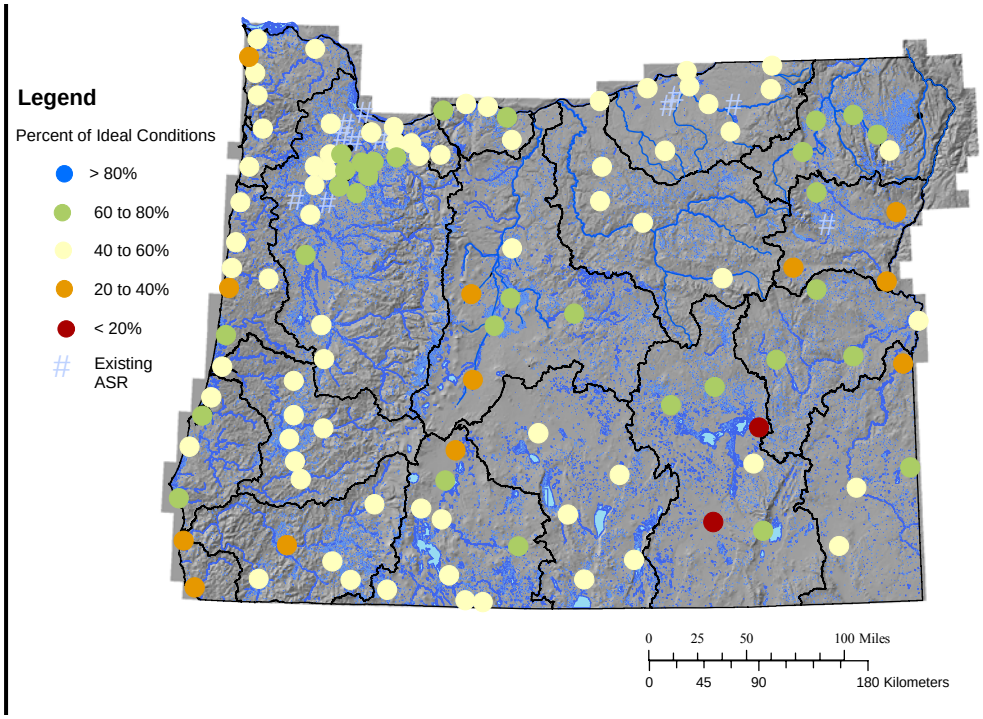


Figure 22-2. Brown's site rating system. Moderately suitable sites are distributed across the state. Data listed in Appendix C and D.

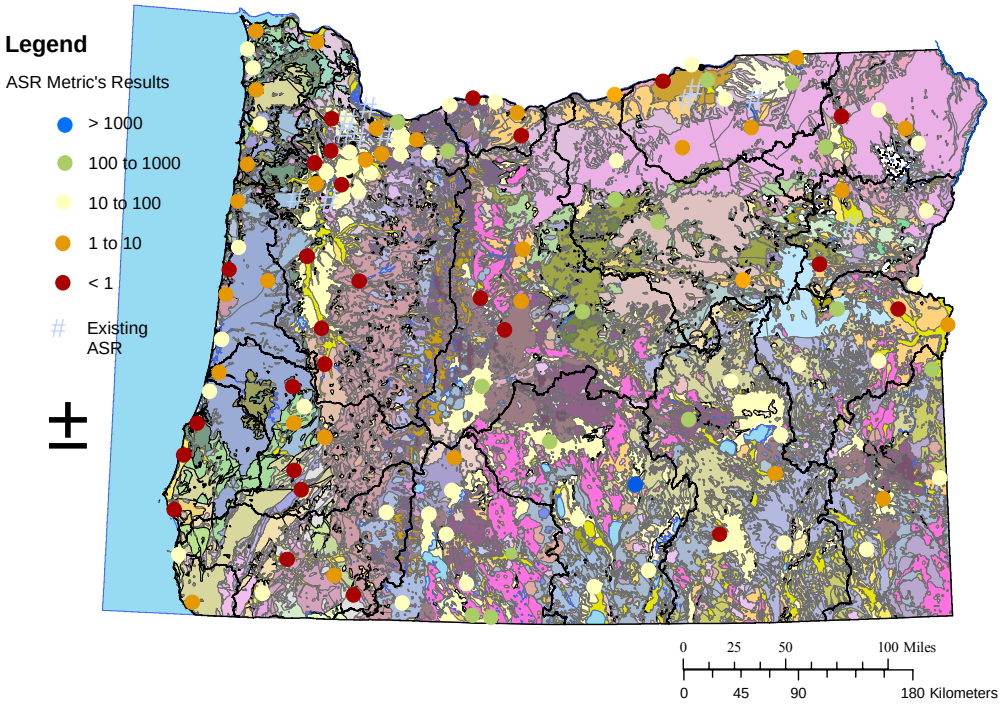


Figure 22-3. ASR metric results and geologic map. Poor ASR metrics correspond with south coast terraces, Western cascades ash and tuff deposits, and the Deschutes Formation. Suitable ASR metrics correlate with Columbia River Basalts, alluvial and dune deposits. Data listed in Appendix B and D.

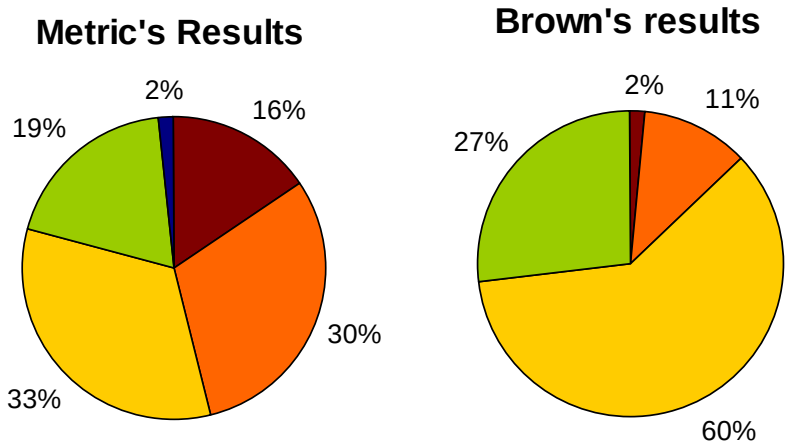


Figure 22-3. Distribution of results. While Figure 22-1 and 22-2 shows the spatial distribution of assessment results, these charts illustrate the portion of newly assessed sites in Oregon that produced results in each range. While the ASR Metric's results are spread evenly across the categories, Brown's system found 60% of newly assessed sites have between 40 to 60% of ideal parameters for ASR.

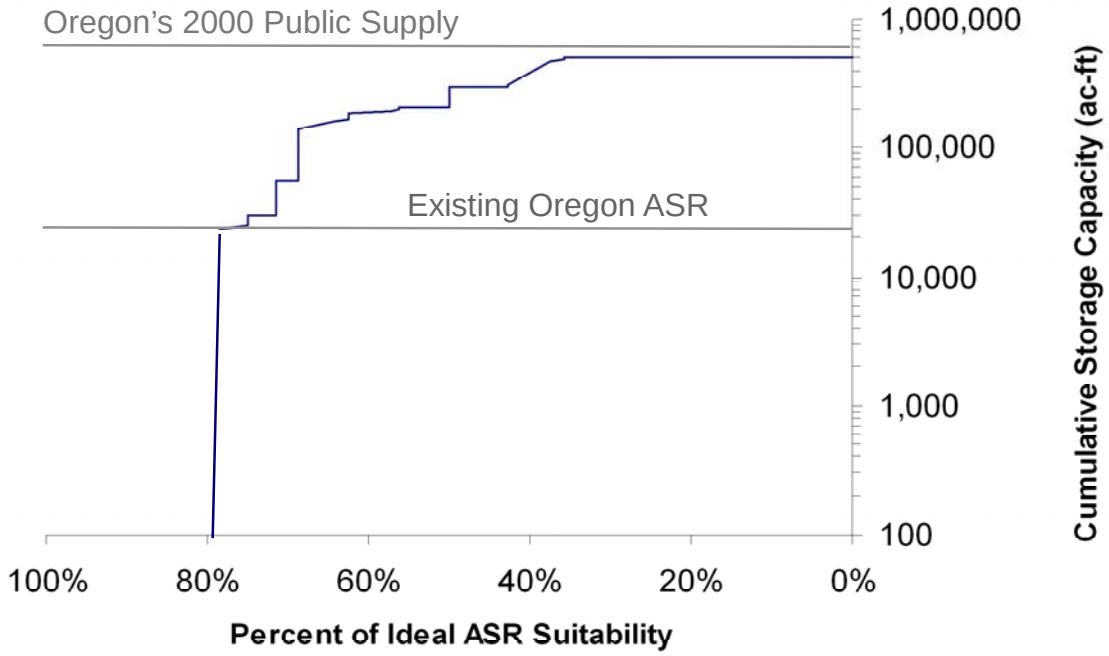


Figure 22-4. Potential Cumulative ASR Capacity in Oregon. The cumulative capacity of potential ASR sites approaches the volume of Oregon's total public supply withdrawals in 2000, including water drawn from both surface and groundwater sources.

Conclusions

While many of the sites assessed showed suitability only for small projects, their cumulative storage capacity is significant. According to Hutsen et al. (2004), Oregon's total public supply withdrawal in 2000 was approximately 634,000 ac-ft (7.8×10^8 m^3), while the total ASR capacity identified by this study is approximately 502,800 ac-ft (6×10^8 m^3). This means Oregon can theoretically meet its municipal water storage needs through ASR expansion state-wide.

It is important to note that not all sites are equally favorable (Figure 22-4), and the total storage identified by this study may be overly optimistic. Storage at sites with less than 50% of ideal ASR suitability accounts for roughly half of the total, and depending on which parameters are unsuitable, this storage may not be accessible. However, cumulative storage identified includes only specific points across the state, and there is potential storage that is not investigated in this study. The potential storage found at sites

that have more than 50% of ideal ASR suitability is approximately 202,500 ac-ft (2.5 x 10^8 m^3).

There are other limitations. Oregon's public supply represents 6% of annual water use, while 81% of our annual state-wide water withdrawal is channeled to agricultural uses (Bastach, 2006). This indicates that ASR cannot replace the above-ground storage capacity provided by large reservoirs, but it can provide significant additional capacity and flexibility in water resource management. In addition, the economics of meeting present water quality standards for ASR require advances in cost effective water treatment technologies to facilitate agricultural ASR development. Further study, particularly on water quality and water treatment technology, is necessary to enable more agricultural ASR in the future.

REFERENCES

Allen, John Eliot. 1960. Geologic field guide to the Columbia River Gorge trip. Portland State University. 21 p.

Armentrout, John M., Suek, David H. 1985. Hydrocarbon exploration in western Oregon and Washington. American Association of Petroleum Geology Bulletin 69(4):627-643.

Aronson, David A., Lindner, Julie B., Katz, Brian G. 1983. Geohydrology of the Meadowbrook artificial-recharge site at East Meadow, Nassau County, New York U.S. Geological Survey Water-Resources Investigations Report 82-4084. 50 p.

Aspect Consulting, LLC. 2005. Aquifer Storage and Recovery assessment, City of Kennewick, WRIA 31 Supplemental Water Storage Project. Kennewick, Washington: 43 p.

Baquai, Hisam A. 2002. Effects of recharge of chlorinated state water projects waters to groundwater in the Lancaster area of California. Water Engineering and Management 149(4): 10-13.

Barry, Jeff. 2006. Groundwater Solutions, Inc.: Principal Hydrogeologist, conversation with the author February 21.

Bastasch, Rick. 1998. Waters of Oregon: A source book on Oregon's water and water management. Corvallis: Oregon State University Press. 278 p.

Bastasch, Rick. 2006. The Oregon water handbook: A guide to water and water management. Corvallis: Oregon State University Press. 352 p.

Beeson, Marvin H., Moran, Michael R. 1979. Columbia River Basalt group stratigraphy in western Oregon. Oregon Geology 41(1):11-14.

Bertagna, Paul. 2006. City of Sisters, email communication with the author, July 2006.

Bloetscher, Frederick, Muniz, Albert, Witt, Gerhardt M. 2005. Groundwater Injection. New York: McGraw-Hill. 437 p.

Bower, Bob. 2007. Walla Walla Basin Watershed Council, Hydrologist. Personal communication with the author, October 31, 2007.

Brooks, H.C. 1979. Plate tectonics and the geologic history of the Blue Mountains. Oregon Department of Geology and Mineral Industries. 71-80 p.

Brown, Chris J. 2005. Planning decision framework for brackish water aquifer storage and recovery (ASR) projects, PhD dissertation: University of Florida. 414 p.

Brown, Chris J., Weiss, Rebecca, Verrastro, Robert, Schubert, Steve. 2005. Development of an Aquifer, Storage and Recovery (ASR) site selection suitability index in support of the comprehensive Everglades restoration project. Journal of Environmental Hydrology 13(20):1-13.

Brown, R.F., Keys, W.H. 1985. Effects of artificial recharge on the Oglalla aquifer, Texas. U.S. Geological Survey Water-Supply Paper 2251. 63 p.

Brown and Caldwell. 2001. City of Florence: Existing well field aquifer characterization report. Florence, Oregon: 57 p.

Cadamuro, A.L., Campos, J.E.G., Troger, U. 2002. Artificial recharge in fractured rocks- an example from the Federal District of Brazil for the sustainability of the system. In: Dillon, P.J., editor; 2002; Adelaide, South Australia. A.A. Balkema. p 523-526.

Caldwell, Rodney R. 1998. Chemical study of regional ground-water flow and ground-water surface water interaction in the Upper Deschutes Basin, Oregon. U.S. Geological Survey Water-Resources Investigations Report 97-4233. 49 p.

Caldwell, Rodner R., Truini, Margot. 1997. Groundwater and water chemistry data for the Upper Deschutes Basin, Oregon. U.S. Geological Survey Open-File Report 97-197. 83 p.

Campbell, Bruce G., Conlon, Kevin J., Mirecki, June E., Petkewich, Matthew D. 1997. Evaluation of Aquifer Storage Recovery in the Santee Limestone/Black Mingo aquifer near Charleston, South Carolina, 1993-1995. U.S. Geological Survey Water-Resources Investigations Report 96-4283. 89 p.

Castro, Joffre E. 1995. Aquifer Storage and Recovery Myrtle Beach, South Carolina. South Carolina Water Resources Commission Open File Report 21. Columbia, South Carolina: 50 p.

Century West. 1982. LaPine Aquifer Management Plan. LaPine, Oregon: 43 p.

CH2M Hill. 1993. Aquifer Storage and Recovery feasibility study. Echo Junction, OR: 76 p.

CH2M Hill. 1997. Aquifer Storage and Recovery hydrogeologic feasibility study of Cooper Mountain Basalt: Tualatin Valley Water District. Tualatin, Oregon: 127 p.

CH2M Hill. 1999. Preliminary Aquifer Storage and Recovery feasibility evaluation, final report submitted to Green Bay Water Utility. St. Louis, Missouri: 73 p.

CH2M Hill. 2000a. Columbia South Shore Well Field Aquifer Storage and Recovery Feasibility Report. Portland, Oregon: 85 p.

CH2M Hill. 2000b. Tualatin Valley Water District Schuepbach well ASR pilot test results. Tualatin, Oregon: 46 p.

CH2M Hill. 2002. Aquifer Storage and Recovery hydrogeologic feasibility study for the City of Pendleton, OR. Pendleton, Oregon: 98p.

Chastain-Howley, Andrew, Pyne, R. David G., editors. 2002. A preliminary assessment of hydrogeologic suitability for Aquifer Storage Recovery (ASR) in north-central Texas. In: Transactions-Gulf Coast Association of Geological Societies, 2002. p. 111-119.

Conlon, Kevin J., Wozniak, Karl C., Woodcock, Douglas, Herrera, Nora B., Fisher, Bruce J., Morgan, David S., Lee, Karl K., Hinkle, Stephen R. 2005. Groundwater hydrology of the Willamette Basin, Oregon. U.S. Geological Survey Scientific Investigations Report 2005-5168. 95 p.

Connor, Jeffery D, Perry, Gregory M. 1999. Analyzing the potential for water quality externalities as the result of market water transfers. Water Resources Research 35(9):2833–2839.

Conrey, R.M. 1985. Volcanic stratigraphy of the Deschutes Formation- Green Ridge to Fly Creek north central Oregon, Master's Thesis. Corvallis: Oregon State University. 349 p.

Cooper, H.H., Jr., Jacob, C.E. 1946. A generalized graphical method for evaluating formation constants and summarizing well-field history. Transactions, American Geophysical Union 27(4): pp. 526-534.

DEFRA. 2006. Our approach to evidence and innovation. London: United Kingdom Department for Environment, Food and Rural Affairs. 23 p.

Driscoll, Fletcher G. 1986. Groundwater and wells. St. Paul: Johnson Division. 1,089 p.

Ehman, Kenneth D., Cramer, Richard S. 1997. Application of sequence stratigraphy to evaluate groundwater resources. Conjunctive use of water resources: Aquifer Storage and Recovery. Long Beach, CA: American Water Resource Association.

Ferns, Mark L. 1997. Field trip guide to the eastern margin of the Oregon-Idaho graben and the middle Miocene calderas of the Lake Owyhee volcanic field. Oregon Geology 59(1):9-20.

Fitzpatrick, Daniel J. 1986. Tests for injecting, storing, and recovering freshwater in a saline artesian aquifer, Lee County, Florida U.S. Geological Survey. Water-Resource Investigations Report 85-4249. 58 p.

Fitzpatrick, Daniel J. 1990. A preliminary assessment of the potential for artificial recharge in eastern Arkansas. U.S. Geological Survey Water-Resources Investigations Report 90-4123. 32 p.

Foxworthy, B.L. 1970. Hydrologic conditions and artificial recharge through a well in the Salem Heights area of Salem, OR. U.S. Geological Survey Water Supply Paper 1594-F. 56 p.

Foxworthy, B.L., Bryant, C.L. 1967. Artificial Recharge through a well tapping basalt aquifers at The Dalles, Oregon U.S. Geological Survey Water-Supply Paper 1594-E. 60 p.

Frank, F.J. 1970. Groundwater resources of the Clatsop Plains sand dune area, Clatsop County, Oregon. U.S. Geological Survey Water Supply Paper 1899-A. 41 p.

Gale, I. N., Williams, A.T., Gaus, I., Jones, H.K. 2002. ASR-UK: Elucidating the hydrogeological issues associated with aquifer storage and recovery in the UK. British Geological Society Report CR/02/156/N. 45 p.

Gannett, Marshall W. 1990. Hydrogeology of the Ontario Area, Malheur County, Oregon. Oregon Water Resources Department Groundwater Report No. 40. 39 p.

Gannett, Marshall W., Caldwell, Rodney R. 1998. Geologic framework of the Willamette Lowland aquifer system, Oregon and Washington. U.S. Geological Survey Water Resources Investigations 1424-A. 32 p.

Gannett, Marshall W. 2001. Groundwater hydrology of the Upper Deschutes Basin, Oregon. U.S. Geological Survey Water Resources Investigation 00-4162. 77 p.

Gannett, Marshall W., Lite, Kenneth E. 2004. Simulation of regional groundwater flow in the Upper Deschutes Basin, Oregon. U.S. Geological Survey Water Resources Investigations Report 03-4195. 84 p.

Gannett, Marshall W., Lite, Jr., Kenneth E. La Marche, Jonathan L., Fisher, Bruce J., Polette, Danial J. 2007. Ground-water hydrology of the Upper Klamath Basin, Oregon and Washington. U.S. Geological Survey Scientific Investigations Report 2007-5050. 84 p.

Garrett, A.A., Londquist, C.J. 1972. Feasibility of artificially recharging basalt aquifers in eastern Washington. U.S. Geological Survey Open-File Report 57-51. 42 p.

Gerges, N.Z., Dillon, P.J., Sibernaler, X.P., Martin, R.R., Pavelic, P., Howles, S.R, Dennis, K., editors. 2002. South Australian experience in aquifer storage and recovery. Adelaide, South Australia: A.A. Balkema. 453- 458 p.

Golder Associates, Inc., Montgomery Watson. 1994. Groundwater recharge for an Aquifer Storage and Recovery pilot program in Salem, Oregon: Hydrogeologic feasibility report. Lake Oswego, Oregon: 82 p.

Golder Associates, Inc. 2001. City of Tigard Phase I-Feasibility study. Lake Oswego: 52 p.

Golder Associates, Inc. 2003. Portland Aquifer Storage and Recovery pilot testing: 2003 annual report. Lake Oswego, Oregon: 53 p.

Golder Associates, Inc. 2004. Phase two groundwater resources study: prepared for the Bandon Cranberry Water Control District. Bandon, Oregon: 156 p.

Golder Associates, Inc. 2005. Aquifer Storage and Recovery hydrogeologic feasibility study: City of Dallas, Oregon water treatment plant site. Lake Oswego, Oregon: 26 p.

Golder Associates, Inc. 2007. Results for the first year of ASR pilot testing at the City of Dallas, Oregon. Lake Oswego, Oregon: 67 p.

Gonthier, Joseph B. 1985. A description of aquifer units on eastern Oregon. U.S. Geological Survey Water-Resources Investigations Report 84-4095. 39 p.

Gonthier, J.B., Collins, C.A., Anderson, D.B. 1977. Groundwater data for the Drewsey Resource Area, Harney and Malheur Counties, Oregon. U.S. Geological Survey Open File Report 77-741. 31 p.

Grady, Stephen J. 1983. Ground-water resources in the Hood Basin, Oregon. U.S. Geological Survey Water-Resources Investigations Report 81-1108. 42 p

Groundwater Solutions, Inc., Anderson Perry & Associates. 2003a. Baker City Aquifer Storage and Recovery (ASR) feasibility report. Portland, Oregon: 113 p.

Groundwater Solutions, Inc., Murray, Smith & Associates, Inc. 2003b. Aquifer Storage and Recovery limited license application and pilot test program for the City of Tualatin. Portland, Oregon. 16 p.

Groundwater Solutions, Inc. 2006a. Deep alluvial aquifer Aquifer Storage and Recovery (ASR) feasibility study for Sunrise Water Authority. Portland, Oregon: 31 p.

Groundwater Solutions, Inc. 2006b. Aquifer Storage and Recovery (ASR) feasibility study for Clackamas River Water. 46 p.

Haggerty, Roy and Gorelick, Steven M. 1995. Multiple-rate mass transfer for modeling diffusion and surface reactions in media with pore-scale heterogeneity. Water Resources Research 31(10):2383-2400.

Hampton, E.R., Brown, S.G. 1964. Geology and groundwater resources of the Upper Grande Ronde River Basin Union County, Oregon. U.S. Geological Survey Water-Supply Paper 64-1597. 106 p.

Hardy, Mark A., Maret, Terry R., George, David L. 2004. Reconnaissance of chemical and biological quality in the Owyhee River from the Oregon state line to the Owyhee Reservoir, Oregon, 2001-2002. U.S. Geological Survey Water-Resources Investigations Report 03-4327. 57 p.

Harrington, G.A., Love, A.J., Sanford, W.E. Aquifer Storage and Recovery in a fractured rock aquifer of the Clare Valley, South Australia. In: Dillon, P.J., editor. Management of Aquifer Recharge for sustainability; 2002; Adelaide, South Australia. A.A. Balkema. p. 567.

Hart, D.H. 1958. Artificial Recharge to groundwater in Oregon and Washington. U.S. Geological Survey Water Supply Paper 58-1592-C. 70 p.

Hogenson, G.M. 1964. Geology and groundwater of the Umatilla River Basin, Oregon. U.S. Geological Survey Water Supply Paper 1620. 168 p.

Hogenson, G.M. and Foxworthy, B.L. 1965. Ground water in the East Portland area, Oregon. U.S. Geological Survey Water Supply Paper 1793. 78 p.

Hotz, Preston E. 1971. Plutonic rocks of the Klamath Mountains, California and Oregon. U.S. Geological Survey Professional Paper 684-B. 24 p.

Howles, S.R. 2000. Development of potable town water supplies in saline aquifers using ASR. MESA Journal 16:11-15.

Hutchinson, Adam. 1997. A graphical method of estimating injection well clogging using the modified fouling index. In: Conjunctive use of water resources: Aquifer Storage and Recovery. Long Beach, CA: American Water Resources Association.

Hutson, Susan S., Barber, Nancy L., Kenny, Joan F., Linsey, Kristin S., Lumia, Deborah S., Maupin, Molly A. 2004. Estimated use of water in the United States in 2000. U.S. Geological Survey Circular 1268. 46 p.

Irwin, William P., Wooden, Joseph L. 1999. Plutons and accretionary episodes of the Klamath Mountains, California and Oregon. U.S. Geological Survey Open File Report 99-374.

Iverson, Justin. 2002. Investigation of the hydraulic, physical, and chemical buffering capacity of the Missoula Flood deposits for water quality and supply in the Willamette Valley of Oregon. Corvallis, Oregon: Oregon State University, M.S. thesis, 147 p.

Johnson, A. I., Moston, R. P., Versaw, S. F. 1966. Artificial Recharge of groundwater Grand Prairie Region, Arkansas: Laboratory study of aquifer properties and well design for an Artificial Recharge site. U.S. Geological Survey Water-Supply Paper 1615-H. 41 p.

Johnson, Jenda A., Hawkesworth, Chris J., Hooper, Peter R., Binger, G. Ben. 1998. Major and trace element analyses of Steens Basalt, Southeastern Oregon. U.S. Geological Survey Open-File Report 98-482. 31 p.

Kimbler, O.K., Kaymann, R.G., Whitehead, W.R. 1975. Cyclic storage of freshwater in saline aquifers. Lousiana Water Resources Research Institute Bulletin No. 10. Baton Rouge, Louisiana: 78 p.

Kupillas, Malia. 2006. Pacific Hydro-Geology, Inc., owner, certified water rights examiner and Hydrogeologist. Conversation with the author, July 20.

Leonard, A.R., Collins, C.A. 1983. Groundwater in the northern part of Clackamas County, Oregon. Oregon Water Resources Department Ground Water Report No. 29. Salem, Oregon: 85 p.

Lichtler, William F., Stannard, David I., Kouma, Edwin. 1980. Investigation of Artificial Recharge of aquifers in Nebraska. U.S. Geological Survey Water-Resources Investigations 80-93. 112 p.

Lindholm, G.F. 1996. Summary of the Snake River Plain regional aquifer system analysis in Idaho and eastern Oregon. U.S. Geological Survey Professional Paper 1408-A. 68 p.

Lissner, Frederick G. 1977. Groundwater conditions on the Harbor Bench, Southwestern Curry County, Oregon. Oregon Water Resources Department Ground Water Report No. 26. Salem, Oregon: 75 p.

Lite, Kenneth E., Grondin, Gerald H. 1988. Hydrogeology of the basalt aquifers near Mosier, Oregon: A groundwater resource assessment. Oregon Water Resources Department Ground Water Report No. 33. Salem, Oregon: 119 p.

Lite, Kenneth E., Gannett, Marshall W. 2002. Geologic framework of the regional groundwater flow system in the Upper Deschutes Basin, Oregon. U.S. Geological Survey Water Resources Investigation 02-4015. 44 p.

Lite, Kenneth E. 2007. U.S. Geological Survey and Oregon Water Resources Department, Hydrogeologist. Written communication with the author, June, 2007.

Lowry, Christopher S., Anderson, Mary P. 2006. An assessment of Aquifer Storage Recovery using ground water flow models. Groundwater 44(5):661-667.

McFarland, William D. 1983. A description of aquifer units in western Oregon. U.S. Geological Survey Open-File Report 82-165 35 p.

McFarland, W.D., and Morgan, D.S. 1996. Simulation analysis of the groundwater flow system in the Portland Basin, Oregon and Washington. U.S. Geological Survey Water-Supply Paper 2470-B. 83 p.

Merritt, Michael L. 1997. Tests of subsurface storage of freshwater at Hialeah, Dade County, Florida, and numerical simulation of the salinity of recovered water. U.S. Geological Survey Water-Supply Paper 2431. 114 p.

Miller, Donn W. 1986. Ground water conditions in the Fort Rock Basin, Northern Lake County, Oregon. Oregon Water Resources Department Groundwater Report No. 31. Salem, Oregon: 196 p.

Miller, Donn W. 2007. Oregon Water Resources Department: Hydrogeologist, conversation with the author, July 27.

Miller, T.J. 2001. Aquifer Storage and Recovery of drinking water using Cambrian-Ordovician aquifer in Wisconsin. Cooperative report prepared for the Oak Creek Water and Sewer Utility and the AWWA Research Foundation, published by AWWA Research Foundation. Denver, Colorado: 122 p.

Mirecki, June E., Campbell, Bruce G., Conlon, Kevin J., Petkewich, Matthew D. 1998. Solute changes during aquifer storage recovery testing in a limestone/clastic aquifer. Groundwater 36(3):394-403.

Montomgery Watson, Inc., Golder Associates. 2000. Hydrogeologic feasibility of Clackamas River Water well no. 1 for Aquifer Storage and Recovery. Portland, Oregon: 142 p.

Montgomery Watson, Inc., Golder Associates. 2001. City of Tigard Phase I: ASR feasibility study. Portland, Oregon: 74 p.

Mukhopadhyay, A., Al-Sulaimi, J., Al-Sumait, A.A. 1998. Creation of potable water reserve in Kuwait through artificial recharge. In: Peters, J.H. et al., editor. Artificial Recharge of Groundwater; Amsterdam. A.A. Balkema. p. 271-276.

Murray, E.C., Tredoux, G. 2002. Borehole injection tests on Windhoek's fractured quartzite aquifer. In: P.J. Dillon, editor. Management of aquifer recharge for sustainability, Proceedings of the 4th International Symposium on artificial recharge, Adelaide Sept. 22-26, 2002, Swets & Zeitlinger, Lisse: Netherlands. p. 251-256.

National Research Council. 2007. Managed underground storage of recoverable water. The National Academies Press.

Newcomb, R.C. 1960. Summary of groundwater in subareas of the Snake River Basin in Oregon south of the Wallowa Mountains. U.S. Geological Survey Open File Report 60-105. 19 p.

Newcomb, R.C. 1969. Effect of tectonic structure on the occurrence of groundwater in the basalt of the Columbia River Group of the Dalles Area Oregon and Washington. U.S. Geological Survey Professional Paper 383-C. 33 p.

Newcomb, R.C., Brown, S.G. 1956. Groundwater resources of Cow Valley near Ironside, Mahleur County, Oregon. U.S. Geological Survey Open File Report 56-17. 78 p.

Neuman, S.P. 1972. Theory of flow in unconfined aquifers considering delayed response of the water table. Water Resources Research 8(4): pp. 1031-1045.

Neuman. S.P. 1974. Effect of partial penetration on flow in unconfined aquifers considering delayed gravity response. Water resources Research 10(2): pp.303-312.

Neuman, S.P. 1975. Analysis of pumping test data from anisotropic unconfined aquifers considering delayed gravity response. Water Resources Research 11(2): pp.329-342.

O'Hare, Margaret, P., Fairchild, Deborah M., Hajali, Paris A., Canter, Larry W. 1986. Artificial Recharge of groundwater: status and potential in the contiguous United States. Chelsea, Michigan: Lewis Publishers, Inc. 419 p.

Oregon Climate Service. 2007. Normal annual precipitation GIS coverage, State of Oregon: Oregon State University.

Oregon Department of Environmental Quality. 1995. Report on hydrogeology, groundwater chemistry and land uses in the lower Umatilla Basin Groundwater Management Area. 90 p.

Oregon Geospatial Data Clearinghouse. Retrieved March, 2006. http://www.oregon.gov/DAS/IRMD/GEO/alphalist.shtml.

Oregon Health Division. 1998. Oregon drinking water quality standards. Oregon Health Division. Salem, Oregon: 16 p.

Oregon Water Resources Board. 1965. Hood Basin Report. Salem, Oregon. 114 p.

Oregon Water Resources Department. 1985. Rogue River Basin Report. Salem, Oregon: 296 p.

Oregon Water Resources Department. 1986. John Day River Basin Report. Salem, Oregon: 264 p.

Oregon Water Resources Department. 1992. Willamette Basin Report. Salem, Oregon: 350 p.

Oregon Water Resources Department. 2004a. Aquifer Storage and Recovery (ASR) Limited License #007. Salem, Oregon.

Oregon Water Resources Department. 2004b. Aquifer Storage and Recovery (ASR) Limited License #008. Salem, Oregon.

Oregon Water Resources Department. Oregon Well Log Database. Retrieved 2006-2007, Salem. http://apps2.wrd.state.or.us/apps/gw/well_log/Default.aspx.

Oregon Water Resources Department. Water Allocation Resource System (WARS). Retrieved 2006-2007 Salem. www.Telnet wars.wrd.state.or.us.

Oregon Water Resources Department. Water Rights Information System (WRIS). Retrieved 2006-2007. Salem. http://apps2.wrd.state.or.us/apps/wr/wrinfo/.

Oregon Water Resources Department. Groundwater Level database. Retreived 2006-2007. http://map.wrd.state.or.us/apps/wr/wr_mapping/?TOC_CFG=WELLS.

Oregon Water Resources Department. 2007. Aquifer Storage and Recovery (ASR) Limited License #012. Salem, Oregon.

Orr, Elizabeth, Orr, William. 2000. Geology of Oregon. Dubuque, Iowa: Kendall/Hunt Pub. Co. 254 p.

Owyhee Local Advisory Committee. 2003. Owyhee Agricultural Water Quality Management Area Plan. Oregon Department of Agriculture Malheur County Soil and Water Conservation District. 30 p.

Palmer, Ron, Wendell, Daniel, Hutchinson, Adam, Foreman, Terry. 1997. Optimization of ASR operations in a nitrate and PCE contaminated aquifer. Conjunctive use of water resources: Aquifer Storage and Recovery. Long Beach, California: American Water Resources Association. p. 123-131.

Pavelic, P., Dillon, P.J., Toze, S., Barber, C., Yin Foo, D.A. , Knapton, A., Jolly, P.B. 2002. Water banking in the Australian tropics: results from a trial on South Goulburn Island, Northern Territory. In: Dillon, P.J., editor. Management of Aquifer Recharge for sustainability; Adelaide, South Australia. A.A. Balkema. p 441-446.

Pendleton Public Works Department. 2006. City of Pendleton ASR Project: 2nd Annual Report, Pilot Test Cycle 4. Pendleton, Oregon. 32 p.

Petkewich, Matthew D., Parkhurst, David L., Conlon, Kevin J. 2004. Hydrologic and geochemical evaluation of the Aquifer Storage Recovery in the Santee limeston/Black Mingo aquifer, Charleston, South Carolina, 1998-2002. U.S. Geological Survey Scientific Investigations Report 2004-5046. 51 p.

Pitt, William, Magenheimer, Stewart.1997. ASR technology: avoidance and solutions to aquifer clogging problems. Conjunctive use of water resources: Aquifer Storage and Recovery. Long Beach, CA: American Water Resources Association.

Piper, A.M., Robinson, T.W., Park, C.F. 1939. Geology and groundwater resources of the Harney Basin, Oregon. U.S. Geological Survey Water Supply Paper 841. 223 p.

Price, C.E. 1961. Artificial Recharge through a well tapping basalt aquifers, Walla Walla Area. U.S. Geological Survey Water Supply Paper 1594-A. 33 p.

Price, Don. 1967. Groundwater reconnaissance in the Burnt River Valley area, Oregon. U.S. Geological Survey Water Supply Paper 1839-I. 32 p.

Priest, George R. 1990. Volcanic and tectonic evolution of the Cascade volcanic arc, central Oregon. Journal of Geophysical Research 95(B12):19583-19599.

Pyne, R. David G. 1995. Artificial recharge and wells. Ann Arbor: Lewis Publishers. 376 p.

Pyne, R. David G. 2005. Artificial recharge and wells: A guide to groundwater recharge through wells. Gainesville, Florida: ASR Systems Publications. 608 p.

Pyne, R. David G. Water quality changes during Aquifer Storage and Recovery. In: Dillon, P.J., editor. Management of Aquifer Recharge for sustainability; 2002; Adelaide, Australia. A.A.Balkema. p. 65-68.

Quinones-Aponte, Vicente, Whitesides, Douglas V., Zack , Allen. 1989. Single well injection and recovery of freshwater from an aquifer containing saline water at Arecibo, Puerto Rico. U.S. Geological Survey Water-Resources Investigations Report 88-4037. 25 p.

Razack, M., Huntley, David. 1991. Assessing transmissivity from specific capacity in a large and heterogeneous alluvial aquifer. Groundwater 29(6): 856-861.

Reeder, Harold O., Wood, Warren W., Ehrlich, Garry G., Sun, Ren Jen. 1976. Artificial Recharge through a well in fissured carbonate rock, west St. Paul, Minnesota. U.S. Geological Survey Water-Supply Paper 2004. 78 p.

Reilinger, Robert, Adams, J. 1982. Geodetic evidence for active landward tilting of the Oregon and Washington coastal ranges. Geophysical Research Letters 9(4):401-403.

Rinella, Frank A., Mullins, William H., Schuler, Carol A. 1994. Reconnaissance investigation of water quality, bottom sediment, and biota associated with irrigation drainage in the Owyhee and Vale Projects, Oregon and Idaho, 1990-1991 U.S. Geological Survey Water Resources Investigations Report 93-4156. 108 p.

Robinson, P.T., Brem, G.F., McKee, E.H. 1984. John Day Formation in Oregon- a distal record of early Cascade volcanism. Geology 12(4):229-232.

Saaltink, Maarten W., Ayora, Carlos, Stuyfzand, Pieter J., Timmer, Harrie. 2003. Analysis of a deep well recharge experiment by calibrating a reactive transport model with field data. Journal of Contaminant Hydrology 65:1-18.

Scanlon Engineering. 2003. Response to Baker City ASR Proposal. Baker City, Oregon: 30 p.

Sceva, Jack E. 1966. A reconnaissance of the groundwater resources of the Hood River Valley and the Cascade Locks Area, Hood River County, Oregon. Oregon Water Resources Department Ground Water Report No. 10. Salem, Oregon: 45 p.

Schlicker, Herbert J., Deacon, Robert J., Newcomb, R.C., Jackson, R.L. 1974. Environmental Geology of Coastal Lane County Oregon. Salem, Oregon: 52 p.

Schneider, Brian J., Ku, Henry F. H., Oaksford, Edward T. 1987. Hydrologic effects of Artificial Recharge experiements with reclaimed water at East Meadow, Long Island, New York. U.S Geological Survey Water-Resources Investigations Report 85-4323. 79 p.

Sheng, Zhuping. 2005. An Aquifer Storage and Recovery system with reclaimed wastewater to preserve native groundwater resources in El Paso, Texas. Journal of Environmental Management 75:367-377.

Snavely, Jr., P.D., MacLeod, N.S., Rau, W.W., Addicott, W.O., Pearl, J.E. 1975. Alsea Formation: an Oligocene marine sedimentary sequence in the Oregon Coast Range. U.S. Geological Survey Bulletin 1395-F. 23 p.

Sneigocki, Richard T. 1964. Artificial Recharge, Grand Prairie Region: Hydrogeology of a part of the Grand Prairie Region, Arkansas. U.S. Geological Survey Water-Supply Paper 1615-B. 72 p.

Sneigocki, Richard T., Bayley, D., Engler, Kyle , Stephens, J. W. 1965. Artificial Recharge of groundwater Prairie Region, Arkansas: Testing procedures and results of studies of Artificial Recharge in the Grand Prairie Region, Arkansas. U.S. Geological Survey Water-Supply Paper 1516-G. 56 p.

Stuyfzand, P.J., Vogelaar, A.J., Wakker, J. 2002. Hydrogeochemistry of prolonged deep well injection and subsequent aquifer storage in pyritiferous sands; DIZON pilot, Netherlands In: Dillon, P.J., editor. Management of Aquifer Recharge for sustainability; 2002; Adelaide, South Australia. A.A. Balkema. p. 107-110.

Swansen, R.D., McFarland, W.D., Gonthier, J.B., Wilkinson, J.M. 1993. A description of hydrogeologic units in the Portland Basin, Oregon and Wasington. U.S. Geological Survey Water Resources Investigation 90-4196. 64 p.

Theis, C.V. 1935. The relation between the lowering of the peizometric surface and the rate and duration of discharge of a well using groundwater storage. Transactions, American Geophysical Union 16: pp. 519-524.

Topper, Ralf, Barkmann, Peter, Bird, David, Sares, Matthew. 2003. Artificial Recharge of Ground Water in Colorado: A state-wide assessment. Colorado Geological Survey. 180 p.

U.S. Department of Energy website. 2007. Accessed February, 2007. http://www.energy.gov/oregon.htm

U. S. Census Bureau. 2004, 2006. Population database, http://factfinder.census.gov.

U.S. Geological Survey. 1999. State Boundaries of the Unites States. National Atlas of the United States of America Web Site. Accessed August 23, 2007. Reston, Virginia: U.S. Geological Survey.

Vaccarro, J.J. 1999. Summary of the Columbia Plateau Regional aquifer system analysis, Washington, Oregon, and Idaho. U.S. Geological Survey Professional Paper 1413-A. 64 p.

Vallier, Tracy L., Brooks, Howard C. 1986. Geology of the Blue Mountains region of Oregon, Idaho, and Washington. U.S. Geological Survey Professional Paper 1435. 93 p.

Walker, G.W, MacCleod, N.S. 1991. Geologic Map of Oregon: U.S. Geological Survey.

Walker, George W. 1990. Miocene and younger rocks of the Blue Mountain region, excluding Columbia River Basalt Group and associated mafic lava flows. U.S. Geological Survey Professional Paper 1437. 101-118 p.

Weight, Willis D., Sonderegger, John L. 2001. Manual of applied field hydrology. New York: McGraw-Hill. 608 p.

Western Governor's Association and Western States Water Council. 2007. Population Projections and Water Availability. In: Water Policies and Planning in the West: Ensuring a Sustainable Future. Salt Lake City, Utah, October 10-12. 6 p.

Whiteman, K.J., Vaccarro, J.J., Gonthier, J.B., Bauer, H.H. 1994. The hydrogeologic framework of the Columbia Plateau aquifer system, Washington, Oregon, and Idaho. U.S. Geological Survey Professional Paper 1413-B. 73 p.

Wood, Warren W., Kraemer, Thomas R., Hearn, Jr., Paul P. 1990. Intragranular diffusion: An important mechanism influencing solute transport in clastic aquifers? Science 247: 1569-1572.

Woodcock, Douglas. 2006. Oregon Water Resources Department, Groundwater Section manager, written communication with the author, September, 2006.

Woodward, D. G.; Gannett, Marshall W.; Vaccaro, J. J. 1998. Hydrogeologic framework of the Willamette Lowland aquifer system, Oregon and Washington. U.S. Geological Survey Professional Paper 1424-B. 82 p.

Wooton, Richard S., Belanger, David W., Robinson, James W., Schmidt, Thomas W., Pyne, R. David G. 1997. Aquifer Storage Recovery in Mannheim, Ontario. In: conjunctive use of water resources: Aquifer Storage and Recovery. Long Beach, California: American Water Resources Association. p. 221-230.

Wozniak, Karl C. 1995. Report on hydrogeology, groundwater chemistry and land uses in the Lower Umatilla Basin Groundwater Management Area. Oregon Water Resources Department. Salem, Oregon: 90 p.

Wright, Dawn. 2006. Oregon state wide digital elevation models. Oregon State University, Corvallis Oregon. http://jollyroger.science.oregonstate.edu/dem/.

Yeats, Robert S., Graven, Erik P., Werner, Kenneth S., Goldfinger, Chris, Popowski, Thomas. 1991. Tectonics of the Willamette Valley, Oregon. U.S. Geological Survey Open-File Report 91-441P. 47 p.

Zinn, Brendan, Meigs, Lucy C., Harvey, Charles F., Haggerty, Roy, Peplinski, William J., Freiherr Von Schwerin, Claudius. 2004. Experimental visualization of solute transport and mass transfer in two-dimensional conductivity fields with connected regions of high conductivity. Environmental Science and Technology 38: 3916-3926.

Zollweg, J.E., Jacobson, R.S. 1986. A seismic zone on the Oregon-Idaho border: The Powder River earthquakes of 1984. Bulletin of the Seismological Society of America 76(4): 985-999.

APPENDICES

Appendix A: ASR Case Study Data Table

Source	Case Study Location	Confined?	Aquifer Lithology	Source Water	Structural Features	Aquifer thickness (m)	T (m^2/d)	T (ft^2/d)	Porosity (m^3/m^3)	Storativity (m^3/m^3)	Specific Capacity (m^3/d)	Injection Rate (gpm)	Injection Time (d)	Max. Δ h (m)	Vol Injected (MG per recharge cycle)	Percent Recovered	Well Density (#wells/ mi^2)	GW Gradient (m/m)	ASR Metric	Brown's Site Rating (%)	Project Comments, is it considered successful?
Golder Associates (1994) and	ASR LL #001 Salem, OR	yes	CRB interflow zones	N. Santiam R		3 to 30	1347	14494		4.00E-04	197.00	13800		95	457	97	2.2	0.003	1.6E+02	81%	Yes, some clogging due to sediment in the water
CH2M Hill (1997) J. Barry	ASR LL #002 Beaverton: Hanson Rd Well	yes	CRB interflow zones	Bull Run River, Tualatin R		174	6092	65550		4.40E-04	441.00	1594*	130	56	303*		1.5	N/D	1.3E+01	75%	Yes, recovering 100% stored water, project has paid for itself
	TVWD: Schuepbach Well	yes	CRB interflow zones	Bull Run River, Tualatin R	1,000 ft displacement faults	115	634	6822		no data	287.00	450^h	5	77	4^h						No, fault truncation of AQ limited storage capacity, too small, leaks to surface
Golder Associates (2000) and	ASR LL #003 Clackamas, OR	yes	CRB interflow zones	Clackamas River Water			163	1754			771.00	552^a	150	122	130^a		10	0	3.9E+01	86%	Radon in recovered water > 300pCi/L, must be aerated to meet Drinking WQ
Montgomery Watson	Clackamas River Water		Grande Rhonde/Wanapum				1858	19992		1.00E-05											Discontinued in 2003 b/c source water became too expensive
CH2M Hill (2000) and Portland	ASR LL #004 Portland, OR Coumbia South	yes	Troutdale Sandstone	Bull Run River		85	100	1076	0.15		520.00	1000^e	150	5	90^e		5.4	0.002	3.9E-02	63%	Project incomplete: not neccesary to meet supply needs at present; decrease
Bureau Water Works et al.	Shore Well Field		Sand and gravel																		in specific capacity after Pilot Testing
Golder Associates (2001) and	ASR LL #005 Tigard, OR	yes	CRB interflow zones	Bull Run River	faults truncate CRB AQ	14 to 57	81	872		1.10E-05	89.00	605^b	134	44	116^b			0.02	2.4E+00	50%	One undocumented domestic well showing water level response to injection:
Montgomery Watson			Grande Rhonde/Wanapum																		becoming an artesian well, city is working w/landowner to cap the well
CH2M Hill (2002)	ASR LL #006 Pendleton, OR: Stillman Well	yes	CRB interflow zones	Umatilla R	no apparent faults	30	3286	35357	0.15	N/D	825.00	862^c	83	76	493		6	0.0003	3.4E+01	61%	Entrained air is decreasing SC at Stillman Well
Pendleton Public Works (2005)	Pendleton, OR: Byers Well	yes	CRB interflow zones	Umatilla R							1111.00	1105^c	83								Yes, cycle 4 (2005) Inj: 133 MG, rec. 222 MG
CH2M Hill (1993) J. Barry, P Brody	Echo Junction Subbasin:Umatilla,OR	yes		Alluvial well	folds and faults truncate AQ	7.6	3344	35981		2.30E-04	50.00	500	30	53	21.6		3	0.0004			Nitrate in source water > 5mg/L, licenses modified to require WQ monitoring while injected
	ASR LL #007 Madison Farms		CRB interflow zones	Alluvial well	folds and faults truncate AQ	7.6	994	10695		1.20E-04		400			5.4^i	98			1.6E+01	88%	
	ASR LL #008, #013 McCarty Ranches		CRB interflow zones	Alluvial well								464^f	16	53	10.7						
Groundwater Solutions (2003)	ASR LL # 009 Baker City, OR	yes	CRB interflow zones	Spring and creeks trib to Powder R	faults truncate CRB AQ		90.8	977		1.00E-03	296.00	745^d	150^d	60	161^d				1.1E+01	57%	Controversial project: citizens concerned about water system waste, leaks license requires repairs
Groundwater Solutions (2003)	ASR LL #010 Tualatin, OR	yes	CRB Grande Rhonde/Wanapum	Bull Run R	faults truncate CRB AQ		329	3540		1.0E -03	313.00	2750	no testing yet	57	95		4	0.005	1.4E+01	88%	Leaky confined AQ, faults connect CRB to valley sediments
Golder Associates (2005)	ASR LL # 011 Dallas, OR	partially	Siletz R Basalt	Dallas Water Tr. Plant: Rickreal Cl	Willamette Basin	38	124	1334	0.15		19.70	168^g	70	190	16.8^g	23		0.0077			Injection and recovery rates must be limited to minimize mixing w/saline AQ, seep developed
Groundwater Solutions,Inc(2006)	ASR LL #012 Sunrise Water Authority(SE PDX)	yes	Troutdale Sand Aquifer	Clackamas River Water	Portland Basin, faults	37 to 61	131	1410		3.00E-04		650	no testing yet	225	145						No results reported as of 7/31/07, values are estimated in feasibility report
Foxworthy and Bryant (1967)	The Dalles, OR	yes	CRB interflow zones	Columbia R		12	3983	42857			4966.00	1440	180	59	52.2	85			7.4E+01	43%	Yes, cold recharge water decreased specific capacity
Aronson et al. (1983)	Nassau Co., Long Is, NY	yes	Magothy Sand w/clay lenses	Reclaimed wastewater		219	4376	47086		5.00E-05	3500.00	350		30	4				8.6E+02	67%	No, clogging due to biological activity, iron, aluminum, phosphorous
and Schneider et al. (1987)			(brackish)																		AR more effective, less expensive
Brown (2005) and Pyne (2006)	Seattle, WA	semi	Glacial Sand/Gravel	Treated Lake Youngs Reservoir			279	3002			223.00					near 100					Algae in source water caused clogging, demand has declined but provides drought supply
Brown (2005)	Salt Lake City, Utah	no	Cobbles/Sand/Silt	Treated Deer CR Reservoir			460	4950			368.00										No, permitting process became too expensive
Brown (2005)	Washoe County, Nevada	no	Glacial Sand/Gravel	Treated Truckee River	radial soil fractures		278	2991			223.00										No, Subsidence due to previous over-drafting created leaking through soil fractures
Brown (2005)	Huron, SD	yes	Glacial Till	Treated James River		12	372	4003			298.00										Naturally high water tables limited storage capacity
Brown (2005), Pyne (2006)	Las Vegas, NV	no	Basin Fill Sediments	Treated Colorado River	Some subsidence from decline	309	93 to 3716			0.001	2973.00										Largest site in world, 42 ASR wells, have raised groundwater level 100 ft from 260 ft decline
Brown (2005), Pyne (1995)	Calleguas, CA	yes	Sand and gravel	CA State Water Project		90	1800	19368	0.23	4.00E-06	1400.00				65 MGD						26 ASR wells, 11˚C temp difference between native and injected water lowered T emergency supply
Brown (2005), Baqai (2002)	Lancaster, CA	no	Alluvial Sediments	CA State Water Project		223	232	2496													In-situ formation of DBP's too high
Brown (2005) and Pyne (2006)	Denver, CO Highlands Ranch	yes	Sand and sandstone	McClellan Reservoir		61	93	1001	0.25	3.00E-04	74.00	198		281				0.0008			Meets needs, hydraulic fracturing of AQ decreased response to ASR, pH control needed
Brown (2005)	Alamogordo, NM	no	Basin Fill Sediments	Treated spring water	Closed basin	914	232	2496			186.00					85					ASR allowed municipality to fully use water allocation
Brown (2005) and CH2M Hill (1999)	Green Bay, WI	yes	Sandstone	Treated Lake Michigan			93	1001		5.50E-04	74.00				10 over 30 d	100					No, recovery of heavy metals oxidized from pyrite caused project abandonment
Brown (2005)and Miller (2001)	Milwaukee, WI	yes	Sandstone	Oak Creek		34	307	3303	0.2	2.00E-04	246.00			268		100					
Brown (2005) and CH2M Hill (2001)	Hilton Head, SC	yes	Limestone and Dolostone	Chelsea Water Treatment Plant			3567	38381		2.40E-04	2854.00					67					Yes
Brown(2005) and Castro (1995)	Myrtle Beach, SC	yes	Unconsolidated Sediments	Atlantic Intercoastal Waterway		205	148	1592			118.00			88	16	70					
Brown (2005), Gaus (2000),	Lychett Minster, Dorchester,	yes	Chalk with dual porosity	Treated surface water		30	200	2152			160.00										No, Poor water Quality in recovered water due to in-situ mixing/ diffusion
Stanfield (2001)	England																				
Cadamuro et al. (2002)	Federal District of Brazil	yes	Fractured Quartzites			120	1.3 to 40														Yes
Campbell et al. (1997)	Charleston, SC	yes	Brackish Limestone/Sand	municipal supply		21.3	20.4	220		5.50E-04	14.10	30	1	122	116	94 to 110			2.8E+02	64%	Yes
Fitzpatrick (1986)	Lee County, FL	yes	Tampa Limestone	Caloosahatchee River		36	74	796		1.00E-04	96.00	300		15		9.8 to 38.7					Yes, storing freshwater in saline AQ, successive tests increased % recovered
																					Specific Capacity decreased during injection, increased after acidizing the AQ
Gale et al. (2002)	Entire United Kingdom:																				
	Lincolnshire Limestone	varies	Limestone	municipal supply		10 to 40	1375	14795	0.005 to .5	6.00E-06	N/D										
	Cretaceous Chalk	varies	Chalk			50 to 400	6250	67250	0.005 to 2	1.00E-06											Yes, but requires water treatment as natve GW not potable
	Sherwood Sandstone	varies	Sandstone			50 to 300			0.1	1.00E-05											
	Lower Greensand	varies	Greensand			10 to 40	1250	13450	0.10 to 0.25	1.00E-05											
Gerges et al. (2002)and Pyne (2006)	Adelaide, Australia	yes	Tertiary Limestone	Reclaimed wastewater		18	180	1937		1.90E-04		1									Yes, gravity fed injection of stormwater, largely as WQ tests for ASR storage attenuation
Lichtler et al. (1980)	Aurora, Nebraska	partially	Fine Sand			33	1170	12589		1.10E-01		370									Yes
Merrit (1997)	Dade County, Florida	yes	Sand/Shells/Limestone	Fresh surface water		6.4	990	10652	0.35.	7.80E-05	502.00	455 to 785		60	334	32 to 47			5.6E+00	58%	N/D
Mukhopadhyay (1998), Pyne (2006)	Kuwait	yes	Damman Fm.Limestone	Desalinated water			4000	43040			3200.00	1058		176	45	100					Testing still in progress: storing desalinated water in brackish AQ
Murray and Tredoux (2002)	Windhoek, Namibia	partially	Fractured Quartzites, Schists	City water supply from dams	fault controlled flow paths		60	646		6.50E-03		120		40.8							Yes, could replenish over-drafted AQ extending under Auas Mts.for city supply
Palmer et al. (1997)	N. of Pasadena, CA	yes	Alluvial Sediments			91	1525	16409		2.10E-04		680				60 to 85					Yes, AQ has Nitrate contamination that was diluted to acceptable levels
																					through insitu mixing
Pavelic et al. (2002)	S. Goulburn Island, Australia	yes	Brackish Marligur Sandstone			8	70	753	0.30 to 0.30	2.00E-04						75					Yes, but clogging by iron oxyhydroxides occurs, requiring backflushing
Price (1961)	Walla Walla, WA	yes	CRB		possible structural boundaries	330	4824	51906		2.00E-04	2568.00	630		90	23				3.7E+02	63%	Yes, but air entrainment and sediment clogging issues had to be resolved
Pyne (1995)	Peace River, FL:			Treated Peace R																	
	Tampa Formation	yes	Brackish Limestone			30	455	4896	0.15	0.0004		347		122				0.0002			Low yields have led to no further ASR development in this formation
	Suwanee Formation	yes	Limestone			100	560	6026		0.0001		347		174	4 to 25	74 to 131		0.0003			21 ASR wells, provided water after 2004 hurricane Charley
Pyne (1995, 2005)	Cocoa, FL	yes	Brackish Limestone	Taylor CR Reservoir, wastewater		21	447	4810		2.3E-4 to 3.0E-4	717.00	1000		11	7.2 to 60.1	100 to 115			4.0E+01	64%	10 ASR wells, one poor WQ prevents use, helps to meet peak water demands
Pyne (1995)	Chesapeake, VA:			Northwest R															2.4E+01	75%	
	Upper Potomac Formation		Clayey Sand			18	911	9802		4.50E-05	591.00	1800		27	5 to 88	80 to 87					Yes, but Mn mobilized by pH< 8.0, pH control and Mn removal required
Pyne (1995, 2005)	Wildwood, NJ	no	Sand and gravel	City surface water supply		65	1078	11599			863.00	650		4	100	80					Operating 4 ASR wells since 1968, SC declining due to Fe in source water, salt water barrier
Quinones-Aponte (1989)	Arecibo, Puerto Rico	yes	Aymamon Limestone	River water	solution openings	15	5109	54973			5946.00	61 to 180		3	0.6 to 6.6	21 to 47		0.0008	1.5E+02	67%	Not for water supply due to chemical reactions, but useful as salinity barrier
Reeder et al. (1976)	Minneapolis-St. Paul, MN	yes	Prairie du Chien Dolomite		fractured w/ solution openings	46	696	7489		4.00E-04	228.00	176		107	2.7						Yes, Dolomite is hydraulically connected to underlying sandstone
Saaltink et al. (2003)	Langerak, The Netherlands	yes	Sand with calcite, pyrite			25	640	6886													Yes, recharge water saturated with respect to Ca to prevent calcite dissolution
Sheng (2005)	El Paso, Texas	no	Sand with clay lenses			162	1242	13364			1000.00	550	365	107	1094 per yr				1.5E+01	69%	Yes, for 18 yrs., in conjunction with AR spreading basins
Sneigocki (1964, 1965)	Grand Prairie Region, Arkansas	yes	Quaternary Sand/Gravel			7 to 38	529	5692		0.14	423.00	120- 350		27	65				1.2E+01	79%	Yes, recharge water Temp lower than native water decreased Spec. Capacity
Stuyfzand et al. (2002)	Southern Netherlands	yes	Miocene Sand			39	510	5488													No, high dissolved iron, Mn and ammonia from pyritiferous sands
Wootton et al. (1997)	Mannhein, Ontario	no	Alluvial Sediments				5500	59180			658.00	705									Yes, but some decrease in specific capacity due to air binding to AQ
					case study average =		1279	13762													
					case study std dev =		1705	18341													

Abbreviations: AQ= Aquifer, CRB=Columbia River Basalt, Fm= Formation, TVWD= Tualatin Valley Water District, SC = Specific Capacity, AR= Artificial Recharge through infiltration basins.

Sources: *Annual Report 2006, [a]Annual Report 2002, [b]Annual Report 2005, [c]Annual Report 2005, dAnnual Report 2005, [e]Annual Report 2002 (avg. rate, vol per well), [f]Annual Report 2006, [g]Annual Report 2006, [h]Pilot Test Results 2001, [i]Annual Report 2006.

Appendix B: Complete Well Data Tables

Well No.: Oregon Water Resources Department well log number assigned at the time of drilling.
Location: Township, Range, Section and Quarter-Quarter location of well as reported on the well log.
Open Intervals: Depth to top and bottom of perforated or open hole intervals in the well.
Aquifer Lithology: Aquifer material as reported in well log or inferred from well log description.
Well Yield: Production rate of the well, reported in the well log in gallons per minute (gpm).
Drawdown/time: Total water level decline per hours of pumping at the time of well installation.
Well Density: Number of wells per square mile, calculated from Oregon Water Resources Department well log database as the number of wells per section of similar depth.
SC: Specific capacity of the well, in gallons per minute per foot of drawdown, or m^2/d, as reported at the time of installation.
Est. T: Transmissivity as estimated from specific capacity using Meier et al. (1999) equation T = K (SC)^0.67, where K is a scaling factor based on the units used. K = 15.3 for m^2/d.
Max Δh: Head space in the well, as reported on the well log.
Water Rights: Municipality's surface water rights, in cubic feet per second (cfs), and the name of the source river.
Treatm. Capacity: Volume capacity of water treatment plant in the vicinity of source water, if a plant exists.
Volume recharge: For the purpose of estimating the amount of storage required, 1/2 of treatment plant capacity is used for recharge volume. If there is no treatment plant, 1/2 of surface water rights is used instead.
Time to recharge: The number of days that the city might inject water into storage, usually estimated at 120 days, or 4 months, which is an average winter season.
ASR Metric: Dimensionless volumetric use to analyze whether the aquifer has storage available that is less than, equal to, or greater than 1/2 the municipal surface water rights or 1/2 treatment plant capacity. The equation is as follows: Transmissivity* MaxΔh / 5.6(Volume recharge/ time to recharge).
Grad: Hydraulic gradient.
DTW: Depth to water observed in nearby state observation well, in 1995 and 2005, which helps determine whether groundwater levels are stable in the area.
Population: United States Census reported population data for the town.
Precipitation: Average annual precipitation in inches (in/yr).

Table B-1. Deschutes Basin Well Data

Well No.	Location	T-R-S QQ-Q	Open Intervals Depth (ft)	Aquifer thick-ness(ft)	Aquifer Lithology	Formation	Well Yield (gpm)	Draw down (ft)	Well Density (#/mi^2)	SC (gpm/ft)	SC (m^2/d)	Est. T (ft^2/d)	Est. T (m^2/d)	Max Δh (ft)	Max Δh (m)	Water Rights[a] (cfs)	Treatm. Capacity (MGD)	Volume re-charge** (m3/d)	Time to recharge (d)	ASR Metric	Grad[c] (m/m)	DTW[e] 1995/ 2005 (ft)	Pop-ulation[b] 1990/2006	Precip-itation[d] (in/yr.)
JEFF 426	Madras-1	11S 13E 2A	110-114 134-140	10	Basalt Gravel	Tob	85	60.714	10	1.4	25	1420	132	341.12	104	none	N/D	453646	120	0.65	N/D	1979/1990 340/ 275.7	3,443 / 5,146	11
JEFF 427	Madras-2	11S 13E 2A	129-134	5	Sand/gravel	Ts	470	47		10.00	179.00	5315	494	324.72	99.0			453646	120	2.31				
JEFF 428	Madras-3	11S 13E 2D	123-124 128-143	16	Sand/gravel/clay Sand/gravel	Ts	329	N/D		N/D	N/D	N/D	N/D	N/D	N/D									
JEFF 823[g]	Madras-4	11S 13E 1B			Sand/gravel	Ts	22	1.6667		13.20	237	1646	153	341.12	104			453646	120	0.75				
DESC 2387	Terrebonne	14S 13E 16A	71-116	45	Gravel/sandstone	Ts	20	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D	120	N/D	N/D	1962/2006 105/ 117	1,143 / 1,469	11
DESC 3023	Sisters	15S 10E 9B	15-30 29-59	45	Basalt Sand/conglomerate	Tob	1310	5.3036	25	247	4423	28460	2645	85.28	26	Whycus CR 2.9	N/D	3507.84	120	420	N/D	N/D	679 / 1,173	14
DESC 3853	Redmond-1	15S 13E 9A	61-91	30	Basalt/gravel	Tob	1300	39.394	25	33.00	592	11836	1100	167.28	51	Deschutes R 35	N/D	42336	120	28.40	N/D	1980/2005 295/ 312		9
DESC 3879	Redmond-2	15S 13E 16B	78-129	51	Sandstone	Ts	1170																7,163	
DESC 407[g]	Redmond-3	15S 13E 22D	162-168 224-230	12	Conglomerate Sandstone/ gravel	Ts	1300	0.8508		1528	27391	5993	557	324.72	99	35		42336	120	4.98			/ 18,017	
DESC 3953	Redmond-4	15S 13E 22	106-138	32	Sand/gravel	Ts	1100																	

Table B-1. Deschutes Basin Well Data (continued).

Well No.	Location	T-R-S QQ-Q	Open Intervals Depth (ft)	Aquifer thick-ness(ft)	Aquifer Lithology		Well Yield (gpm)	Draw down (ft)	Well Density (#/mi^2)	SC (gpm/ft)	SC (m^2/d)	Est. T (ft^2/d)	Est. T (m^2/d)	Max Δh (ft)	Max Δh (m)	Water Rights[a] (cfs)	Treatm. Capacity (MGD)	Volume re-charge** (m^3/d)	Time to recharge (d)	ASR Metric	GW Grad[c] (m/m)	DTW[e] 1995/ 2005 (ft)	Pop-ulation[b] 1990/200	Precip-itation[d] (in/yr.)
DESC 3951[g]	Redmond-5	15S 13E 22C	157-164	40	Sand/gravel	Ts	N/D	N/D		7131	127830	199921	18580	308.32	94	35	N/D	42336	120	884	N/D			9
			181-194		Sandstone																			
			198-210		Sand/gravel																			
			231-236		Basalt																			
			241-244		Basalt																			
																Tumalo CR						2000/2003		
DESC 5526[g]	Bend-1	18S 11E 27C	43-91	48	Basalt	Tob	310	9.118	10	34.00	609	1917	178	131.2	40	36	N/D	43545.6	120	3.51	N/D	505/ 507		11
DESC 5524	Bend-2	18S 11E 27C	69-91	22	Basalt	Tob	460	104.5		4.40	79	3077	286	167.28	51	36		43545.6	120	7.18				
DESC 5578	Bend-3	18S 12E 5C	215-243	28	Basalt	Tob	2000							242.72	74								20649	
DESC 5577	Bend-4	18S 12E 5C	194-274	80	Basalt	Tob	1837	4.002		459	8228	69143	6426	N/D	N/D	36		43545.6	120	N/D			/ 62937	
DESC 1738	Bend-5	18S 12E 7B	167-197	30	Basalt	Tob	800	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D		N/D	N/D	120	N/D	N/D	N/D		11
DESC 9108	Bend-6	18S 12E 7B	127-151	24	Basalt	Tob	550	23.91		23.00	412	9297	864	373.92	114	36		43545.6	120	48				
																none avail						1985/2006	N/D	
DESC 55049	La Pine-1	22S 11E 18B	48-77	29	Basalt	Tob	1300	13	25	100	1793	24912	2315	118.08	36	1	N/D	2419.2	120	738		27/ 37		17
DESC 54968	La Pine-2	22S 11E 18B	47-62	25	Basalt	Tob	1300	24.07	25	54.00	968	16483	1532	114.8	35	1		2419.2	120	475				
																Ochoco CR							5355/	
CROO 53453	Prineville	15S 15E 11B	447-539	92	Basalt/gravel	Tob	700	11.5	3	60.87	1091	17860	1660	408	124.4	5	N/D	6048	120	731			9313	11

Formation: Tob = Deschutes Formation basalts, Ts = Deschutes Formation unconsolidated sediments.

Sources: [a] Oregon Water Resources Water Rights Information System (accessed January 2007), [b]United States Census Population Database (accessed January 2007), [c] Gonthier (1985), [d]Oregon Climate Service (2007), [e](Oregon State Observation Well data (accessed January 2007), [g]Gannet et al. (2001): low end of reported T.

*Denotes this municipality does not have surface water rights at this time. According to Oregon Water Resources Water Availability Report System (WARS) Database, water available at nearest surface water source is noted.

**When a municipality has no current surface water rights, this study has made a conservative estimate of water right volume that may be acquired for storage, 1.5 to 2 cfs.

Table B-2. Goose and Summer Lakes Basin Well Data

Well No.	Location	T-R-S QQ	Open Intervals Depth (ft)	Aquifer thick-ness(ft)	Aquifer Lithology	Formation	Well Yield (gpm)	Draw down (ft)	Well Density (#/mi^2)	SC (gpm/ft)	SC (m^2/d)	Est. T (ft^2/d)	Est. T (m^2/d)	Max Δh (ft)	Max Δh (m)	Water Rights[a] (cfs)	Treatm. Capacity (MGD)	Volume re-charge** (m^3/d)	Time to recharge (d)	ASR Metric	GW Grad[c] (m/m)	DTW[e] 1995/ 2005 (ft)	Pop-ulation[b] 1990/2000	Precip-itation[d] (in/yr.)
LAKE 1023	Christmas Valley	27S 17E 17	630-660	30	Pumice/ Conglomerate	Tvm or Tat	800	1	1	500	8963	73223	6805	34	10	1 cfs hypothetical	N/D	2419	120	625	0.00008	1985/1995 51/52.5	989 -0.0053	9
LAKE 4570	Paisley	33S 18E 24D	83-121	38	Sand/gravel	Qs	120	29	2	4	74	2948	274	52	15.8	1 cfs available Chewaucan R	N/D	2419	120	38	N/D	75/82	350/242	11
LAKE 1852	Plush	36S 24E 28C	33-43	10	Gravel	Qs	15	7	3	2	38	1897	176	23	7.0	1 cfs available Honey CR	N/D	2419	120	11	N/D	N/D	93 -.54%	11
LAKE 2468	Lakeview-1	39S 20E 15A	2072-2380	308	Basalt		150	320	2	0.5	8	685	64	50	15.2	1.5 cfs from 18	N/D	3629	120	6	N/D		2526/	
LAKE 2471	Lakeview-2	39S 20E 15B	100-452	352	Sand/gravel	Qs/Qal	250	50	2	5	90	3347	311	20	6.1	springs	N/D	3629	120	11	N/D	20/20	2378	17
LAKE 3107	Alkali Lake	30S 23E 24C	60-120	60	Basalt	Tob or Tba	30	0.1	1	300	5378	52001	4833	90	27.4	1 cfs hypothetical	N/D	2419	120	1174	N/D	20/21	N/D	11

Formation: Qs = Lacustrine and fluvial sediments, Tvm = Mafic vent rocks, Tat = Ash-flow tuff, Tba = Basalt and andesite, Tob = Olivine basalt.

Sources: [a] Oregon Water Resources Water Rights Information System (accessed March 2007),[b]United States Census Population Database (accessed March 2007), [c] Mcfarland and Ryals (1991), [d]Oregon Climate Service (2007), [e]Oregon State Observation Well data (accessed April 2007).

Table B-3. Grande Ronde Basin Well Data

Well No.	Location	T-R-S-QQ	Open Intervals Depth (ft)	Aquifer thick-ness(ft)	Aquifer Lithology	Formation	Well Yield (gpm)	Draw down (ft)	Well Density (#/mi^2)	SC (gpm/ft)	SC (m^2/d)	Est. T (ft^2/d)	Est. T (m^2/d)	Max Δh (ft)	Max Δh (m)	Water Rights[a] (cfs)	Treatm. Capacity (MGD)	Volume re-charge (m^3/d)	Time to recharge (d)	ASR Metric	GW Grad[c] (m/m)	DTW[e] 1995/ 2005 (ft)	Pop-ulation[b] 1990/2000	Precip-itation[d] (in/yr.)
WALL 50195	Enterprise	1S 44E 36d	421-1315	894	Basalt	CRB	1023	81	1	13	226	6227	579	61.6	18.8	14.75 Spring BranchC	N/D	35683	120	7	N/D	WALL 249 12_/12	1905/ 1800	15
UNIO 778	La Grande-1	3S 38E 3F	115-340	385	Gravel	Qal	1000	108	23	9	166	5058	470	27	8.2	0.75	N/D	1814	120	46	0.003	UNIO 680 100/100	11766/ 12440	20
UNIO 50520	La Grande-2	3S 38E 16	360-520 265-541	276	Gravel/Clay Gravel/Sand/Clay	Qal	2000	58	5	34	618	12205	1134	30	9.1	Grande Ronde R		1814	120	122				
UNIO 2098	La Grande-3	3S 38E 8cd	1107-2430	1323	Basalt/Clay	CRB	2600	N/D	1	N/D	N/D			0	0.0	Morgan L Res.		1814	120	0				
UNIO 1743	Elgin	1N 39E 22b	620-655	35	Basalt	CRB	1095	87	1	13	226	6213	577	0	0	134 Grande Ronde F	N/D	324173	120	0	N/D	UNIO 1717 21/21	1586/ 1642	22
WALL 146	Wallowa	1N 42E 14b	440-864	424	Basalt/Clay	CRB	1700	94	2	18	324	7920	736	106	32.31	10.15 Bear Cr	N/D	24555	120	21	N/D		748/824	18
WALL 50774	Joseph	2S 45E 30d	98-247	149	Cobbles/Gravel	Qal	400	54	1	7	133	4355	405	76	23.16	6.66	N/D	16112	120	12	N/D	WALL 870	1073/ 1005	16

Formation: Qal = Quaternary alluvium, CRB = Columbia River Basalt.

Sources: [a] Oregon Water Resources Water Rights Information System (accessed January 2007),[b]United States Census Population Database (accessed January 2007), [c] McFarland (1984), [d]Hogeson (1964), [e]Oregon State Observation Well data (accessed January 2007), [f]Hampton and Brown (1964).

Table B-4. Hood Basin Well Data

Well No.	Location	T-R-S-QQ	Open Intervals Depth (ft)	Aquifer thick-ness(ft)	Aquifer Lithology	Formation	Well Yield (gpm)	Draw down (ft)	Well Density (#/mi^2)	SC (gpm/ft)	SC (m^2/d)	Est. T (ft^2/d)	Est. T (m^2/d)	Max Δh (ft)	Max Δh (m)	Water Rights[a] (cfs)	Treatm. Capacity (MGD)	Volume re-charge** (m^3/d)	Time to recharge (d)	ASR Metric	Grad[c] (m/m)	DTW[e] 1995/ 2005 (ft)	Pop-ulation[b] 1990/200	Precip-itation[d] (in/yr.)
																	N/D					25_/25	930/	
HOOD 352	Cascade Locks-1	2N 8E 6AD	75-100	25	Sand and Gravel	Qs	390	1	6	390	6996	62023	5764	62	19	Dry Cr		88087	180	40.0	N/D		1101	85
HOOD 346	Cascade Locks-2	2N 8E 1BA	0-12	83	Basalt	Qs			1							12					N/D			
(private well)			12-83		Sand and Gravel		30	3		10	179	5328	495	66	20			88087	180	3.61				
HOOD 354	Cascade Locks-3	2N 8N 5AD	158-173	15	Seds/conglomerate	ECF	4	160	3	0.03	0	96	9	31	9.4			88087	180	0.0	N/D			
(US Forest Service)																								
																Cold Spr Cr	N/D						4632/	30
HOOD 609	Hood River-1	3N 11E 31CA	54- 600	546	Basalt	CRB	2	125	2	0.02	0.3	71	7	476	145	19		139470	180	0.2	N/D	45_/48	6480	
HOOD 50350	Hood River-2	2N 9E 22CD	60-120	60	Basalt	CRB	1	100	1	0.01	0.2	52	5	79	24	Laurel Cr		139470	180	0.0	N/D			
(county park)																19								
																Columbia R	about 2.2					artesian:	11060/	14
WASC 2419	The Dalles-1	1N 13E 3B	62-200	33	Basalt	CRB	2500	5.5	7	455	8154	68725	6387	23	7	40		1500000	180	1.0	N/D	40 ft	11894	
WASC 2416	The Dalles-2	1n 13E 3C	62-224	16	Basalt		70	106	7	0.7	12	863	80	82	25	Crow Cr		1500000	180	0.0	N/D	above		
																3055						ground		
																Fifteen Mile CF	N/D					60_/40	N/D	12
WASC 51004	Durfur	1S 14E 11D	120-300	180	Basalt	CRB	160	100		2	29	1561	145	16	5	10*		73405	180	0.3	N/D			
(domestic well)																								
																Mosier CR						WASC 2759	244/408	25
WASC 2856	Mosier-1	2N 12E 7A	120-190	70	Basalt	CRB	167	2.09	37	80	1433	21442	1993	89	27	10*	N/D	73405	180	23.6	0.04	25/75		
WASC 2764	Mosier-2	2N 11E 12C	340-404	64	Basalt	CRB	357	16.6	17	22	386	8899	827	0	0					0.0	0.05			

Formation: Qs = Quaternary sediments, CRB = Columbia River Basalt, ECF= Eagle Creek Formation.

Sources: [a] Oregon Water Resources Water Rights Information System (accessed January 2007), [b] United States Census Population Database (accessed January 2007), [c] McFarland and Morgan (1996), [d] Leonard and Collins (1983), [e] Oregon State Observation Well data (accessed January 2007).

*Denotes this municipality does not have surface water rights at this time. According to Oregon Water Resources Water Availability Report System (WARS) Database, water available at nearest surface water source is noted.

**When a municipality has no current surface water rights, this study has made a conservative estimate of water right volume that may be acquired for storage, 1.5 to 2 cfs.

Table B-5. John Day Basin Well Data

Well No.	Location	T-R-S QQ	Open Intervals Depth (ft)	Aquifer thick-ness(ft)	Aquifer Lithology	Formation	Well Yield (gpm)	Draw down (ft)	Well Density (#/mi^2)	SC (gpm/ft)	SC (m^2/d)	Est. T (ft^2/d)	Est. T (m^2/d)	Max Δh (ft)	Max Δh (m)	Water Rights[a] (cfs)	Treatm. Capacity (MGD)	Volume re-charge** (m^3/d)	Time to recharge (d)	ASR Metric	Grad[c] (m/m)	DTW[e] 1995/ 2005 (ft)	Pop-ulation[b] 1990/200	Precip-itation[d] (in/yr.)
GILL 166	Arlington-1	3N 21E 28BB	64-619	555	Basalt	CRB	400	294	3	1.4	24	1399	130	93	28.0	Columbia R	N/D	20000	120	3.9	N/D	180/186	425/491	9
GILL 50142	Arlington-2	3N 21E 28BB	195-280	100	Basalt	CRB										8.16								
			375-385		Basalt	CRB	200	N/D	3	N/D	N/D	N/D	N/D	204	62.0									
			450-455		Basalt	CRB																		
GILL 170	Arlington-3	3N 21E 26AB	632-770	138	Basalt	CRB	930	5		186	3334	37749	3508	N/D	N/D									
GILL 205	Condon-1	4S 21E 10	40-630	590	Basalt	CRB	300	240		1.3	22	1322	123	130	40.0	Hay Cr	N/D	2417	120	43.6	N/D	N/D	635/709	13.7
GILL 50081	Condon-2	3S 21E 19DB	67-92	25	Breccia/Seds	Qal	90	48	3	1.9	34	1735	161	18.5	5.6	1		2417	120	8.0				
GILL 50079	Condon-3	3S 21E 19AC	33-38	5	Gravel	Qal	108	28		3.9	69	2813	261	10.5	3.2			2417	120	7.4				
																							399/435	12
WHEE 50304	Fossil	6S 21E 33AC	222-227	5	Basalt	CRB	250	600	7	0.42	7	633	59	250	76	Stars Spring	N/D	483	120	198.4	N/D	N/D		
			430-525	95	Basalt	CRB										0.2								
																springs							149/130	15
WHEE 50057	Spray	8S 24E 36AB	30-51	21	Sand/Gravel	Qal	100	10	20	10	179	5325	495	9	2.7	0.1	N/D	242	120	118.3	N/D	N/D		
																						6/_7	1836	
GRAN 434	John Day-1	13S 31E 23BD	59-250	191	Basalt/Gravel	CRB	876	100	15	9	157	4873	453	0	0	Long Gulch	N/D	8467	120	0.0	N/D		/1605	10.3
GRAN 50574	John Day-2	13S 31E 23AC	121-161	40	Basalt	CRB	840	58	10	14	260	6825	634	8.5	2.6	3.5		8467	120	4.2				

Formation: Qal = Quaternary alluvium, CRB = Columbia River Basalt.

Sources: [a] Oregon Water Resources Water Rights Information System (accessed January 2007), [b] United States Census Population Database (accessed January 2007), [c] Gonthier (1985), [d] Oregon Water Resources Department (1986), [e] Oregon State Observation Well data (accessed January 2007).

Table B-6. Klamath Basin Well Data

Well No.	Location	T-R-S QQ	Open Intervals Depth (ft)	Aquifer thick-ness(ft)	Aquifer Lithology	Formation	Well Yield (gpm)	Draw-down (ft)	Well Density (#/mi^2)	SC (gpm/ft)	SC (m^2/d)	Est. T (ft^2/d)	Est. T (m^2/d)	Max Δh (ft)	Max Δh (m)	Water Rights[a] (cfs)	Treatm. Capacity (MGD)	Volume re-charge** (m^3/d)	Time to recharge (d)	ASR Metric	Grad[c] (m/m)	DTW[e] 1995/ 2005 (ft)	Pop-ulation[b] 1990/200	Precip-itation[d] (in/yr.)
KLAM 10202	Lenz	30S 8E 14BC	90-300	210	Basalt	Qv/Tv	4000	41	1	98	1749	24499	2277	10.5	3	N/D	N/D	2419	120	65	0.008	N/D	N/D	20
KLAM 10189	Fort Klamath	33S 7E 8AB	100-240	140	Sand/gravel	Qs	750	200	1	4	67	2760	257	34	10.4	water for storage in Wood R**	N/D	2419	120	24	0.04	N/D	3300	20
KLAM 10179	Klamath Falls-1	38S 9E 32C	125-215	90	Basalt	Tv	1650	110	5	15	269	6987	649	4	1.2	Upper Klamath	none	2419	120	7	0.001	N/D	17,737/	
KLAM 12050	Klamath Falls-2	38S 9E 28D	190-900	710	Sediments/basalt	Ts	720	10	1	72	1291	3800[c]	354	64	19.5	Lake		2419	120	61			19,882	
KLAM 12167	Klamath Falls-3	38S 9E 35D	62-422	360	Sand/clay	Qs	750	194	2	4	69	2817	262	33	10.1	2		2419	120	23				14
JACK 21221	Pinehurst	40S 4E 8BB	24-140	116	Basalt	Qv/Tv	30	11.5	8	3	47	2164	201	25	7.6	water for storage Jenny CR**	N/D	2419	120	14	N/D	N/D	N/D	24
KLAM 14959	Merrill	41S 10E 11AA	760-1012	252	Basalt	Tv	2450	19	1	129	2312	29533	2745	33	10.1	water for storage Lost R**	N/D	2419	120	245	0.001	N/D	897/897	10
KLAM 2160	Bly-1	36S 14E 34D	50-204	154	Basalt	Tv	125	5	2	25	448	9839	914	27	8.2	water for storage	N/D	2419	120	67	0.01	10/21	in 2000: 486	14
KLAM 51725	Bly-2	36S 14E 34C	40-455	415	Basalt	Tv	1450	32	1	45	812	14656	1362	160	48.8	in Sprague R**		2419	120	588				
KLAM 14821	Malin	40S 12E 28D	19-647	628	Sediments/basalt	Ts/Tv	975	16	4	61	1092	17874	1661	203	61.9	Mills CR 4	N/D	4838	120	455	0.0008	30/45	725/638	10
KLAM 51568	Chemult-1	26S 7E 1BB	18-22	4	Sand/gravel	Qv	1	13	25	0.08	1.4	204	19	12	3.7	no surface water		2419	120	1	0.008	N/D	297/297	28
KLAM 54538	Chemult-2	26S 7E 1BD	135-145	10	Clay/cinders	Qvp	10	4	2	2.5	44.8	2104	195	11	3.4	within 3 miles	N/D	2419	120	6				
KLAM 951*	Chiloquin-1	34S 7E 33	38-460	422	Shale/basalt	Tv	20	175	2	0.11	2.0	266	25	125	38.1	1 cfs avail for storage	N/D	2419	120	8	0.04	2002/2006 100/25	708/708	18
KLAM 53392*	Chiloquin-2	34S 7E 22	3 zones	9	Sand/clay		10	215	3	0.05	0.8	146	14	25	7.6	Williamson R**		2419	120	1		(June)		

Formation: Qs = Lacustrine and fluvial sediments, Qv = Basalt and andesite flows, Tv = Basalt and andesite flows, Ts = Tuffaceous sediments.

Sources: [a] Oregon Water Resources Water Rights Information System (accessed March 2007), [b]United States Census Population Database (accessed March 2007), [c]Gannett et al. (2007), [d]Oregon Climate Service (2007), [e]Oregon State Observation Well data (accessed April 2007).

Abbreviations: N/D = no published data found by this study

**When a municipality has no current surface water rights, this study has made a conservative estimate of water right volume that may be acquired for storage as 1 cfs.

*Domestic well

Table B-7. Malheur Lake Basin Well Data

Well No.	Location	T-R-S QQ	Open Intervals Depth (ft)	Aquifer thick-ness(ft)	Aquifer Lithology	Formation	Well Yield (gpm)	Draw down (ft)	Well Density (#/mi^2)	SC (gpm/ft)	SC (m^2/d)	Est. T (ft^2/d)	Est. T (m^2/d)	Max Δh (ft)	Max Δh (m)	Water Rights[a] (cfs)	Treatm. Capacity (MGD)	Volume re-charge** (m^3/d)	Time to recharge (d)	ASR Metric	Grad[c] (m/m)	DTW[e] 1995/ 2005 (ft)	Pop-ulation[b] 1990/200	Precip-itation[d] (in/yr.)
HARN 290	Burns-1	23S 30E 13B	140-356	216	basalt	Tb/Qb	1500	32	3	47	840	14992	1393	30	9	1 cfs**	none	2419	120	113	0.0008	8/_10	2913/	10.55
HARN 478	Burns-2	23S 31E 18B	250-290	40	Conglomerate/clay	Qs	1737	18	1	97	1730	24320	2260	13.5	4.1	avail Silvies R		2419	120	82			2755	
HARN 1061	Crane	24S 34E 30	35-125	90	Sand/Gravel	Qs	1500	28	7	54	960	16395	1524	22	6.7	1cfs avail** Malheur Sl mouth	none	2419	120	91	0.0005	55/40	Harney County:	9
HARN 156	Riley	23S 27E 3	25-295	270	Sandstone	Qs	2763	71	1	39	698	13235	1230	39	11.9	1cfs avail** Silver CR	none	2419	120	130	0.002	N/D	7609/7670 !000/200	9
HARN 50010	Diamond	29S 33E 12C	80-320	240	Sand/gravel	Qal	250	80	1	3	56	2443	227	8	2.4	1 cfs avail** Kiger CR	none	2419	120	5	0.02	N/D		12.34
HARN 4699	Blitzen	34S 31E 3A	375-685	310	Sand/clay/gravel	Qs	1500	38	1	39	708	13362	1242	60	18.3	no water avail	none	0.001	120	0.0000	0.002	N/D	0	8.5
HARN 17311	Andrews	35S 33E 23B	184-424	240	Sand/gravel	Qal	2300	146	2	16	282	7221	671	30	9.1	1cfs avail** Wildhorse CR	none	2419	120	54	0.004	18/18	0	6.69

Formation: Qal = Quaternary alluvium, Qs = Quaternary Sediments, Qb/Tba = Basalt or basaltic andesite.

Sources: [a] Oregon Water Resources Water Rights Information System (accessed January 2007),[b]United States Census Population Database (accessed January 2007), [c] Gonthier (1985), [d]Oregon Climate Service (2007), [e]Oregon State Observation Well data (accessed February 2007),[f]Piper et al.,(1977).

**When a municipality has no current surface water rights, this study has made a conservative estimate of water right volume that may be acquired for storage as 1 cfs.

Table B-8. Malheur River Basin Well Data

Well No.	Location	T-R-S QQ	Open Intervals Depth (ft)	Aquifer thick-ness(ft)	Aquifer Lithology	Formation	Well Yield (gpm)	Draw down (ft)	Well Density (#/mi^2)	SC (gpm/ft)	SC (m^2/d)	Est. T (ft^2/d)	Est. T (m^2/d)	Max Δh (ft)	Max Δh (m)	Water Rights[a] (cfs)	Treatm. Capacity (MGD)	Volume re-charge** (m^3/d)	Time to recharge (d)	ASR Metric	Grad[c] (m/m)	DTW[e] 1995/ 2005 (ft)	Pop-ulation[b] % decrea	Precip-itation (in/yr)
MAHL 51791	Ironside	15S 40E 2B	63-103	40	Sand/clay	Qal	1600	43	3	37	667	12843	1194	52	16	Willow CR 1 cfs for storage	N/D	2419	120	168	N/D	18/20	62 -0.59%	13.5
MAHL 1276	Ontario-1	18S 47 E 2	26-40	14	Gravel/clay	Qal	1300	27	15	48	863	15264	1419	5	1.5	20.1	13	48626	120	1	N/D	1985/1995 11/_12	9392/ 11125	9.6
MAHL 1284	Ontario-2	18S 47 E 3	18-40	22	Gravel/sand	Qal	835	35	15	24	428	9535	886	3	0.9	Snake R	13	48626	120	0				
MAHL 1761	Harper	19S 42E 35	13-55	35	Gravel/Shale/Clay	Qal/Ts	390	16	2	24	437	9674	899	5	1.5	Malheur R 1 cfs for storage	N/D	2419	120	12	N/D		260 -0.62%	8.4
MAHL 252	Jamieson-1	16S 43E 16	50-930	880	Basalt	CRB/Tob?	N/D	N/D	1	N/D	N/D	N/D	N/D	115	35.1	Gum CR	N/D	2419	120	N/D	N/D		17 -0.58%	8.4
MAHL 251	Jamieson-2	16S 43E 16	18-400	382	Sand/gravel/shale	Qal/Ts	25	110	3	0.23	4	422	39	30	9.1	1 cfs for storage		2419	120	3				
HARN 50760	Drewsey	20S 35E 25	60-270	210	Clay/basalt	Tlf/Tba	150	8	2	19	336	8114	754	22	6.7	Stinkingwater CR 1 cfs for storage	N/D	2419	120	45	N/D		127 -6.55%	11

Formation: Qal = Quaternary alluvium, Ts = Tertiary sediments, Tba = Basalt and andesite, CRB = Columbia River Basalt, Tlf = lacustrine and fluvial deposits.

Sources: [a] Oregon Water Resources Water Rights Information System (accessed January 2007),[b]United States Census Population Database (accessed January 2007), [c] No Data, [d]Oregon Climate Service (2007), [e]Oregon State Observation Well data (accessed February 2007).

**When a municipality has no current surface water rights, this study has made a conservative estimate of water right volume that may be acquired for storage, 1 cfs.

Table B-9. Middle Coast Basin Well Data

Well No.	Location	T-R-S QQ	Open Intervals Depth (ft)	Aquifer thick-ness(ft)	Aquifer Lithology	Formation	Well Yield (gpm)	Draw-down (ft)	Well Density (#/mi^2)	SC (gpm/ft)	SC (m^2/d)	Est. T (ft^2/d)	Est. T (m^2/d)	Max Δh (ft)	Max Δh (m)	Water Rights[a] (cfs)	Treatm. Capacity (MGD)	Volume re-charge** (m^3/d)	Time to recharge (d)	ASR Metric	Grad[c] (m/m)	DTW[e] 1995/ 2005 (ft)	Pop-ulation[b] 1990/2000	Precip-itation[d] (in/yr.)
																Munsel CR								
LANE 5528	Florence-3	18S 12W 23	76-140	64	Sand dunes	Qd	420	51.4	15^	8.17	146.5	3140[g]	292	13.8	4.2	0.8	3	968	120	27	N/D		5162/	75
LANE 5526	Florence-1	18S 12W 23	115-182	67	Sand dunes	Qd	305	46.4	15	6.57	117.8	4020	374	70	21.3	0.8	for GW	968	120	177			8122	
LANE 63362	Florence-2	18S 12W 23	100-157	57	Sand dunes	Qd	223	44	15	5.07	90.9	3377	314	52	15.8	0.8	at dunes	968	120	110		N/D		
																Yachats R avail								
LANE 6824*	Yachats-1	15S 12W 27	52-66	14	Basalt	Tpd	30	20	4	1.50	26.9	1494	139	5	1.5	1		2419	120	2	N/D	644		75
LANE 6813*	Yachats-2	15S 11W 27	30-280	250	Basalt	Tpd	4	256	1	0.02	0.3	70	7	24	7.3	1		2419	120	0.4				
																Weist CR/Eckman Slough							1595/	65
LINC 168*	Waldport	13S 11W 18	80-85	5	Sand	Qt	30	52	1	0.58	10.3	788	73	28	8.5	7.4	N/D	8951	120	1	N/D	N/D	2051	
																Big CR								
LINC 1290**	Newport-2	11S 11W 20	77-87	10	Sand	Qt	60	35	2	1.71	30.7	1634	152	15	4.6	10	3.5	6624	120	2	N/D		8437/	65
LINC 1291**	Newport-1	11S 11W 20	84-94	10	Sand	Qt	25	5	2	5.00	89.6	3347	311	50	15.2	10	3.5	6624	120	15		stable	9896	
																Schooner CR							doubles on	
LINC 613*	Lincoln City-1	7S 11W 25	26-60	34	Claystone	Ty?	40	24	5	2	30	1603	149	15	4.6	37	6	11355	120	1	N/D	N/D	weekends	75
LINC 614*	Lincoln City-2	7S 11W 25	44-47	3	Sand	Qt	30	20	6	2	27	1494	139	6	1.8	37	6	11355	120	0.5			5892/7944	
																Alsea R avail								90
BENT 7527*	Alsea	14S 8W 12	40-113	73	Claystone/Sandstone	Tt	40	60	5	0.67	12.0	868	81	33	10.1	1		2419	120	7	N/D	N/D	N/D	

Formation: Qt = Terrace deposits, Qd = Dune deposits, Tpd = Eocene porphyritic basalt, Ty = Tertiary marine sandstone, Tt = Marine siltstone.

Sources: [a] Oregon Water Resources Water Rights Information System (accessed July 2007), [b] United States Census Population Database (accessed July 2007), [c] N/D, [d] Oregon Climate Service (2007), [e] Oregon State Observation Well data (accessed July 2007), [f] Orr and Orr (2000), [g] Brown and Caldwell (2001).

Abbreviations: N/D = no published data found by this study

*Domestic or irrigation well

**Industrial Well or park well

Table B-10. North Coast Basin Well Data

Well No.	Location	T-R-S QQ	Open Intervals Depth (ft)	Aquifer thick-ness(ft)	Aquifer Lithology	Formation	Well Yield (gpm)	Draw-down (ft)	Well Density (#/mi^2)	SC (gpm/ft)	SC (m^2/d)	Est. T (ft^2/d)	Est. T (m^2/d)	Max Δh (ft)	Max Δh (m)	Water Rights[a] (cfs)	Treatm. Capacity (MGD)	Volume re-charge** (m^3/d)	Time to recharge (d)	ASR Metric	Grad[c] (m/m)	DTW[e] 1995/ 2005 (ft)	Pop-ulation[b] 1990/200	Precip-itation[d] (in/yr.)
CLAT 304**	Warrenton	8N 10W 20	105-160	55	Sand	Qd	98	22	2	4.5	79.9	3475	323	11.5	3.5	Lewis&Clark R 20		24192	120	1.0	N/D	stable CLAT 5023	2681/ 4394	80
COLU 2541*	Clatskanie	7N 4W 22	88-118	30	Sandstone	Tmst	27	98.5	7	0.27	4.9	478	44	18.5	5.6	Roaring CR 1.4		1693	120	3	N/D	N/D	1629/ 1645	50
CLAT 164	Cannon Beach	5N 10W 29A	36-43	7	Gravel/Clay/Basalt	Qal/Tms/Tc	120	3	4	40.0	717.0	13481	1253	3	0.9	Ecola CR springs 1	N/D	1210	120	20	N/D	N/D	1221/ 1720	80
CLAT 52022	Gearhart	7N 10W 28D	75-95	20	Sand	Qd	90	54	4	1.7	29.9	1603	149	33.5	10.2	none 1		1210	120	27	N/D	N/D	1027/ 1106	75
TILL 1122	Manzanita	3N 10W 29	27-52	25	Sand	Qal	50	10	2	5.0	89.6	3347	311	5	1.5	Anderson CR 2.5		3024	120	3	N/D	N/D	513/ 630	90
TILL 654***	Tillamook	2N 9W 5B		10	Gravel	Qal	1320	66	2	20	359	8473	787	21	6.4	Killam, Fawcett CR 1		1210	120	89	N/D	N/D	4000/ 4424	85
TILL 115	Pacific City	4S 10W 19B	45-75	30	Sand	Qal	125	34	3	4	66	2724	253	7	2.1	Horn CR 2.7	N/D	3266	120	4	N/D	N/D	1027/ N/D	80

Formation: Qal = Alluvial deposits, Qd = Dune deposits, Tmst = Tuffaceous marine sediments, Tc = Columbia River Basalt.

Sources: [a] Oregon Water Resources Water Rights Information System (accessed July 2007), [b]United States Census Population Database (accessed July 2007), [c], [d]Oregon Climate Service (2007), [e]Oregon State Observation Well data (accessed July 2007), [f]Orr and Orr (2000), [g].

Abbreviations: N/D = no published data found by this study

*Domestic or irrigation well

**USGS well

***Tillamook Water Commission

Table B-11. Owyhee Basin Well Data

Well No.	Location	T-R-S QQ	Open Intervals Depth (ft)	Aquifer thick-ness(ft)	Aquifer Lithology	Formation	Well Yield (gpm)	Draw down (ft)	Well Density (#/mi^2)	SC (gpm/ft)	SC (m^2/d)	Est. T (ft^2/d)	Est. T (m^2/d)	Max Δh (ft)	Max Δh (m)	Water Rights[a] (cfs)	Treatm. Capacity (MGD)	Volume re-charge** (m^3/d)	Time to recharge (d)	ASR Metric	Grad[c] (m/m)	DTW[e] 1995/ 2005 (ft)	Pop-ulation[b] % change	Precip-itation[d] (in/yr.)
MAHL 52787	Adrian	21S 46E 16	165-215	50	Sand/gravel	Qal	150	32	2	5	84	3205	298	136	41	Owyhee R** 1cfs storage	N/D	2419	120	109	N/D	N/D	730 0% decre	9
MAHL 2435	Rome	31S 41E 24	22-398	376	Sandstone/clay	Qal/Ts	20	100	2	0.2	4	387	36	30	9.1	Owyhee R** 1cfs storage	N/D	2419	120	3	N/D	N/D	N/D	8
MAHL 2471	Basque	36S 41E 36	270-300	30	Gravel	Qal/Qt	100	70	4	1	26	1446	134	210	64.0	Crooked CR** 1cfs storage	N/D	2419	120	76	N/D	N/D	N/D	11
MAHL 2430	Jordan Valley	30S 46E 23	75-382	307	Sand/clay/gravel	Ts	1800	110	1	16	293	7407	688	24	7.3	Jordan CR** N/D	N/D	2419	120	45	N/D	10/10	201 9% decre	10

Formation: Qal = Quaternary alluvium, Qt =Quaternary terrace gravels, Ts = Tertiary sediments.

Sources: [a] Oregon Water Resources Water Rights Information System (accessed March 2007),[b]United States Census Population Database (accessed March 2007), [c] N/D,

[d]Oregon Climate Service (2007), [e]Oregon State Observation Well data (accessed February 2007).

Abbreviations: N/D = no data found by this study.

**When a municipality has no current surface water rights, this study has made a conservative estimate of water right volume that may be acquired for storage as 1 cfs.

Table B-12. Powder Basin Well Data

Well No.	Location	T-R-S QQ	Open Intervals Depth (ft)	Aquifer thick-ness(ft)	Aquifer Lithology	Formation	Well Yield (gpm)	Draw down (ft)	Well Density (#/mi^2)	SC (gpm/ft)	SC (m^2/d)	Est. T (ft^2/d)	Est. T (m^2/d)	Max Δh (ft)	Max Δh (m)	Water Rights[a] (cfs)	Treatm. Capacity (MGD)	Volume re-charge** (m^3/d)	Time to recharge (d)	ASR Metric	Grad[c] (m/m)	DTW[e] 1995/ 2005 (ft)	Pop-ulation[b] 1990/200	Precip-itation[d] (in/yr.)
UNIO 1537	North Powder-1	6S 39E 22C	227-490	263	Sand/Gravel/Clay	Qal	800	166	1	5	86	3265	303	0	0	N Powder R, mouth Anthony	N/D	4838	120	0	0.007	20/20	448/485	14.4
UNIO 1542	North Powder-2	6S 39E 22C	0-150	150	Unknown	Qal	1500	40	2	38	672	12910	1200	4	1.2	Cr available*		4838	120	6				
BAKE 1542	Huntington	14S 44E 13C	331-550	219	Shale/Basalt	CRB	520	163	1	3	57	2478	230	24	7.3	3.33 * none	N/D	4028	120	9	N/D	N/D	522/481	11.38
MAHL 51426	Unity	13S 37E 16B	37-209	172	Sandstone/Clay	Qfl	15	190	3	0.08	1.4	208	19	37	11.3	reservoir* none	N/D	4838	120	1	N/D	45/45	87/124	10.64
BAKE 782	Halfway-1	8S 46E 17	78-189	111	Gravel/Cobbles	Qal	300	38	2	8	142	4547	422	45	13.7	unknown rate springs	N/D	3629	120	34	N/D		311/319	21.6
BAKE 2063	Halfway-2	8S 46E 8C	198-403	205	Sand/Gravel	Qal	650	111	2	6	105	3722	346	12	3.7	8S 45 E 13		3629	120	7		10_/10		

Formation: Qal = Quaternary alluvium, CRB = Columbia River Basalt, Qfl = Quaternary fluviolacustrine deposits.

Sources: [a] Oregon Water Resources Water Rights Information System (accessed January 2007),[b]United States Census Population Database (accessed January 2007), [c] McFarland (1984),

[d]Western Reginal Climate Center (2006), [e]Oregon State Observation Well data (accessed January 2007).

*Denotes this municipality does not have surface water rights at this time. According to Oregon Water Resources Water Availability Report System (WARS) Database, water available at nearest surface water source is noted.

Table B-13. Rogue Basin Well Data

Well No.	Location	T-R-S QQ	Open Intervals Depth (ft)	Aquifer thick-ness(ft)	Aquifer Lithology	Formation	Well Yield (gpm)	Draw-down (ft)	Well Density (#/mi^2)	SC (gpm/ft)	SC (m^2/d)	Est. T (ft^2/d)	Est. T (m^2/d)	Max Δh (ft)	Max Δh (m)	Water Rights[a] (cfs)	Treatm. Capacity (MGD)	Volume re-charge** (m^3/d)	Time to recharge (d)	ASR Metric	Grad[c] (m/m)	DTW[e] 1995/ 2005 (ft)	Pop-ulation[b] 1990/200	Precip-itation[d] (in/yr.)
JACK 6961	Medford-1	36S 2W 14D	48-165	117	Gravel/Shale	Qal/Tn	45	60	2	0.75	13.4	939	87	80	24.4	Butte Springs 67	45	85163	120	0.5	N/D	N/D	46,951/	20
JACK 6852*	Medford-2	36S 2W 4B	24-400	376	Claystone	Tn	20	30	1	0.67	12.0	868	81	200	61.0	Rogue River 100		85163	120	1.2			70147	
JOSE 18119	Grants Pass	36S 5W 30C	40-60	20	Granite	KJg	30	32	10	0.94	16.8	1090	101	20	6.1	Rogue River 50	20	37850	120	0.3	N/D	Jose54649 stable	17488/ 28882	32
JACK 20656*	Ashland-1	39S 1E 26	40-203	163	Conglomerate		150	180	3	0.83	14.9	1008	94	23	7.0	Reeder Res. 15	7	13248	120	1	N/D	N/D	16234/ 20829	20
JACK 35427*	Ashland-2	39S 1E 25C	49-249	200	Granite	KJg	5	190	3	0.03	0.5	100	9	41	12.5	Mt. Ashland		13248	120	0.2				
JOSE 6631	Cave Junction	39S 8W 28A	13-26	13	Gravel/clay	Qal/Qt	110	2	9	55	985.9	16687	1551	10	3.0	Illinois R 3	N/D	3629	120	28	N/D	Jose 6089 stable	1126/ 1380	56
JACK 18740*	Prospect	32S 3E 29	120-300	180	Basalt	QTba	60	200	12	0.30	5.4	508	47	100	30.5	Rogue River avail for storag	N/D	2419	120	13	N/D	N/D	530	44
CURR 236	Gold Beach-1	36S 14W 16	25-50	25	Sand/gravel	Qs/Qal	2200	2.5	4	880	15775	106940	9939	2	0.6	Rogue River 10	N/D	12096	120	11	N/D	N/D	1546/ 1930	80
CURR 267	Gold Beach-2	36S 14W 30A	15-33	18	Sand/gravel/cobbles	Qs/Qal	225	11.5	1	20	350.7	8349	776	10.5	3.2			12096	120	4				

Formation: Qal = Quaternary alluvium, Qs = Quaternary Sediments, QTba = Late Tertiary to Early Quaternary High Cascades basalt, Tn = Nonmarine sedimentary rocks.

note: Medford Water Commission supplies medford, Pheonix, Central Point, Eagle Point, Jacksonville, Talent. With Butte Springs and Rogue R water.

Sources: [a] Oregon Water Resources Water Rights Information System (accessed March 2007), [b]United States Census Population Database (accessed June 2007), [c]Gannett et al. (2007), [d]Oregon Climate Service (2007), [e]Oregon State Observation Well data (accessed June 2007).

Abbreviations: N/D = no published data found by this study

**When a municipality has no current surface water rights, this study has made a conservative estimate of water right volume that may be acquired for storage as 1 cfs.

*Domestic well

Table B-14. Sandy Basin Well Data

Well No.	Location	T-R-S QQ	Open Intervals Depth (ft)	Aquifer thick-ness(ft)	Aquifer Lithology	Formation	Well Yield (gpm)	Draw down (ft)	Well Density (#/mi^2)	SC (gpm/ft)	SC (m^2/d)	Est. T (ft^2/d)	Est. T (m^2/d)	Max Δh (ft)	Max Δh (m)	Water Rights[a] (cfs)	Treatm. Capacity (MGD)	Volume re-charge** (m^3/d)	Time to recharge (d)	ASR Metric	Grad[c] (m/m)	DTW[e] 1995/ 2005 (ft)	Pop-ulation[b] 1990/200	Precip-itation[d] (in/yr.)
MULT 1442	Troutdale-1	1N 3E 36CC	340-350	10	Sand/clay	QTs	300	93	9	3	58	2495	232	201	61	Troutdale spring 0.22	1.6	3028	120	100	0.01	65/68	7852/ 14,898	40
MULT 1444	Troutdale-2	1N 3E 36CC	360-385	35	Gravel/clay	QTs	1000	40	9	25	448	9839	914	174	53			3028	120	343				
			465-475		Gravel/sand	QTs																		
CLAC 1843	Welches	3S 7E 4BA	104-116	12	Gravel/sand	QTs	80	N/D	1.4			N/D	N/D	50	15	Salmon R trib. 0.25	N/D	306	120	N/D	N/D	N/D	N/D	20+
CLAC 7598	Wemme	2S 7E 31BA	110-114	4	Gravel/sand	QTs	200	84	3	2.4	43	2036	189	6	2	no surface water rights	N/D	306	120	27	N/D	N/D	N/D	20+
CLAC 7554	ZigZag	2S 7E 26BB	171-187	16	Gravel/sand	QTs	155	98	1.3	1.6	28	1548	144	35	11	no surface water rights	N/D	306	120	111	N/D	N/D	N/D	20+
CLAC 1575 fire district well)	Sandy-1	3S 5E 4DB	159-161	20	Cemented gravel	QTs	35	107	16	0.3	6	538	50	16	5	Alder Creek	2.6 at Alder Creek	4914	120	1.1	0.02	167/162	4152/ 7871	60
CLAC 57640	Sandy-2	2S 5E 8AC	500-560	60	Basalt	Tfc	20	N/D		median= 0.5 N/D				407	124	Salmon River 16.3								

Formation: Qal = Quaternary alluvium, CRB = Columbia River Basalt, Qfl = Quaternary fluviolacustrine deposits.

Sources: [a] Oregon Water Resources Water Rights Information System (accessed January 2007), [b]United States Census Population Database (accessed January 2007), [c] Woodward et al. (2000), [d]Oregon Climate Service (2007), [e]Oregon State Observation Well data (accessed January 2007).

*Denotes this municipality does not have surface water rights at this time. According to Oregon Water Resources Water Availability Report System (WARS) Database, water available at nearest surface water source is noted.

**When a municipality has no current surface water rights, this study has made a conservative estimate of water right volume that may be acquired for storage, 1.5 to 2 cfs.

Table B-15. South Coast Basin Well Data

Well No.	Location	T-R-S QQ	Open Intervals Depth (ft)	Aquifer thick-ness(ft)	Aquifer Lithology	Formation	Well Yield (gpm)	Draw-down (ft)	Well Density (#/mi^2)	SC (gpm/ft)	SC (m^2/d)	Est. T (ft^2/d)	Est. T (m^2/d)	Max Δh (ft)	Max Δh (m)	Water Rights[a] (cfs)	Treatm. Capacity (MGD)	Volume re-charge** (m^3/d)	Time to recharge (d)	ASR Metric	Grad[c] (m/m)	DTW[e] 1995/ 2005 (ft)	Pop-ulation[b] 1990/2000	Precip-itation[d] (in/yr.)
																Chetco R							4400/	
CURR 124*	Brookings -1	41S 13W 16	18-30	12	Gravel	Qt	40	14	20	2.86	51.2	12600[g]	1170	22	6.7	10	N/D	24192	120	7	N/D			70
CURR 473**	Brookings-2	40S 13W 34	20-41	21	Gravel	Qal	1500	4	7	375	6722	60386	5612	4	1.2	10		24192	120	6		N/D	6344	
																Hubbard CR	exists						1025/	
CURR 1684*	Port Orford	33S 15W 5	30-110	80	Sandstone	Qt	4.6	110	3	0.04	0.7	136	13	21	6.4	3.25	N/D	7862	120	0.2	N/D	N/D	1164	75
																Ferry CR	exists						2215/	
COOS 51117*	Bandon-1	28S 14W 29	40-95	45	Sandstone/Clay	Tmss	47.5	26	3	1.83	32.7	500 [h]	46	10	3.0	14	N/D	33869	120	0.1			2900	65
COOS 3921*	Bandon-2	28S 14W 28	110-130	20	Sand/Clay		37	21	4	1.76	31.6	500	46	79	24.1	14		33869	120	0.7	N/D	stable		
																Chickses CR								
COOS 1960^	Coos Bay-1	24S 13W 28	56-104	48	Sand/Sandstone	Qd	500	22	3	23	407	6000 [i]	557	3	0.9	0.26	8	629	120	17		N/D	15076/	65
COOS 2424***	Coos Bay-2	25S 13W 36	12-107	95	Shale/Sandstone	Tss	50	2	3	25	448	6000	557	12	3.7	0.26	8	629	120	69	N/D		16000	
																Joe Ney Slough							9614/	
COOS 2350*	North Bend	25S 13W 16	68-118	50	Sand/Clay	Qt	15	10	1	1.50	26.9	1494	139	30	9.1	0.35	8	847	120	32	N/D	N/D	9846	65

Formation: Tmss = Marine sandstone and siltstone, Qt = Terrace deposits, Qd = Dune deposits, Qal = Alluvial deposits.

Sources: [a] Oregon Water Resources Water Rights Information System (accessed March 2007), [b]United States Census Population Database (accessed June 2007), [c]Gannett et al. (2007), [d]Oregon Climate Service (2007), [e]Oregon State Observation Well data (accessed June 2007), [g]Lisner (1977), [h]Golder Asssociates (2004), [i]Schlicker et al.(1974).

Abbreviations: N/D = no published data found by this study

**Harbor Rural Water District well

*Domestic or irrigation well

***Industrial Well

Table B-16. Umatilla Basin Well Data

Well No.	Location	T-R-S QQ	Open Intervals Depth (ft)	Aquifer thick-ness(ft)	Aquifer Lithology	Formation	Well Yield (gpm)	Draw down (ft)	Well Density (#/mi^2)	SC (gpm/ft)	SC (m^2/d)	Est. T (ft^2/d)	Est. T (m^2/d)	Max Δh (ft)	Max Δh (m)	Water Rights[a] (cfs)	Treatm. Capacity (MGD)	Volume re-charge** (m^3/d)	Time to recharge (d)	ASR Metric	Grad[c] (m/m)	DTW[e] 1995/ 2005 (ft)	Pop-ulation[b] 1990/200	Precip-itation[d] (in/yr.)
UMAT 3347	Umatilla-1	5N 28E 14 AB	500- 989	489	Basalt	CRB	2500	235	1	11	191	5551	516	200	61	Columbia R	N/D	56271	120	12	0.004	190/175	3046/	6.8
UMAT 3361	Umatilla-2	5N 28E 16 DA	500-1134	634	Basalt	CRB	1245	324	3	4	69	2806	261	156	48	23		56271	120	5		155/146	6306	
MORR 304	Heppner-1	3S 27E 2AD	30-191	161	Basalt	CRB	460	170	4	3	49	2218	206	35	11	Columbia R Heppner Cr	N/D	39145	120	1.2	0.011	0/35	1412/	13.29
MORR 1750	Heppner-2	3S 28E 29	30-211	181	Basalt	CRB	350	114	3	3	55	2414	224	90	27	E Fork Willow Cr 16		39145	120	3		ND	1438	
MORR 745	Boardman	4N 25E 9	539-585	46	Basalt	CRB	490	298	5	2	29	1589	148	63	19	Columbia R 36	N/D	88077	120 120	0.7	0.003	ND	1387/ 3051	6.8
UMAT 89	Pilot Rock	1S 32E 17	100-486	386	Basalt	CRB	450	193	2	2	42	2008	187	20	6	Birch Cr 3.2	N/D	7829	120	3	0.019	0/20	1478/ 1525	13.29
UMAT 3089	Weston-1	4N 35E 22CD	25-1150	1125	Basalt	CRB	450	710	5	1	11	839	78	310	94	Pine Cr 0.2	N/D	489	120	323	0.014	375/470	606/ 714	12.4
UMAT 3093	Weston-2	4N 35E 22CD	65-239	174	Basalt	CRB	300	14	5	21	384	8874	825	115	35			489	120	1267				
UMAT 5450	Hermiston-1	4N 28E 24D	650-1500	900	Basalt	CRB	2500	42	3	60	1067	17595	1635	380	116	springs to Umat R	N/D	8467	120	479	0.004		13154/	
UMAT 2061	Hermiston-2	4N 28E 11A	310-1041	731	Basalt	CRB	2500	253	3	10	177	5283	491	90	27	7 cfs		8467	120	34		60/90	14657	10.4
UMAT 2962	Stanfield	4N 29E 32B	156-1161	1005	Basalt	CRB	1227	185	10	7	119	4044	376	290	88.39	Umat R 11.5	N/D	13910.4	120	51	N/D	134/130	1568/ 1966	9
UMAT 5065	Milton-Freewater	6N 35E 36	55-153	98	Sand/gravel	CRB	45	63	7	1	13	909	84	37	11.28	Walla Walla R* 1	N/D	2419	120	8	N/D	250/275	5533/640	15

Formation: CRB = Columbia River Basalt.

Sources: [a] Oregon Water Resources Department Water Rights Information System (accessed January 2007), [b] United States Census Population Database (accessed January 2007), [c] Gonthier (1985), [d] Oregon Climate Service (2007), [e] Oregon State Observation Well data (accessed January 2007).

*When a municipality has no current surface water rights, this study has made a conservative estimate of water right volume that may be acquired for storage, 1.5 to 2 cfs.

Table B-17. Umpqua Basin Well Data

Well No.	Location	T-R-S QQ	Open Intervals Depth (ft)	Aquifer thick-ness(ft)	Aquifer Lithology	Formation	Well Yield (gpm)	Draw-down (ft)	Well Density (#/mi^2)	SC (gpm/ft)	SC (m^2/d)	Est. T (ft^2/d)	Est. T (m^2/d)	Max Δh (ft)	Max Δh (m)	Water Rights[a] (cfs)	Treatm. Capacity (MGD)	Volume re-charge** (m^3/d)	Time to recharge (d)	ASR Metric	Grad[c] (m/m)	DTW[e] 1995/ 2005 (ft)	Pop-ulation[b] 1990/200	Precip-itation[d] (in/yr.)
DOUG 2255	Reedsport	21S 12W 33	139-142	3	Sand/gravel	Qal	1800	20	3	90.00	1613	23210	2157	38	11.6	Clear Lake 35	N/D	84672	120	6	N/D	N/D	4796/ 4361	80
DOUG 2341	Drain	22S 5W 16	26-195	169	Sandstone	Tt	6	157	3	0.04	0.7	128	12	38	11.6	Bear CR Res. 5		12096	120	0.2	N/D	N/D	1011/ 1039	46
DOUG 4606*	Sutherlin	25S 5W 22	19-185	166	Clay/Sandstone	Tmss	14	185	2	0.08	1.4	202	19	91	27.7	Cooper CR: 5 Calapooya CR:	approx 2	4838	121	2	N/D	N/D	5020/ 7281	38
DOUG 5296*	Glide	26S 3W 17C	25-80	55	Claystone/Basalt	Tmss/ Tu	7	30	5	0.23	4.2	429	40	27	8.2	N.Umpqua 2.2		5322	120	1.3	N/D	N/D	1690	40
KLAM 11171	Diamond Lake	24S 6E 15	138-140	2	Cinders/gravel/sand	Qma/Qg	20	52	2	0.38	6.9	600	56	88	26.8		none		120	0	N/D	N/D		
DOUG 6487*	Roseburg-1	26S 6W 14	19-150	131	Sandstone/basalt	Tsr	120	150	10	0.80	14.3	980	91	9	2.7	Umpqua R:13 N Umpqua R:6	12	45420	120	0.1	N/D	N/D	17032/ 20727	34
DOUG 6679*	Roseburg-2	26S 6W 24	38-350	312	Basalt	Tsr	4	0.1		40.00	717.0	13481	1253	8	2.4			45420	120	1				
DOUG 8475	Myrtle Creek	29S 5W 28B	17-100	83	Granite	KJg	1.5	20	3	0.08	1.3	201	19	55	16.8	springs, N Umpq 20	est. 13	48384	120	0.1	N/D	N/D	3063/ 3528	38
DOUG 875*	Canyonville	30S 5W 17	57-97	40	Decomposed Granite	KJg	5	35	3	0.14	2.6	309	29	62	18.9	Canyon CR 3		7258	120	1.6	N/D	N/D	1397/ 1219	40

Formation: Qg = Glacial deposits, Qal = Quaternary alluvium, Qma = Mazama Ash, Tt and Tmss = Marine sandstone and siltstone, Tu = Tuffaceous rocks, Tsr = Marine volcanics, KJg = Granitic rocks.

Sources: [a] Oregon Water Resources Department Water Rights Information System (accessed March 2007), [b]United States Census Population Database (accessed June 2007), [c]N/D

[d]Oregon Climate Service (2007), [e]Oregon State Observation Well data (accessed June 2007).

Abbreviations: N/D = no published data found by this study

*Domestic well

Table B-18. Willamette Basin Well Data

Well No.	Location	T-R-S QQ-Q	Open Intervals Depth (ft)	Aquifer thick-ness(ft)	Aquifer Lithology	Formation	Well Yield (gpm)	Draw down (ft)	Well Density (#/mi^2)	SC (gpm/ft)	SC (m^2/d)	Est. T (ft^2/d)	Est. T (m^2/d)	Max Δh (ft)	Max Δh (m)	Water Rights[a] (cfs)	Treatm. Capacity (MGD)	Volume re-charge** (m^3/d)	Time to recharge (d)	ASR Metric	Grad[c] (m/m)	DTW[e] 1995/ 2005 (ft)	Pop-ulation[b] 1990/2000	Precip-itation[d] (in/yr.)
MULT 1118	Portland-1	1N 2E 13	484-558	36	Sand/gravel	WA	3000	0.67	4.3	4478	80266	317786	29561	124.68	38	Bull Run R	N/D	79834	120	302	0.006	N/D	437319/	40
			558-568		Clay/silt/sand	WCU										200, using 66							533,492	
MULT 1133	Portland-2	1N 2E 15	124-165		Gravel/sand	WA	6000	50		120	2151	28118	2616	72.182	22			79834	120	15				
			165-173		Sand/gravel/silt	WA										assume 33								
			173-220		Gravel /sand	WA										for injection								
MULT 1190	Portland-3	1N 2E 24	400-531		Clay/sand/gravel	WA	2400	80		30	538	11107	1033	223.11	68			79834	120	19				
MULT 1286	Portland-4	1N 3E 21	85-145		Gravel/boulders	WA	10000	24		417	7469	64743	6023	32.81	10			79834	120	16				
			145-165		Gravel	WA																		
MULT 72561	Portland-5	1S 5E 35	65-310		Basalt	CRB	2000	3		N/D	N/D	N/D	N/D	65.62	20			79834	120	N/D				
			310-445		Basalt w/pyrite			40	0.2															
			1445-504		Basalt			110																
			504-570		Basalt			330																
			570-675		Basalt			550																
																							3093/	40
WASH 51903	Sherwood	2S 1W 32	438-466	110	Basalt	CRB	500	10		50.0	896	15640	1455	131.24	40	Clear Cr	N/D	35270	120	35	0.002	N/D	14,540	
			491-501		Basalt				0.3							1.8								
			527-545		Basalt																			
			639-678		Basalt																			
			788-801		Basalt																			
			813-860		Basalt																			
																							18692/	40
CLAC 00315	Milwaukie-1	1S 1E 36	206-313	107	Conglomerate	WA	900	112	5.9	8.0	144	4595	427	46	14	GW	N/D	76400	120	2	0.009	ND/ 10.2	20,755	
CLAC 00305	Milwaukie-2	1S 1E 25	170-180	81	Sand/gravel	WA	750	89		8.4	151	4744	441	101.71	31	3.9		76400	120	4				
			184-214		Sand/gravel																			
			255-274		Sand/gravel																			
			315-322		Sand/gravel																			
			355-370		Sand/gravel																			
																Clackamas R							2016/	52
CLAC 57766	Estacada	3S 4E 19	630-840	210	Basalt	CRB	120	4	1.3	30	538	11107	1033	229.67	70	4_	N/D	78382	120	20	N/D	N/D	2,416	
																							8983/	40
CLAC 012027	Canby-1	3S 1E 32	70-330	260	Clay/sand/silt	WA	400	107	5.9	4	67	2752	256	72	22	Molalla R	N/D	293933	120	0.4	0.003	70/ 90	14,715	
CLAC 12025	Canby-2	3S 1E 32	103-108		Sand/gravel	WA	403	33		12	219	6083	566	66	20	15		293933	120	0.8				
			113-121		Sand																			
			121-134		Sand/gravel																			
			134-138		Sand																			
			193-200		Sand/silt/clay																			
			226-231		Sand																			
			255-260	47	Sand																			
			302-560	258	Basalt	CRB	300	2.9	2.6	103	1854	25456	2368	69	21	Clackamas R		391910	120	2.7	0.004	N/D	14698/	44
CLAC 4396	Oregon City	2S 2E 29														40	N/D						29,767	

Formation: CRB = Columbia River Basalt, WA= Willamette Aquifer, WCU=Willamette Confining Unit,WS= Willamette Silt, MS=Marine Sediments.

Table B-18. Willamette Basin Well Data (continued)

Well No.	Location	T-R-S QQ-Q	Open Intervals Depth (ft)	Aquifer thick-ness(ft)	Aquifer Lithology		Well Yield (gpm)	Draw down (ft)	Well Density (#/mi^2)	SC (gpm/ft)	SC (m^2/d)	Est. T (ft^2/d)	Est. T (m^2/d)	Max Δh (ft)	Max Δh (m)	Water Rights[a] (cfs)	Treatm. Capacity (MGD)	Volume re-charge** (m^3/d)	Time to recharge (d)	ASR Metric	Grad[c] (m/m)	DTW[e] 1995/ 2005 (ft)	Pop-ulation[b] 1990/200	Precip-itation[d] (in/yr.)
YAMH 323	Newberg-1	3S 2W 30	68-280	212	Sand/sandstone	WS/WA	35	144	1.5	0.24	4	441	41	52	16	springs: in different townships, not feasible	N/D	0	120	0	N/D	36/46	20,280	40
MARI 181	Newberg-2	3S 2W 29	70-90	20	Sand/gravel	WA	2575	16		161	2885	34229	3184	36	11									
YAMH 5917	McMinnville-1	4S 4W 30	54-60	6	Mudstone	WS	20	45	1.1	0.44	8	661	61	13	4	Haskins Cr Reservoir 410	N/D	8000000	120	0.001	0.003	N/D	17894/ 28,973	40
YAMH 51052	McMinnville-2	4S 3W 6	101-121		Sandstone/gravel	WS	100		0.5	N/D	N/D	N/D	N/D	20	6									
			141-161	40	Sandstone/ clay	WS/WA																		
YAMH 125	Dayton	1N 3W 35	105-120		Gravel	WA	128	35	1.0	3.66	66	2712	252	59	18	S. Dayton Sprin 0.2	N/D	3920	120	25	0.008	N/D	1526/ 2247	44
			150-160	25	Gravel																			
MARI 1636	Woodburn-1	5S 1W 8	175-270	95	Sand/gravel	WA	1344	79	1.0	17.01	305	7595	707	36	11	Mill Cr 12.5	N/D	245000	120	0.7	0.008	22/ 42	13404/ 22,147	40
MARI 1820	Woodburn-2	5S 1W 17	106-134	50	Sand/gravel		907	58		15.64	280	7178	668	43	13			245000	120	0.8				
			161-165		Gravel																			
			192-210		Sand/gravel																			
MARI 18414	Woodburn-3	5S 2W 8			Sand/gravel	WCU	750	4.4	0.7	22	394	9023	839	23	7			245000	120	0.5				
YAMH 2787	Amity	5S 4W 20	67-77	10	Gravel/sand	WA	37.5	21	0.7	1.8	32	1677	156	39	12	S. Yamhill R 0.475	N/D	9300	120	4	0.03	N/D	1175/ 1464	44
MARI 57164	Mount Angel-1	6S 1W 3	520-640	110	Basalt	CRB	1200	127	0.8	9	169	5122	476	111.55	34	GW 2.12	N/D	42000	120	8	0.004	N/D	2778/ 3,339	40
MARI 50456	Mount Angel-2	6S 1W 9	160		Basalt	CRB	950	3.9		244	4367	45185	4203	0	0			42000	120	0.00				
POLK 420	Independence	8S 4W 28	55-74	19	Sand/gravel	WA	60	1	0.9	60	1076	17672	1644	49	15	S. Fork Ash Cr 1_	N/D	20000	120	26	0.006_	N/D	4425/ 8764	44
LINN 12855	Sweet Home	13S 1E 34	20-335	315	Sandstone	WA	13	27	1.0	0.48	9	697	65	N/D	N/D	S. Santiam R 13.1	N/D	257000	120	N/D	0.003	N/D	6850/ 8576	48
BENT 5264	Corvallis-1	12S 5W 22	30-46	57	Gravel	WA	80	N/D	1.1	N/D	N/D	N/D	N/D	10	3	Willamette R 90	N/D				0.0006	12.5/ 16.5	44757/ 50,380	44
BENT 51479	Corvallis-2	12S 5W 12	79-120		Clay/silt/sand		370	67		6	99	3574	332	16	5			1800000	120	0.02				
LANE 8286	Eugene-1	17S 4W 34	60-81	31	Gravel/sand/clay	WA	110	17	3.1	6.5	116	3974	370	9.8	3.0	McKenzie R 3592	N/D	70000000	120	0.00	0.003		112669/ 142,681	40
			91-101		Gravel/sand/clay																			
LANE 57266	Eugene-2	16S 4W 33	15-79	98	Sand/gravel	WA	165	35	0.8	4.7	85	3215	299	197	60			70000000	120	0.01		22.5/25		
			136-160		Sand/gravel																			
			225-235		Sand/gravel																			

Formation: CRB = Columbia River Basalt, WA= Willamette Aquifer (Qs), WCU=Willamette Confining Unit (Qs),WS= Willamette Silt (Qs), MS=Marine Sediments (Tmss).

Table B-18. Willamette Basin Well Data (continued)

Well No.	Location	T-R-S QQ-Q	Open Intervals Depth (ft)	Aquifer thick-ness(ft)	Aquifer Lithology		Well Yield (gpm)	Draw down (ft)	Well Density (#/mi^2)	SC (gpm/ft)	SC (m^2/d)	Est. T (ft^2/d)	Est. T (m^2/d)	Max Δh (ft)	Max Δh (m)	Water Rights[a] (cfs)	Treatm. Capacity (MGD)	Volume re-charge** (m^3/d)	Time to recharge (d)	ASR Metric	Grad[c] (m/m)	DTW[e] 1995/ 2005 (ft)	Pop-ulation[b] 1990/2000	Precip-itation[d] (in/yr.)
LANE 58776	Cottage Grove	20S 3W 35	59-190	131	Sandstone	WA	60	178	1.1	0.34	6	549	51	13	4	Row R 6.2	N/D	122000	120	0.036	0.001	N/D	7402/ 8859	48
CLAC 4488	Wilsonville	3S 1W 12	366-880	514	Basalt	CRB	1000	300	2	24.00	430	9565	890	116	35	Willamette R 35	15	28387.5	120	24	N/D	N/D	7106/ 16533	40
CLAC 60002**[3]	West Linn	2S 1E 26	400-1075	675	Basalt	CRB	60	510	6	9	166	5058	470	565	172	South Fork Water Board	20	37850	120.00	46	N/D	N/D	16367/ 25209	45
WASH 5581***[4]	Hillsboro	1N 2W 27	445-455	10	Sand/gravel	WA	20	215	1	0	2	232	22	15.0	5	Tualatin R 27	73	138152.5	120.00	0.0	N/D	N/D	37520/ 87732	40
CLAC 62338	Boring	1S 4E 32	435-605	170	Sand/gravel	WA	400	335	3	1.19	21	1281	119	215	66	Deep CR** 1cfs	N/D	2419	120.00	69	N/D	N/D	N/D	50

Formation: CRB = Columbia River Basalt, WA= Willamette Aquifer(Qs), WCU=Willamette Confining Unit(Qs), WS= Willamette Silt(Qs), MS=Marine Sediments (Tmss).

Sources: [a] Oregon Water Resources Water Rights Information System (accessed January 2007),[b]United States Census Population Database (accessed January 2007), [c] Woodward et al. (1999),

[d]National Weather Information Service (accessed 2006), [e](Oregon State Observation Well data (accessed January 2007).

*Denotes this municipality does not have surface water rights at this time. According to Oregon Water Resources Water Availability Report System (WARS) Database, water available at nearest surface water source is noted.

**When a municipality has no current surface water rights, this study has made a conservative estimate of water right volume that may be acquired for storage, 1.5 to 2 cfs.

***Denotes municipality does not have wells, domestic well substituted to represent local aquifer environment.

Appendix C: Brown's Site Rating System Results

Well Number: Oregon Water Resources Department Well Log Number, assigned at the time of drilling.
Location: City which owns this well.
Within 3 Mi of source: Surface water must be less than 3 miles from injection well to be viable for ASR according to this index, P = Passes this "test", F = Fails.
Land Use: Land Use must NOT be landfill, lakes, streams or protected habitat to be considered suitable.
Threatened Species: 0 = very likely to be habitat of threatened species, 1= somewhat likely, 2 = unlikely.
Well Density: 0 = more than 5 wells per square mile, 1= 1 to 5 wells, 2 = no wells.
Recharge Water Quality: 0 = recharge water meets no drinking water standards, 1 = meets some, 2 = meets all (only treated municipal water can rate 2).
Ambient Ground Water Quality: 0 = groundwater meets no drinking water standards, 1 = meets some, 2 = meets all.
T: Transmissivity 0 = T< 5,000 ft2/d or T> 25,000 ft2/d, 2 = 5,000 ft2/d < T < 25,000 ft2/d.
Gradient: 0 = Hydralic Gradient > 0.01 ft/ft, 1 = 0.01 to 0.001, 2 = gradient < 0.001.
Proximity to Source: 0 = Distance to source water is more than 3 mi, 1 = 1 to 3 mi, 2 = less than 1 mi.
Aquifer thickness: 0 = aquifer less than 25 ft thick, 2 = aquifer is greater than 25 ft thick.
Score: The sum of location's points, divided by the total available points in a perfect score. The perfect score varies because not all data is available for each location.
Percent Score: The score is expressed as a percentage.

Table C-1. Deschutes Basin Brown's System

Well No.	Location	Within 3 mi of source	Land Use	Threatened Species	Well Density	Recharge Water Quality	Ambient GW Quality	T	Gradient	Proximity to source	Aquifer thickness	Score	Percent Score
JEFF 426	Madras	P	P	1	1	1	1	0	1	1	0	8/16	50%
DESC 3853	Redmond	P	P	1	0	1	1	2	1	2	1	10/16	63%
DESC 3023	Sisters	P	P	1	0	1	1	0	1	2	0	6/16	38%
DESC 9108	Bend	P	P	1	1	1	1	2	1	2	1	11/16	69%
DESC 54968	La Pine	P	P	1	0	1	N/D	0	1	1	1	5/14	36%
CROO 53453	Prineville	P	P	1	1	1	1	2	N/D	1	2	9/14	64%

Table C-2. Goose and Summer Lakes Basin Brown's System

Well No.	Location	Within 3 mi of source	Land Use	Threatened Species	Well Density	Recharge Water Quality	Ambient GW Quality	T	Gradient	Proximity to source	Aquifer thickness	Score	Percent Score
LAKE 1023	Christmas Valley	nknown	P	2	1	1	1	0	2	0	2	9/16	56%
LAKE 4570	Paisley	P	P	0	1	1	1	0	N/D	2	2	7/14	50%
LAKE 1852	Plush	P	P	1	1	1	1	0	N/D	2	0	6/14	43%
LAKE 2471	Lakeview-2	P	P	0	1	1	0	0	N/D	2	2	6/14	43%
LAKE 2468	Lakeview-1	P	P	0	1	1	0	0	N/D	2	2	6/14	43%
LAKE 3107	Alkali Lake	nknown	P	1	1	1	0	0	N/D	0	2	5/14	36%

*No perennial streams in the area, intermittent springs are the only surface water source.

Table C-3. Grande Ronde Basin Brown's System

Well No.	Location	Within 3 mi of source	Land Use	Threat-ened Species	Well Density	Re-charge Water Quality	Ambient GW Quality	T	Grad ient	Prox-imity to source	Aq-uifer thick-ness	Score	Per-cent Score
WALL 50195	Enterprise	P	P	1	1	1	1	2	N/D	2	2	10	63%
UNIO 778	La Grande-1	P	P	1	0	1	1	2	1	2	2	10	63%
UNIO 50520	La Grande-2	P	P	1	1	1	1	2	1	2	2	11	69%
UNIO 2098	La Grande-3	P	P	1	1	1	1	2	1	2	2	11	69%
UNIO 1743	Elgin	P	P	1	1	1	1	2	N/D	2	2	10	71%
WALL 146	Wallowa	P	P	1	1	1	1	2	N/D	2	2	10	63%
WALL 50774	Joseph	P	P	1	1	1	1	0	N/D	2	2	8	57%

Table C-4. Hood Basin Brown's System

Well No.	Location	Within 3 mi of source	Land Use	Threat-ened Species	Well Density	Re-charge Water Quality	Ambient GW Quality	T	Grad ient	Prox-imity to source	Aq-uifer thick-ness	Score	Per-cent Score
HOOD 352	Cascade Locks-1	P	P	0	2	1	1	2	N/D	2	2	10/14	71%
HOOD 346	Cascade Locks-2	P	P	0	2	1	1	2	N/D	2	2	10/14	71%
HOOD 354	Cascade Locks-3	P	P	0	2	1	1	0	N/D	2	0	6/14	43%
HOOD 609	Hood River-1	P	P	0	2	1	1	0	N/D	2	2	8/14	57%
HOOD 50350	Hood River-2	P	P	0	2	1	1	0	N/D	2	2	8/14	57%
WASC 2419	The Dalles-1	P	P	0	2	2	1	2	N/D	2	2	10/14	71%
WASC 2416	The Dalles-2	P	P	0	2	2	1	0	N/D	2	0	7/14	50%
WASC 51004	Durfur	P	P	0	2	1	1	0	N/D	2	2	8/14	57%
WASC 2856	Mosier-1	P	P	0	0	1	1	2	0	2	2	8/16	50%
WASC 2764	Mosier-2	P	P	0	1	1	1	2	0	2	2	9/16	56%

Table C-5. John Day Basin Brown's System

Well No.	Location	Within 3 mi of source	Land Use	Threat-ened Species	Well Density	Re-charge Water Quality	Ambient GW Quality	T	Grad ient	Prox-imity to source	Aq-uifer thick-ness	Score	Per-cent Score
GILL 166	Arlington-1	P	P	0	1	1	1	0	N/D	2	2	7/14	50%
GILL 205	Condon-1	P	P	0	1	1	1	0	N/D	1	2	6/14	43%
GILL 50081	Condon-2	P	P	0	1	1	1	0	N/D	1	2	6/14	43%
GILL 50079	Condon-3	P	P	0	1	1	1	0	N/D	1	0	4/14	29%
WHEE 50304	Fossil	P	P	1	0	1	1	0	N/D	1	2	6/14	43%
WHEE 50057	Spray	P	P	1	0	1	1	2	N/D	2	2	8/14	57%
GRAN 434	John Day-1	P	P	0	0	1	1	0	N/D	2	2	6/14	43%
GRAN 50574	John Day-2	P	P	0	0	1	1	2	N/D	2	2	8/14	57%

Table C-6. Klamath Basin Brown's System

Well No.	Location	Within 3 mi of source	Land Use	Threat-ened Species	Well Density	Re-charge Water Quality	Ambient GW Quality	T	Grad ient	Prox-imity to source	Aq-uifer thick-ness	Score	Per-cent Score
KLAM 10202	Lenz	F	P	0	1	1	1	2	1	2	2	10/16	63%
KLAM 10189	Fort Klamath	P	P	0	1	1	1	0	0	2	2	7/16	44%
KLAM 10179	Klamath Falls-1	P	P	0	1	1	1	2	1	1	2	9/16	56%
KLAM 12050	Klamath Falls-2	P	P	0	1	1	1	2	1	1	2	9/16	56%
KLAM 12167	Klamath Falls-3	P	P	0	1	1	1	0	1	1	2	7/16	44%
JACK 21221	Pinehurst	P	P	0	0	1	1	0	N/D	2	2	6/14	43%
KLAM 14959	Merrill	P	P	0	1	1	1	0	2	2	2	9/16	56%
KLAM 2160	Bly-1	P	P	0	1	1	1	2	1	2	2	10/16	63%
KLAM 51725	Bly-2	P	P	0	1	1	1	2	1	2	2	10/16	63%
KLAM 14821	Malin	F*	P	0	1	1	1	2	2	0	2	9/16	56%
KLAM 54538	Chemult	F	P	0	1	1	1	0	1	0	0	4/16	25%
KLAM 951	Chiloquin	P	P	0	1	1	1	0	0	2	2	7/16	44%

*while there is no natural surface water, irrigation canals are within 3 mi

Table C-7. Malheur Lake Basin Brown's System

Well No.	Location	Within 3 mi of source	Land Use	Threat-ened Species	Well Density	Re-charge Water Quality	Ambient GW Quality	T	Grad ient	Prox-imity to source	Aq-uifer thick-ness	Score	Per-cent Score
Burns-1	HARN 290	P	P	1	1	1	1	2	2	2	2	12/16	75%
Burns-2	HARN 478	P	P	1	1	1	1	2	2	2	2	12/16	75%
Crane	HARN 1061	F	P	0	0	0	0	2	0	0	0	F	F
Riley	HARN 156	P	P	1	1	1	1	2	1	2	2	11/16	69%
Diamond	HARN 50010	P	P	1	1	1	1	0	0	2	2	8/16	50%
Blitzen	HARN 4699	F	P	0	0	0	0	2	0	0	0	F	F
Andrews	HARN 17311	P	P	1	1	1	1	2	1	2	2	11/16	69%

Table C-8. Malheur River Basin Brown's System

Well No.	Location	Within 3 mi of source	Land Use	Threat-ened Species	Well Density	Re-charge Water Quality	Ambient GW Quality	T	Grad ient	Prox-imity to source	Aq-uifer thick-ness	Score	Per-cent Score
MAHL 51791	Ironside	P	P	1	1	1	1	2	N/D	2	2	10/14	71%
MAHL 1276	Ontario-1	P	P	1	0	1	1	2	N/D	2	0	7/14	50%
MAHL 1284	Ontario-2	P	P	1	0	1	1	2	N/D	2	0	7/14	50%
MAHL 1761	Harper	P	P	1	1	1	1	2	N/D	2	2	10/14	71%
HARN 50760	Drewsey	P	P	1	1	1	1	2	N/D	2	2	10/14	71%

Table C-9. Middle Coast Basin Brown's System

Well No.	Location	Within 3 mi of source	Land Use	Threat-ened Species	Well Density	Re-charge Water Quality	Ambient GW Quality	T	Grad ient	Prox-imity to source	Aq-uifer thick-ness	Score	Per-cent Score
LANE 5528	Florence - 3	P	P	0	0	2	1	0	N/D	2	2	7/14	50%
LANE 5526	Florence - 1	P	P	0	0	2	1	0	N/D	2	2	7/14	50%
LANE 63362	Florence - 2	P	P	0	0	2	1	0	N/D	2	2	7/14	50%
LANE 6824	Yachats - 1	P	P	0	1	1	1	0	N/D	1	0	4/14	29%
LANE 6813	Yachats - 2	P	P	0	1	1	1	0	N/D	1	2	6/14	43%
LINC 168	Waldport	P	P	1	1	2	1	0	N/D	2	0	7/14	50%
LINC 1290	Newport - 2	P	P	1	1	2	1	0	N/D	2	0	7/14	50%
LINC 1291	Newport - 1	P	P	1	1	2	1	0	N/D	2	0	7/14	50%
LINC 613	Lincoln City - 1	P	P	0	1	2	1	0	N/D	2	2	8/14	57%
LINC 614	Lincoln City - 2	P	P	0	0	2	1	0	N/D	2	0	5/14	36%
BENT 7527	Alsea	P	P	0	1	1	1	0	N/D	1	2	6/14	43%

Table C-10. North Coast Basin Brown's System

Well No.	Location	Within 3 mi of source	Land Use	Threat-ened Species	Well Density	Re-charge Water Quality	Ambient GW Quality	T	Grad ient	Prox-imity to source	Aq-uifer thick-ness	Score	Per-cent Score
CLAT 304	Warrenton	P	P	0	1	1	1	0	N/D	1	2	6/14	43%
COLU 2541	Clatskanie	P	P	1	0	1	1	0	N/D	1	2	6/14	43%
CLAT 164	Cannon Beach	P	P	0	1	2	1	2	N/D	1	0	7/14	50%
CLAT 52022	Gearhart	P	P	1	1	1	1	0	N/D	0	0	4/14	29%
TILL 1122	Manzanita	P	P	1	1	1	1	0	N/D	1	2	7/14	50%
TILL 654	Tillamook	P	P	0	1	2	1	2	N/D	1	0	7/14	50%
TILL 115	Pacific City	P	P	1	1	1	1	0	N/D	1	2	7/14	50%

Table C-11. Owyhee Basin Brown's System

Well No.	Location	Within 3 mi of source	Land Use	Threat-ened Species	Well Density	Re-charge Water Quality	Ambient GW Quality	T	Grad ient	Prox-imity to source	Aq-uifer thick-ness	Score	Per-cent Score
MAHL 52787	Adrian	F*	P	0	1	1	1	0	N/D	0	2	5/14	36%
MAHL 2435	Rome	P	P	0	1	1	1	0	N/D	2	2	7/14	50%
MAHL 2471	Basque	P	P	0	1	1	1	0	N/D	2	2	7/14	50%
MAHL 2430	Jordan Valley	P	P	1	1	1	1	2	N/D	2	2	10/14	71%

*Adrian is greater than 3 miles from Owyhee River, but less than 3 miles from Snake River.

Table C-12. Powder Basin Brown's System

Well No.	Location	Within 3 mi of source	Land Use	Threat-ened Species	Well Density	Re-charge Water Quality	Ambient GW Quality	T	Grad ient	Prox-imity to source	Aq-uifer thick-ness	Score	Per-cent Score
UNIO 1537	N. Powder-1	P	P	1	1	1	1	0	1	2	2	9/16	56%
UNIO 1542	N. Powder-2	P	P	1	1	1	1	2	1	2	2	11/16	69%
BAKE 1542	Huntington	P	P	1	1	0	1	0	N/D	2	2	7/14	50%
MAHL 51426	Unity	P	P	1	1	0	1	0	N/D	1	2	6/14	43%
BAKE 782	Halfway-1	P	P	1	1	0	1	0	N/D	2	2	7/14	50%
BAKE 2063	Halfway-2	P	P	1	1	0	1	0	N/D	2	2	7/14	50%

Table C-13. Rogue Basin Brown's System

Well No.	Location	Within 3 mi of source	Land Use	Threat-ened Species	Well Density	Re-charge Water Quality	Ambient GW Quality	T	Grad ient	Prox-imity to source	Aq-uifer thick-ness	Score	Per-cent Score
JACK 6961	Medford -1	P	P	0	1	2	1	0	N/D	2	2	8/14	57%
JACK 6852	Medford -2	P	P	0	1	2	1	0	N/D	2	2	8/14	57%
JOSE 18119	Grants Pass	P	P	0	0	2	1	0	N/D	2	0	5/14	36%
JACK 20656	Ashland - 1	P	P	0	1	2	1	0	N/D	2	2	8/14	57%
JACK 35427	Ashland - 2	P	P	0	1	2	1	0	N/D	2	2	8/14	57%
JOSE 6631	Cave Junction	P	P	0	0	1	1	2	N/D	2	0	6/14	43%
JACK 18740	Prospect	P	P	0	0	1	1	0	N/D	2	2	6/14	43%
CURR 236	Gold Beach-1	P	P	0	1	1	1	0	N/D	2	0	5/14	36%
CURR 267	Gold Beach-2	P	P	0	1	1	1	2	N/D	2	0	7/14	50%

Table C-14. Sandy Basin Brown's System

Well No.	Location	Within 3 mi of source	Land Use	Threat-ened Species	Well Density	Re-charge	Ambient GW Quality	T	Grad ient	Prox-imity to source	Aq-uifer thick-ness	Score	Per-cent Score
MULT 1444	Troutdale-2	P	P	1	2	1	1	2	0	2	0	9/16	56%
CLAC 1843	Welches	P	P	2	2	1	1	0	N/D	2	0	8/14	57%
CLAC 7598	Wemme	P	P	1	2	1	1	0	N/D	2	0	7/14	50%
CLAC 7554	ZigZag	P	P	1	2	1	1	0	N/D	2	0	7/14	50%
CLAC 1575	Sandy-1	P	P	2	1	1	1	0	0	2	0	7/16	44%

Table C-15. South Coast Basin Brown's System

Well No.	Location	Within 3 mi of source	Land Use	Threat-ened Species	Well Density	Re-charge	Ambient GW Quality	T	Grad ient	Prox-imity to source	Aq-uifer thick-ness	Score	Per-cent Score
CURR 473	Brookings	P	P	0	0	2	1	0	N/D	2	0	5/14	36%
CURR 1684	Port Orford	P	P	1	1	2	1	0	N/D	2	2	9/14	64%
COOS 51117	Bandon -1	P	P	0	1	2	1	0	N/D	2	2	8/14	57%
COOS 3921	Bandon -2	P	P	0	1	2	1	0	N/D	2	2	8/14	57%
COOS 1960	Coos Bay -1	P	P	0	1	2	1	2	N/D	2	2	10/14	71%
COOS 2424	Coos Bay - 2	P	P	0	1	2	1	2	N/D	2	2	10/14	71%
COOS 2350	North Bend	P	P	0	1	2	1	0	N/D	2	2	8/14	57%

Bandon = coho, chinook
Brookings = coho
North Bend and Coos Bay = coho

Table C-16. Umatilla Basin Brown's System

Well No.	Location	Within 3 mi of source	Land Use	Threat-ened Species	Well Density	Re-charge	Ambient GW Quality	T	Grad ient	Prox-imity to source	Aq-uifer thick-ness	Score	Per-cent Score
UMAT 3347	Umatilla-1	P	P	1	1	1	2	2	1	2	2	12/16	75%
UMAT 3361	Umatilla-2	P	P	1	1	1	2	0	0	2	2	9/16	56%
MORR 304	Heppner-1	P	P	1	1	1	1	0	0	2	2	8/16	50%
MORR 1750	Heppner-2	P	P	1	1	1	1	0	0	2	2	8/16	50%
MORR 745	Boardman	P	P	1	1	1	1	0	0	2	2	8/16	50%
UMAT 89	Pilot Rock	P	P	1	1	1	1	0	0	2	2	8/16	50%
UMAT 3089	Weston-1	P	P	1	1	1	1	0	0	2	2	8/6	50%
UMAT 3093	Weston-2	P	P	1	1	1	1	2	0	2	2	10/16	63%
UMAT 5450	Hermiston-1	P	P	1	1	2	1	2	1	1	2	11/16	69%
UMAT 2061	Hermiston-2	P	P	1	1	2	1	2	1	1	2	11/16	69%
UMAT 2962	Stanfield	P	P	1	0	1	1	0	N/D	2	2	7/14	50%
UMAT 5065	Milton-Freewater	P	P	1	0	1	1	0	N/D	2	2	7/14	50%

Table C-17. Umpqua Basin Brown's System

Well No.	Location	Within 3 mi of source	Land Use	Threat-ened Species	Well Density	Re-charge Water Quality	Ambient GW Quality	T	Grad ient	Prox-imity to source	Aq-uifer thick-ness	Score	Per-cent Score
DOUG 2255	Reedsport	P	P	1	1	2	1	2	N/D	2	0	9/14	64%
DOUG 2341	Drain	P	P	1	1	2	1	0	N/D	2	2	9/14	64%
DOUG 4606*	Sutherlin	P	P	1	1	2	1	0	N/D	2	2	9/14	64%
DOUG 5296*	Glide	P	P	1	1	2	1	0	N/D	2	2	9/14	64%
DOUG 6487*	Roseburg-1	P	P	1	0	2	1	0	N/D	2	2	8/14	57%
DOUG 6679*	Roseburg-2	P	P	1	0	2	1	2	N/D	2	2	10/14	71%
DOUG 8475	Myrtle Creek	P	P	1	1	2	1	0	N/D	2	2	9/14	64%
DOUG 875	Canyonville	P	P	1	1	2	1	0	N/D	2	2	9/14	64%

Table C-18. Willamette Basin Brown's System

Well No.	Location	Within 3 mi of source	Land Use	Threat-ened Species	Well Density	Re-charge Water Quality	Ambient GW Quality	T	GW Grad ient	Prox-imity to source	Aq-uifer thick-ness	Score	Per-cent Score
MULT 1190	Portland-3	P	P	1	1	1	1	2	1	2	2	11/16	69%
WASH 51903	Sherwood	P	P	1	2	1	1	2	1	1	2	11/16	69%
CLAC 00305	Milwaukie-2	P	P	1	0	1	1	0	1	2	2	8/16	50%
CLAC 57766	Estacada	P	P	1	1	1	1	2	N/D	2	2	10/14	71%
CLAC 12025	Canby-2	P	P	1	0	1	1	2	1	2	2	10/16	63%
CLAC 4396	Oregon City	P	P	1	1	1	1	2	1	1	2	10/16	63%
YAMH 323	Newberg-1	F	P	1	1	1	1	0	N/D	0	2	6/14	43%
YAMH 5917	McMinnville-1	P	P	1	1	1	1	0	1	2	2	9/16	56%
YAMH 125	Dayton	P	P	2	1	1	1	0	1	1	2	9/16	56%
MARI 1820	Woodburn-2	P	P	1	1	1	1	2	1	2	2	11/16	69%
YAMH 2787	Amity	P	P	1	1	1	1	2	0	2	0	8/16	50%
MARI 57164	Mt. Angel-1	P	P	2	1	1	1	2	1	2	2	12/16	75%
POLK 420	Independence	P	P	1	1	1	1	2	1	1	0	8/16	50%
LINN 12855	Sweet Home	P	P	1	1	1	1	0	1	2	0	7/16	44%
BENT 51479	Corvallis-2	P	P	1	1	1	1	0	2	2	2	10/16	63%
LANE 57266	Eugene-2	P	P	1	1	1	1	0	1	2	2	9/16	56%
LANE 58776	Cottage Grove	P	P	1	1	1	1	0	2	2	0	8/16	50%
CLAC 4488	Wilsonville	P	P	1	1	2	1	2	N/D	2	2	11/14	79%
CLAC 60002	West Linn	P	P	1	0	2	1	2	1	2	2	11/16	69%
WASH 5581	Hillsboro	P	P	1	1	2	1	0	N/D	2	0	7/14	50%
CLAC 62338	Boring	P	P	1	1	1	1	0	1	1	2	8/16	50%

Appendix D: ASR Site Assessment Results

Basin	Location	Well Log Number	ASR Metric	Brown Results All Parameters	Brown Results Aquifer Parameters
Deschutes	Madras-2	JEFF 427	2.3	50%	17%
	Madras-1	JEFF 426	0.7	50%	17%
	Bend-1	DESC 5526	3.5	69%	83%
	Bend-2	DESC 5524	7.2	69%	83%
	Bend-6	DESC 9108	48.0	69%	83%
	Sisters	DESC 3023	420.0	38%	17%
	Redmond-3	DESC 407	4.9	63%	83%
	Redmond-5	DESC 3951	884.0	63%	83%
	La Pine-2	DESC 54968	475	36%	50%
	La Pine-1	DESC 55049	738	36%	50%
	Prineville	CROO 53453	731	64%	100%
Goose and Summer Lakes	Lakeview-1	LAKE 2468	6	43%	0%
	Lakeview-2	LAKE 2471	11	43%	50%
	Plush	LAKE 1852	11	43%	0%
	Paisley	LAKE 4570	38	50%	50%
	Christmas Valley	LAKE 1023	625	56%	67%
	Alkali Lake	LAKE 3107	1174	36%	50%
Grande Ronde	La Grande-1	UNIO 778	46	63%	83%
	La Grande-2	UNIO 50520	122	69%	83%
	La Grande-3	UNIO 2098	0.02	69%	83%
	Elgin	UNIO 1743	0.02	71%	100%
	Enterprise	WALL 50195	7	63%	100%
	Joseph	WALL 50774	12	57%	50%
	Wallowa	WALL 146	21	63%	100%
Hood	Cascade Locks-1	HOOD 352	40	71%	100%
	Cascade Locks-2	HOOD 346	4	71%	100%
	Cascade Locks-3	HOOD 354	0	43%	0%
	Hood River-1	HOOD 609	0.2	57%	50%
	Hood River-2	HOOD 50350	0	57%	50%
	The Dalles-1	WASC 2419	1	71%	100%
	The Dalles-2	WASC 2416	0	50%	0%
	Durfur	WASC 51004	0	57%	50%
	Mosier-1	WASC 2856	24	50%	67%
	Mosier-2	WASC 2764	0	56%	67%
John Day	John Day-1	GRAN 434	0	43%	50%
	John Day-2	GRAN 50574	4	57%	100%
	Arlington-1	GILL 166	4	50%	50%
	Condon-1	GILL 205	44	43%	50%
	Condon-2	GILL 50081	8	43%	50%
	Condon-3	GILL 50079	7	29%	0%
	Spray	WHEE 50057	118	57%	100%
	Fossil	WHEE 50304	198	43%	50%

Appendix D: ASR Site Assessment Results (continued)

Basin	Location	Well Log Number	ASR Metric	Brown Results All Parameters	Brown Results Aquifer Parameters
Klamath	Chemult-1	KLAM 51568	0.7	25%	17%
	Chemult-2	KLAM 54538	6	25%	17%
	Chiloquin-1	KLAM 951	8	44%	33%
	Chiloquin-2	KLAM 53392	1.0	44%	33%
	Fort Klamath	KLAM 10189	24	44%	33%
	Merrill	KLAM 14959	145	56%	67%
	Pinehurst	JACK 21221	14	43%	50%
	Klamath Falls-1	KLAM 10179	7	56%	83%
	Klamath Falls-2	KLAM 12050	61	56%	83%
	Klamath Falls-3	KLAM 12167	23	44%	50%
	Lenz	KLAM 10202	65	63%	83%
	Bly-1	KLAM 2160	67	63%	83%
	Bly-2	KLAM 51725	588	63%	83%
	Malin	KLAM 14821	455	56%	100%
Malheur Lake	Blitzen	HARN 4699	0.0	0%	33%
	Diamond	HARN 50010	5	50%	33%
	Andrews	HARN 17311	54	69%	83%
	Crane	HARN 1061	91	0%	33%
	Burns-1	HARN 290	113	75%	100%
	Burns-2	HARN 478	82	75%	100%
	Riley	HARN 156	130	69%	83%
Malheur River	Ontario-1	MAHL 1276	1.0	50%	50%
	Ontario-2	MAHL 1284	0.4	50%	50%
	Harper	MAHL 1761	12	71%	100%
	Drewsey	HARN 50760	45	71%	100%
	Ironside	MAHL 51791	168	71%	100%
Middle Coast	Lincoln City-1	LINC 613	1.0	57%	50%
	Lincoln City-2	LINC 614	0.5	36%	0%
	Alsea	BENT 7527	7	43%	50%
	Waldport	LINC 168	1.0	50%	0%
	Yachats-1	LANE 6824	2	29%	0%
	Yachats-2	LANE 6813	0.4	43%	50%
	Newport-1	LINC 1291	15	50%	0%
	Newport-2	LINC 1290	2	50%	0%
	Florence-1	LANE 5526	177	50%	50%
	Florence-2	LANE 63362	110	50%	50%
	Florence-3	LANE 5528	27	50%	50%
North Coast	Warrenton	CLAT 304	1.0	43%	50%
	Clatskanie	COLU 2541	3	43%	50%
	Manzanita	TILL 1122	3	50%	50%
	Pacific City	TILL 115	4	50%	50%
	Cannon Beach	CLAT 164	20	50%	50%
	Gearhart	CLAT 52022	27	29%	0%
	Tillamook	TILL 654	89	50%	50%

Appendix D: ASR Site Assessment Results (continued)

Basin	Location	Well Log Number	ASR Metric	Brown Results All Parameters	Brown Results Aquifer Parameters
Owyhee	Rome	MAHL 2435	3	50%	50%
	Jordan Valley	MAHL 2430	45	71%	100%
	Basque	MAHL 2471	76	50%	50%
	Adrian	MAHL 52787	109	36%	50%
Powder	North Powder-1	UNIO 1537	0	56%	50%
	North Powder-2	UNIO 1542	6	69%	83%
	Halfway-1	BAKE 782	34	50%	50%
	Halfway-2	BAKE 2063	7	50%	50%
	Huntington	BAKE 1542	9	50%	50%
	Unity	MAHL 51426	1.0	43%	50%
Rogue	Ashland-2	JACK 35427	0.2	57%	50%
	Grants Pass	JOSE 18119	0.3	36%	0%
	Medford-1	JACK 6961	0.5	57%	50%
	Ashland-1	JACK 20656	1.0	57%	50%
	Medford-2	JACK 6852	1.2	57%	50%
	Gold Beach-2	CURR 267	4	50%	50%
	Gold Beach-1	CURR 236	11	36%	0%
	Prospect	JACK 18740	13	43%	50%
	Cave Junction	JOSE 6631	28	43%	50%
Sandy	Sandy-1	CLAC 1575	1.1	44%	0%
	Wemme	CLAC 7598	27	50%	0%
	Troutdale-1	MULT 1442	100	56%	33%
	ZigZag	CLAC 7554	111	50%	0%
	Troutdale-2	MULT 1444	343	56%	33%
South Coast	Port Orford	CURR 1684	0.2	64%	50%
	Bandon -1	COOS 51117	0.1	57%	50%
	Bandon -2	COOS 3921	0.7	57%	50%
	Brookings - 1	CURR 124	7	36%	0%
	Brookings - 2	CURR 473	6	36%	0%
	Coos Bay -1	COOS 1960	17	71%	75%
	Coos Bay -2	COOS 2424	69	71%	75%
	North Bend	COOS 2350	32	57%	50%
Umatilla	Boardman	MORR 745	0.7	50%	33%
	Heppner-1	MORR 304	1.2	50%	33%
	Heppner-2	MORR 1750	3	50%	33%
	Pilot Rock	UMAT 89	3	50%	33%
	Umatilla-1	UMAT 3347	12	75%	83%
	Umatilla-2	UMAT 3361	5	56%	33%
	Hermiston-1	UMAT 5450	479	69%	83%
	Hermiston-2	UMAT 2061	34	69%	83%
	Weston-1	UMAT 3089	323	50%	33%
	Weston-2	UMAT 3093	1267	63%	67%
	Stanfield	UMAT 2962	51	50%	50%
	Milton-Freewater	UMAT 5065	8	50%	50%

Appendix D: ASR Site Assessment Results (continued)

Basin	Location	Well Log Number	ASR Metric	Brown Results All Parameters	Brown Results Aquifer Parameters
Umpqua	Myrtle Creek	DOUG 8475	0.1	64%	50%
	Roseburg -1	DOUG 6487	0.1	57%	50%
	Roseburg -2	DOUG 6679	1	71%	100%
	Drain	DOUG 2341	0.2	64%	50%
	Glide	DOUG 5296	1.3	64%	50%
	Canyonville	DOUG 875	2	64%	50%
	Sutherlin	DOUG 4606	2	64%	50%
	Reedsport	DOUG 2255	6	64%	50%
Willamette	Newberg-1	YAMH 323	0.0	43%	50%
	Mount Angel-2	MARI 50456	0.0	75%	83%
	Eugene-1	LANE 8286	0.0	56%	50%
	McMinnville-1	YAMH 5917	0.0	56%	50%
	Eugene-2	LANE 57266	0.0	56%	50%
	Hillsboro	WASH 5581	0.0	50%	0%
	Corvallis-2	BENT 51479	0.0	63%	67%
	Cottage Grove	LANE 58776	0.0	50%	33%
	Canby-1	CLAC 012027	0.4	63%	83%
	Woodburn-3	MARI 18414	0.5	69%	83%
	Woodburn-1	MARI 1636	0.7	69%	83%
	Woodburn-2	MARI 1820	0.8	69%	83%
	Canby-2	CLAC 12025	0.8	63%	83%
	Milwaukie-1	CLAC 00315	2	50%	50%
	Oregon City	CLAC 4396	3	63%	83%
	Milwaukie-2	CLAC 00305	4	50%	50%
	Amity	YAMH 2787	4	50%	33%
	Mount Angel-1	MARI 57164	8	75%	83%
	Portland-2	MULT 1133	15	69%	83%
	Portland-4	MULT 1286	16	69%	83%
	Portland-3	MULT 1190	19	69%	83%
	Estacada	CLAC 57766	20	71%	100%
	Wilsonville	CLAC 4488	24	79%	100%
	Dayton	YAMH 125	25	56%	50%
	Independence	POLK 420	26	50%	50%
	Sherwood	WASH 51903	35	69%	83%
	West Linn	CLAC 60002	45	69%	83%
	Boring/Demascus	CLAC 62338	69	50%	50%
	Portland-1	MULT 1118	302	69%	83%