ANL/EVS-14/14

Water Use in Enhanced Geothermal Systems (EGS): Geology of U.S. Stimulation Projects, Water Costs, and Alternative Water Source Policies

Environmental Science Division

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Water Use in Enhanced Geothermal Systems (EGS): Geology of U.S. Stimulation Projects, Water Costs, and Alternative Water Source Policies

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October 2014

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ACRONYMS AND ABBREVIATIONS

ac-ft	acre-foot
Argonne	Argonne National Laboratory
AWCM	Argonne Water Cost Model
AWSIS	Alternative Water Source Information System
AWWA	American Water Works Association
BLM	Bureau of Land Management
BLS	Bureau of Labor Statistics
BOD_5	5-day biochemical oxygen demand
CCR	California Code of Regulations
CDHS	California Department of Health Services
CDPH	California Department of Public Health
CDWR	California Department of Water Resources
CEC	constituent of emerging concern
CPI-U	Consumer Price Index for All Urban Consumers
CRWTF	California Recycled Water Task Force
DEET	N,N-diethyl-meta-toluamide
DOE	U.S. Department of Energy
DPEEP	Desert Peak East EGS Project
EA	environmental assessment
EERE	Office of Energy Efficiency and Renewable Energy (DOE)
EGS	enhanced geothermal systems
EIA	Energy Information Administration
EPA	U.S. Environmental Protection Agency
EPRI	Energy Policy Research Institute
GETEM	Geothermal Electricity Technology Evaluation Model
GIS	geographic information system
gpm	gallon(s) per minute
GRD	Geothermal Data Repository
hp	horsepower
ID	identification
IDAPA	Idaho Administrative Procedures Act
IDEQ	Idaho Department of Environmental Quality
IDWR	Idaho Department of Water Resources
IMD	Internal Management Directive
in.	inch

LCA	life cycle assessment
LCOE	levelized cost of energy
LCOW	levelized cost of water
mi	mile(s)
mg/L	milligram(s) per liter
MWh	megawatt hour(s)
NAC	Nevada Administrative Code
NDEP	Nevada Division of Environmental Protection
NDWP	Nevada Division of Water Planning
NDWR	Nevada Division of Water Resources
NEPA	National Environmental Policy Act of 1969
NETL	National Energy Technology Laboratory
NGDS	National Geothermal Data System
NPDES	National Pollutant Discharge Elimination System
O&M	operation and maintenance
OAR	Oregon Administrative Rules
ODEQ	Oregon Department of Environmental Quality
psig	pound(s) per square inch gauge
pT1	pre-Tertiary subunit 1
pT2	pre-Tertiary subunit 2 (pT2)
Reclamation	Bureau of Reclamation
RWQCB	Regional Water Quality Control Board
RWUP	Recycled Water Use Plan
s	second(s)
SCTRWPG	South Central Texas Regional Water Planning Group
SEGEP	Southeast Geysers Effluent Pipeline Project
SNWA	Southern Nevada Water Authority
SRGRP	Santa Rosa Geysers Recharge Project
SWRCB	California State Water Resources Control Board
TDS	total dissolved solids
TZIM	thermally degrading zonal isolation material
UCSB	University of California Santa Barbara
UIC	Underground Injection Control
WDR	Waste Discharge Requirement
WLSZ	Walker Lane/Eastern California Shear Zone

WPCF	Water Pollution Control Facility
WRC	water recycling criteria
WWTP	wastewater treatment plant
WTS	water technical sheet
yr	year(s)

1 INTRODUCTION

According to the Energy Information Administration (EIA) of the U.S. Department of Energy (DOE), geothermal energy generation in the United States is projected to more than triple by 2040 (EIA 2013). This addition, which translates to more than 5 GW of generation capacity, is anticipated because of technological advances and an increase in available sources through the continued development of enhanced geothermal systems (EGSs) and low-temperature resources (EIA 2013). Studies have shown that air emissions, water consumption, and land use for geothermal electricity generation have less of an impact than traditional fossil fuel–based electricity generation; however, the long-term sustainability of geothermal power plants can be affected by insufficient replacement of aboveground or belowground operational fluid losses resulting from normal operations (Schroeder et al. 2014). Thus, access to water is therefore critical for increased deployment of EGS technologies and, therefore, growth of the geothermal sector. This paper examines water issues relating to EGS development from a variety of perspectives. It starts by exploring the relationship between EGS site geology, stimulation protocols, and below ground water loss, which is one of the largest drivers of water consumption for EGS projects. It then examines the relative costs of different potential traditional and alternative water sources for EGS. Finally it summarizes specific state policies relevant to the use of alternative water sources for EGS, and finally explores the relationship between EGS site geology, stimulation protocols, and below ground water loss, which is one of the largest drivers of water consumption for EGS projects.

1.1 PURPOSE AND OVERVIEW OF STUDY

The analysis in this report builds off of results presented in previous Argonne National Laboratory (Argonne) reports on this topic, notably Sullivan et al. (2010), Clark et al. (2011, 2012, 2013), and Schroeder et al. (2014). These previous reports have concluded that greenfield EGS may consume significantly more water than conventional hydrothermal systems due primarily to the potential for below ground reservoir loss in artificially created reservoirs. Water consumption for greenfield EGS were found to range anywhere from 230 to 4,200 gallons per MWh, with most systems falling between 800 and 2,800 gallons per MWh (Schroeder et al 2014). These water consumption rates are higher than most conventional power plants, and thus may represent a challenge for EGS development moving forward if only fresh water is used. However, EGS can likely use lower quality water sources than conventional power plants allowing them to meet their water demands with less impact on competing water users.

It should be noted that the water consumption rates discussed above are only likely to be applicable to completely artificially created reservoirs that are not hydrologically connected to existing hydrothermal reservoirs. Stimulation techniques have been utilized within or around the periphery of known hydrothermal resources in order to enhance permeability resulting in improved injection and production flow rates, but these systems are expected to exhibit significantly lower water losses than so called “hot dry rock systems” due to their connection with the hydrothermal resource. Of the systems evaluated in this study, the projects at The Geysers, Brady’s Hot Springs, Desert Peak, and Raft River all take place within or nearby existing hydrothermal resources, while only Newberry Volcano can be considered greenfield EGS projects, occurring outside of known hydrothermal systems.

The report is organized as follows. Chapter 2 presents a summary of geological data for current EGS stimulation projects in the United States. It describes the geology at the location of the stimulated wells, the stimulation protocol used at that site (i.e., pressure[s] and flow rate[s] over time interval[s]), and the results (if available) of the change in flow rate and permeability after stimulation for a given observed water loss. Similarities among these sites in terms of geology are then analyzed.

Chapter 3 estimates the cost of different sources of water in the areas surrounding existing EGS projects in the western United States to provide a better understanding of the impacts that water availability and the type of water utilized can have on the cost of geothermal projects.

Chapter 4 presents an analysis of reclaimed water polices and definitions in states with active EGS development projects: California (the Geysers), Idaho (Raft River), Nevada (Desert Peak), and Oregon (Newberry Volcano).

Chapter 5 presents a summary and conclusions, and Chapter 6 lists the references used to prepare this report.

Appendix A details the modeling methodology of the water cost model used in Chapter 2.

2 EGS GEOLOGICAL ANALYSIS

2.1 INTRODUCTION

From a lifecycle perspective, the long-term maintenance of reservoir pressure for successful, continued operation of EGS facilities requires considerable volumes of water(from 230 to 4,200 gal/MWh) (Schroeder et al. 2014). Historical EGS reservoir loss rates have been found to range from 1-75% (Clark et al. 2013). For EGS projects to successfully generate and sell electricity, acceptable loss rates are generally below 10%. A review of those historical EGS tests suggested a correlation with increase pressure during stimulation and circulation with increased reservoir water loss. This chapter presents an overview of the existing data for current EGS stimulation projects in the United States. It describes the geology at the location of the stimulated wells, the stimulation protocol used at that site (i.e., pressure[s] and flow rate[s] over time interval[s]), and the results (if available) of the change in flow rate and permeability after stimulation for a given observed water loss. The purpose of this is to potentially identify any additional physical characteristics that may be correlated with belowground operational water losses.

2.2 METHODS

The Geothermal Data Repository (GDR) Web portal (http://gdr.openei.org) and National Geothermal Data System (NGDS) web portal (http://www.geothermaldata.org) were extensively searched for entries involving EGS. The goal of these searches were to identify any accessible hard data uploaded to GDR that might contain information about EGS stimulation, in particular, stimulated formation geology and lithology, reservoir performance, and data about the actual stimulation itself (e.g., flow rates, pressures, and number of stages used, etc.). Information of this type was used to help identify and discern potential commonalities among successfully stimulated projects, in an attempt to understand what makes an EGS project successful. The search was conducted using targeted keywords that focused on the areas and topics described above.

During the course of these searches, projects with relevant information were recorded by GDR identification (ID) number. In all, 11 separate GDR IDs were identified. Many of these ID numbers are used to organize multiple documents. For example, the GDR ID 271 for the Newberry Volcano project includes 149 separate items. Once all applicable GDR IDs were recorded, a review was conducted of all documents within each ID number. Relevant information was extracted from each document and recorded in a separate spreadsheet. The information identified included pressure, flow rate of stimulation, initial flow rate, length of stimulation, post stimulation flow rate, geology, total fluid volume used, and total fluid volume lost. The resultant database was analyzed for commonalities among projects in terms of geology, stimulation protocols, and project successes and failures.

2.3 RESULTS

2.3.1 Desert Peak EGS Project

2.3.1.1 Geology

The Desert Peak East EGS project (DPEEP) is located in the Hot Spring Mountains in west-central Nevada (about 50 miles northeast of Reno) near the transitional zone between the Sierra Nevada and the Basin and Range physiographic provinces (Benoit et al. 1982). The mountains are composed mainly of Quaternary sediments and Tertiary (Pliocene to Oligocene) silicic volcanic rocks. These rocks are underlain by a Mesozoic (pre-Tertiary) section consisting of metamorphic rocks and deeper granitic (plutonic) rocks (Lutz et al. 2003; Benoit et al. 1982). The pre-Tertiary subunit 1 (pT1) occurs between depths of about 3,000 to 5,000 feet; it is a sequence of fine-grained metasedimentary rocks, rhyolitic conglomerates, and volcaniclastics. The pT1 subunit has undergone low-grade metamorphism and some hydrothermal alteration. Pre-Tertiary subunit 2 (pT2) occurs at depths of about 5,000 to 7,000 feet. This subunit is composed of metasedimentary rocks and deeper granodioritic intrusive rocks. Foliation and deformation is evident in the metasedimentary rocks, increasing with depth and proximity to the intrusive rocks. A deeper unit, a muscovite-biotite granodiorite, occurs at depths greater than 7,000 feet and intrudes pT2; alteration and recrystallization occurs where the intrusive body contacts the overlying and surrounding rocks. Localized hydrothermal alteration is evident in the pT2 and deeper intrusive units. These units are continuous across the DPEEP field and are considered good candidates for hydraulic stimulation (Lutz et al. 2003).

2.3.1.2 Stimulation Protocol and Results

Well 27-15, located in the low-permeability margins of the DPEEP, was chosen as a candidate for EGS because of its favorable bottom-hole temperatures (355°F to 385°F), its demonstrated hydraulic connectivity to nearby injection wells, and its proximity to infrastructure (Chabora et al. 2012). Studies of stress, fractures, and rock mechanical properties within this portion of the reservoir, along with *in situ* measurements of friction and permeability, aided in predicting optimal pore pressures (of injected water) needed to induce shear failure and generate a zone of enhanced permeability that would reach active geothermal production wells about 0.3 miles to the south-southwest.[1]

Hydraulic stimulation targeting silicified rhyolitic tuffs and metamorphosed mudstones at a depth interval of about 3,000 to 6,000 feet was initiated in 2010 and again in 2013. Stimulation was conducted in four stages in 2010 ranging from 220 to 540 psig (Dempsey et al. 2013). Water injection began at 3 gallons per minute (gpm) during stage one and ramped up to 70 gpm after

[1] The directionality of the enhanced permeability zone was predicted to follow the orientation of the maximum principle stress (S_{Hmax}), which was inferred from observations of borehole failures in geothermal wells 27-15 and 23-1 (see Figure 7 in Hickman and Davatzes 2010).

50 days in stage four (Dempsey et al. 2013). Initial injectivity before stimulation was around 0.014 gpm/psig, and injectivity after the four-stage injection was 0.16 gpm/psig (Dempsey et al. 2013).

2.3.2 The Northwest Geysers EGS Demonstration Project

2.3.2.1 Geology

The Geysers geothermal field is located west of the Basin and Range physiographic province in northern California, about 120 miles north of San Francisco. It is a vapor-dominated geothermal system that is hydraulically confined by low-permeability rocks (Rutqvist et al. 2013). Located within the terrane of the San Andreas Fault system, The Geysers reservoir is strongly influenced by Franciscan-age subduction, Tertiary thrust faulting, and high-angle Quaternary faults (Garcia et al. 2012). The demonstration project is in the northwestern part of The Geysers (currently known as the Northwest Geysers), an undeveloped area of the geothermal field where the high-temperature reservoir is at its shallowest depth (5,500 to 6,000 feet below sea level) just below the steam reservoir. The deep reservoir rock consists of thermally altered metagraywacke and intercalated argillite and is characterized by high temperatures and low permeability (Garcia et al. 2012).

2.3.2.2 Stimulation Protocol and Results

The Northwest Geysers contains a significant portion of the recoverable geothermal energy in the Geysers system. The objective of the demonstration project was to develop and demonstrate technology needed to extract energy from a low-permeability, high-temperature zone underlying an existing conventional high-temperature geothermal system using low pressures (Rutqvist et al. 2013; Walters 2013).[2] Two previously abandoned exploratory wells, P-32 and P-31, were reopened, deepened, and recompleted as an injection-production pair. The geothermal wells are 9,611 feet and 11,143 feet deep, respectively; bottom-hole temperatures in well P-32 are around 752°F. The demonstration project has proceeded through the pre-stimulation and stimulation phases and is now in the final monitoring phase (Rutqvist et al. 2013).

Modeling of the thermal, hydraulic, and mechanical regime within the reservoir helped to predict the spatial extent of the injection-induced stimulation zone. Modeling results were corroborated with observations of microseismic activity and field monitoring data during the first few months of injection. Investigators found that the rock mass within The Geysers geothermal

[2] Rutqvist et al. (2013) noted that another motivation for the demonstration project was that a large EGS was inadvertently created below the production area in the northwestern part of The Geysers in the late 1970s when injected water reached the high-temperature zone below its deepest wells. The demonstration project used the same approach by injecting water (at an injection rate of 500 gpm) directly into the conductively heated, low-permeability reservoir rock to create a water table with a hydraulic head of 1,500 psi to gently stimulate thermal fracturing (Walters 2013).

field was near critically stressed for shear failure; therefore, even small perturbations in the stress field would generate seismicity (Rutqvist et al. 2013). Walters (2013) noted that the generation of microfractures during the Northwest Geysers EGS demonstration relied primarily on thermal effects rather than pressure effects (as used in hydraulic fracturing). This approach had the advantage of lowering the concentrations of noncondensable gases in the native steam (which rendered previous production attempts infeasible due to the corrosive nature of the gases (Rutvquist 2013), and producing a better quality injection-derived steam during the EGS project (Walter 2013). Three physical phenomena have been identified as contributing to the reduction in NCG concentrations: boiling injectate providing a clean source of steam, pressure effects preventing migration of native steam with higher NCG concentrations, and pressure effects impacting solubility of NCG in the condensed phase (Pruess et al 2007).

Stimulation generated a rise of reservoir pressure from 323 psig to 428 psig at P-32, and a rise of reservoir pressure from 345 psig to 367 psig at P-31 (Garcia et al. 2012). The stimulation of P-32 began at an initial flow rate of 1100 gpm and then tailed down to 400 gpm after 55 days (Garcia et al. 2012). This stimulation resulted in an increase of flow at well P-25 of 13,000 lbs./hr. (Garcia et al. 2012).

2.3.3 Newberry Volcano EGS Demonstration Project

2.3.3.1 Geology

The Newberry Volcano EGS demonstration project is located on the western flank of Newberry Volcano in central Oregon (within the Deschutes National Forest, about 22 miles south of Bend) (BLM 2011). The volcano lies at the junction of three geologic provinces: the Cascade Range (to the west), the High Lava Plains portion of the Basin and Range (to the south and east), and the Blue Mountains (to the northeast). It has been active for the past 500,000 years and last erupted about 1,300 years ago (although the most recent caldera-related eruptions occurred about 300,000 and 80,000 years ago); it currently covers an area of about 620 square miles (Frone et al. 2014). Volcanic rocks are predominantly basalt and basalt-andesite flows, pyroclastic deposits, and cinder cones.

The current caldera is thought to be the result of multiple caldera collapse events. Current measurements for geothermal wells in and around the caldera show the highest heat flow within the caldera, with values decreasing away from the caldera center. The reservoir's heat source is a large magma chamber centered below the caldera, at an estimated depth of about 9,800 to 20,000 feet (Frone et al. 2014).

2.3.3.2 Stimulation Protocol and Results

The demonstration project involved stimulation of an existing 10,060-foot geothermal well, NWG 55-29 (drilled in 2008), where bottom hole temperatures exceed 600°F (BLM 2011). The purpose of the project was to engineer a reservoir using a process of well stimulation called hydro-shearing, which uses cold water to create a network of cracks in deep rocks where natural fractures and cracks already exist (BLM 2011).

Stimulation of the well ran from October to December 2012. Three stages of stimulation were used to create the multiple fracture systems within the reservoir. The estimated final injectivity for 55-29 based on injectivity improvements per stage was approximately 0.51 gpm/psig (Petty et al. 2013). Max stimulation flow rate was 368 gpm and a total of 10.9 million gallons was injected over the course of the stimulation (Petty et al. 2013).

Injectivity, downhole temperatures, and seismic analysis indicated that the fracture network was successfully enhanced. The enhanced networks were then sealed using thermally degrading zonal isolation materials (TZIMs) to create three distinct permeable zones within the wellbore. The demonstration showed that targeting deep, high-temperature portions of the reservoir while isolating and preventing stimulation of shallow, low-temperature portions could increase the fluid flow rates, which ultimately could reduce project costs (Petty et al. 2013).

2.3.4 Raft River Geothermal Field

2.3.4.1 Geology

The Raft River geothermal field is located in the Raft River Valley, on the northeastern edge of the Basin and Range physiographic province and on the southern side of the Snake River Plain, in southern Idaho (about 90 miles southwest of Pocatello). The area sits above a basement complex of Proterozoic metamorphic rocks (e.g., schist and quartzite) and igneous rocks (e.g., quartz monzonite) of Archean age. Basement rocks were deformed and intruded during the mid-Tertiary and are covered by a thick sequence of Quaternary basin fill and late-Tertiary sedimentary and volcanic deposits (e.g., ash-flow tuffs, lava flows, tuffaceous siltstone, greywacke, and sandstone). The Tertiary deposits are offset by Cenozoic-age listric normal faults.

A low-angle, normal detachment fault separates the deformed Precambrian basement rocks from the overlying Tertiary deposits. About 15 miles of slip has occurred along this fault, moving the Tertiary rocks to the east away from a rising gneiss dome in the west (Jones et al. 2011). Brecciation and evidence of strong hydrothermal alteration have been observed in samples from deep wells at the contact between the Tertiary and Precambrian rocks (at a depth of about 5,300 feet). The primary reservoir is the Elba Quartzite, a metamorphosed sandstone unit at the top of the Precambrian basement (Jones et al. 2011). Bottom-hole temperatures of geothermal wells drilled into the reservoir rocks range from 271°F to 300°F (Jones et al. 2011; Bradford et al. 2013).

2.3.4.2 Stimulation Protocol and Results

Well RRG-9 was drilled in 2006 to test the southern extension of the productive fracture zone associated with well RRG-7. It is located about a mile southwest of the main well field (Jones et al. 2011; Bradford et al. 2013). The base of the well has a 44° inclination to the west and penetrates Precambrian reservoir rocks at a depth of 5,286 feet (Bradford et al. 2013). Step-rate and step-down stimulation tests were conducted to measure the *in situ* stress regime and to provide friction values for bottom hole pressure calculations to prepare for a series of staged stimulation treatments that were started in June 2013. Results of the stimulation to date show that permeability of the reservoir is increasing and the injectivity index is also increasing (meaning more fluid is being pumped into the formation at equivalent pressures) (Bradford et al. 2014). Investigators suggest that productivity associated with well RRG-9 may also be enhanced by thermal stress alteration and associated natural fracturing within the reservoir rocks (Bradford et al. 2014).

The stimulation of RRG-9 began on June 13, 2013 with injection at a pressure of 275 psig. Next, the pressure and flow rate were increased for approximately one month (Bradford et al. 2014). The highest rate achieved was 258 gpm at a pressure of 741 psig (Bradford et al. 2014). During this time, fluid from the cooler water well was injected for approximately 2 weeks at various pressures. Next, the pumps were removed and plant injection resumed on 25 September 2013. Plant injection continued until the spring of 2014, when a high pressure hydraulic stimulation was conducted. Before thermal stimulation commenced, the flow rate of the well was 43 gpm, and by early spring of 2014, the flow rate was 135 gpm (Bradford et al. 2014).

2.3.5 Coso Geothermal Field

2.3.5.1 Geology

The Coso geothermal area is located in the Coso Range in southeastern California. The area lies within the Walker Lane/Eastern California Shear Zone (WLSZ), a tectonically active region between the eastern flank of the Sierra Nevada Range and the western edge of the Basin and Range physiographic province (Newman et al. 2008). Faults in the region have a predominantly north-south trend and accommodate right-lateral strike-slip motion, with movement of about 11 millimeters per year. This contrasts with the extensional tectonics of the Basin and Range province to the east, characterized by northerly trending fault-block mountains with alternating alluvial valleys (classic horst and graben).

Basement rocks of the Coso Range consist of fractured plutonic rocks of Mesozoic age with minor metamorphic rocks intruded by a series of northwest-trending felsic and mafic dikes of Cretaceous age. These are covered by Late Cenozoic volcanic rocks consisting of both basalts and rhyolites. Rhyolite domes predominate in the Coso geothermal area and over the past 600,000 years, the depth from which the rhyolites have erupted has decreased (from about 33,000 to 18,000 feet). As this has happened, eruptions have become more frequent and more voluminous. This partially molten magma chamber is the likely heat source for the Coso geothermal area (Newman et al. 2008).

2.3.5.2 Stimulation Protocol and Results

The Coso Geothermal Field is in a highly fractured and tectonically stressed reservoir located in the transitional zone between extensional (dip-slip) tectonics associated with the Basin and Range to the east and lateral (strike-slip) tectonics to the west. Some of the geothermal wells within the east flank of the field are relatively impermeable, especially along its margins. Datasets from these wells have been analyzed to characterize fracture orientations and stress magnitudes and orientations to identify the location of critically stressed planes that maintain permeability within the geothermal field (Sheridan and Hickman 2004; Sheridan et al. 2003). Geothermal fluid flow and well production in this area of Coso are mainly controlled by the orientation of steeply dipping fractures and by the orientations of two major sets of faults within the geothermal system (Newman et al. 2008; Sheridan and Hickman 2004). The first system of faults has a west-northwest strike and a vertical dip; movement along these faults is of the strike-slip variety. The second system of faults has a north-northeast strike; these faults generally dip to the east. The most productive wells in the geothermal field are those that target the second system of faults, especially where geothermal wells are drilled with a steep westerly dip (roughly perpendicular to the prevailing fault planes in this area). Because low permeability along the reservoir margins limits fluid recharge, reinjection is necessary to sustain well productivity (Newman et al. 2008; Sheridan et al. 2003).

2.4 DISCUSSION

Geologically, a combination of thermal, tectonic, and hydraulic conditions determine the productivity of a geothermal reservoir. High rock temperatures, a high degree of fracturing, high tectonic stresses, fluid saturation, and high intrinsic permeability all favor productivity (DOE 2012; Hickman and Davatzes 2010; Blake and Davatzes 2011; Sheridan and Hickman 2004). EGS technologies are being applied to reservoirs or portions of reservoirs, such as those described above, where fluid saturation and/or intrinsic permeability are not optimal.[3] The objective of EGS is to intercept and connect, via artificially sheer stimulation or fracture extension (stimulation)of the natural fractures already present within the reservoir, to enhance its permeability and well productivity. The injection of fluids aids in recovery where low permeability limits fluid movement and recharge in reservoir rocks.

The different demonstration projects described here were conducted with various goals in mind: (1) to improve recovery in existing geothermal wells that were not producing (Coso, DPEEP), (2) to take advantage of reservoir hydrothermal alteration and fracture zones (Raft River), and (3) to demonstrate new technologies to improve steam quality (Northwest Geysers) or system efficiency and cost (Newberry Volcano). In each case, the stimulation protocols were

[3] Studies in various tectonic settings have shown that fluid flow in low-porosity crystalline rocks is dominated by fractures which are optimally oriented and critically stressed for frictional failure (Hickman and Davatzes 2010).

adapted to the unique geologic conditions of the targeted reservoir. Geologic conditions common to these projects are those that make a reservoir a candidate for development (as described above)—essentially, high heat and a high degree of fracturing and crustal stress. In addition, these hotspots tend to occur in active hydrothermal (and tectonic) environments, so the resource rock is typically crystalline (igneous)—a nonporous medium prone to fracturing under tectonic stress. However, the geology is unique enough from site to site that stimulation protocols must be tailored accordingly. This might include directional drilling of geothermal wells according to fracture orientation to optimize recovery, using thermal effects over high pressure effects to improve steam quality or reduce microseismicity, targeting major fault planes or zones of hydrothermal alteration, or sealing off low-temperature portions of the reservoir (as the presented projects have demonstrated).

Some key stimulation parameters for the evaluated projects are presented in Table 1. Desert Peak, Newberry Volcano, and Raft River were all able to demonstrate significant increases in injectivity over the course of their stimulation campaigns. One initial goal of this effort however was to attempt to extract information that might be helpful in predicting future below ground operational water losses in the future, unfortunately this was not possible for any of the existing projects. In the case of the projects within existing hydrothermal reservoirs, there are not expected to be any significant below ground operational losses. Newberry Volcano is the only project that can be considered a greenfield site which may experience below ground operational losses, but that project does not currently have any active production wells. If data are to be reported to the National Geothermal Data System (NGDS) in the future, it would be useful to start requiring more standardized data reporting for easier comparison between projects. A description of the stimulation zone geology, as well as information describing the stimulation procedure, including corresponding pressures and flow rates (both injection and eventual production) would be useful. This information would make analysis of commonalities among EGS projects more productive, and lead to better informed decision making regarding sites to target for future EGS projects.

TABLE 1 Summary of Project Stimulation Parameters

Project	Stimulation Flow Rate (gpm)	Maximum Stimulation Pressure (psig)	Stimulation Duration	Initial and Final Injectivity (gpm/psig)
Desert Peak	3-70	540	77 days	0.014 to 0.16
The Geysers[a]	400-1100	-	Ongoing	-
Newberry Volcano	80-370	2400	51 days	0.05 to 0.51
Raft River[b]	43-260	810	~8 months	0.15 to 0.47

Sources: Bradford et al 2014, Petty et al. 2013, Garcia et al. 2012, and Dempsey et al. 2013

[a] The Geysers is a unique case, due to it being a vapor dominated system. Stimulation is primarily through thermal effects and increasing steam pressure in the reservoir.

[b] Values as of 2/10/2014, stimulation was still ongoing at this point.

3 EGS WATER SOURCE COST ANALYSIS

3.1 INTRODUCTION

The goal of this task was to estimate the cost of different sources of water in the areas surrounding existing EGS projects in the western United States to help better understand the impacts water availability and the type of water utilized can have on the cost of geothermal projects. Water costs were evaluated at five existing EGS test sites, Brady Hot Springs, Desert Peak 2, the Geysers, Newberry Volcano, and Raft River. Costs were estimated utilizing the Argonne Water Cost Model (AWCM) described in detail in Appendix A. This Microsoft Excel–based water cost model was designed for easy integration with the Geothermal Electricity Technology Evaluation Model (GETEM).

3.2 METHODOLOGY

The AWCM was used to estimate the cost of supplying water to each of the five study sites. Water costs are provided in terms of the levelized cost of water (LCOW), as described in Section 7 of Appendix A. Key parameters used in the AWCM, which included distance to source and depth to source, were gathered (where available) for each of four different water sources: fresh surface water, fresh groundwater, brackish groundwater, and municipal wastewater. The parameters required included distance to water source and depth to water source. Data on fresh surface water, fresh groundwater, and brackish groundwater were obtained from National Environmental Policy Act of 1969 (NEPA) documents describing existing EGS projects at the selected sites. Information on the availability of municipal wastewater was obtained from a tool developed by ALL Consulting and the National Energy Technology Laboratory (NETL) called the Alternative Water Source Information System (AWSIS) (ALL Consulting 2010).

In addition, a volume of water was required for sizing water delivery capital equipment. To define this required quantity of water, three power plant scenarios were selected from a recent geothermal water life cycle assessment (LCA) study (Schroeder et al. 2014). These three scenarios, as summarized in Table 2, provide for a range of power plant sizes and water consumption rates. These scenarios are used to define the quantity of water required for estimating water costs using the AWCM.

TABLE 2 Power Plant Scenarios and Water Consumption Rates

Parameter	Scenario Name[a]		
	A	B	C
Plant Type	EGS Binary High Temperature	EGS Binary Low Temperature	EGS Flash High Temperature
Capacity (MW)	20	10	50
Resource Temperature (°C)	175	100	325
Water Consumption Rate (gal/MWh)	800	4,200	1,600
Total Annual Consumption (ac-ft/yr)	387	1,020	1,940

[a] Scenarios A, B, and C correspond to EGS Scenarios No. 3 (reference), No. 1 (reference), and No. 5 (improved) respectively from Schroeder et al. (2014).

3.3 MUNICIPAL WASTEWATER AVAILABILITY

The AWSIS tool is a geographic information system (GIS) application that employs a Google Earth interface to allow for the identification of alternative sources of water (ALL Consulting 2010). In this analysis, the AWSIS tool was used to determine the location and specific flow rate of alternative water sources within 100 miles of the study sites. This was achieved by identifying the GIS location of the EGS test site, searching for nearby thermoelectric generators (as this is the method the AWSIS tool uses to search for available nontraditional water sources), then pinpointing sources of water around each generator. Municipal wastewater treatment plant (WWTP) effluent was found to be the sole source of water within range of the test sites. It is important to note that this tool only provides information about the existence of WWTP effluent and does not provide any information concerning the availability of wastewater for actual reuse. That is, given the nature of water rights in the western United States, any available WWTP effluent could potentially be appropriated downstream, and therefore be unavailable for reuse.

The WWTPs identified using the AWSIS tool are listed in Table 3, along with their flow rates and the distance to the relevant test site. It is further noted that WWTPs could only be identified for two of the five test sites. This is due to the fact that, as mentioned previously, the AWSIS tool was designed for use with existing large-scale thermoelectric power plants and, thus, is only capable of identifying locations near such facilities. Because several of the EGS sites in the United States happen to be in remote locations, alternative water sources for these sites were unavailable via the AWSIS tool.

TABLE 3 Wastewater Treatment Plant Locations and Flow Rates

WWTP Address	Flow Rate	Distance to Geothermal Field
The Geysers		
4300 Llano Road Santa Rosa, CA 95407	12.6 mgd[a]	40 mi
Aerojet Road Rancho Cordova, CA 95743	35.8 mgd	75 mi
Power Inn and Fruitridge Rd. Sacramento, CA 95813	6.5 mgd	70 mi
14440 Twin Cities Road Herald, CA 95638	14.4 mgd	88 mi
2301 Wilbur Road Antioch, CA 94509	21mgd	74 mi
Raft River		
4269 North 1360 East Buhl, ID 83316	1.8 mgd	72 mi
10733 North Rio Vista Road Pocatello, ID 83201	12 mgd	74 mi
340 Highland Ave Burley, ID 83318	2.25 mgd	34 mi
218 West Highway 30 Burley, ID 83316	2.651 mgd	34 mi
50 North 100 West Jerome, ID 83338	1.5 mgd	68 mi
350 Canyon Springs Road West Twin Falls, ID 83301	7.84 mgd	58 mi
Highway 30 North (P.O. Box 676) Heyburn, ID 83336	2 mgd	34 mi

[a] Flow reportedly being delivered to the Geysers

3.4 EGS SITE EVALUATIONS

NEPA documents and other supplementary sources, including project websites and presentations, were analyzed in order to extract pertinent information about local surface and groundwater sources surrounding the five existing EGS test sites.

3.4.1 Brady Hot Springs, Nevada

Brady Hot Springs is located 50 miles northeast of Reno, in Churchill County, Nevada. There are no perennial streams in the immediate vicinity of the project site and precipitation in the area averages only 5 inches per year. Previous analyses in the area have confirmed that no fresh water exists in the project area. Past drilling in the area has encountered the groundwater table at depths ranging from 30–150 feet. All waters sampled were found to be in the area are high in sodium chloride and exceed the limits recommended for drinking water (BLM 2013).

Withdrawal of groundwater for all uses in the basin is essentially restricted to geothermal uses. However, it is not clear is this restriction is limited to the extraction of heat, or if the groundwater can be used in other ways for geothermal projects. The stimulation appears to be using water from the existing Brady geothermal plant transported from a surface pipeline (BLM 2013).

3.4.2 Desert Peak 2, Nevada

The Desert Peak 2 project takes place on private land, thus, very little data have been publicly reported on the local hydrology.. However, this site is located in the vicinity of Brady Hot Springs, so water availability is assumed to be similar. Stimulation was successful at an existing unproductive well

3.4.3 The Geysers, California

The Geysers has operated supplementary water injection programs utilizing municipal wastewater for years. Stimulation at The Geysers involves injection into an unproductive well. Water for the stimulation comes from two sources: the Santa Rosa Geysers Recharge Project (SRGRP) and the Southeast Geysers Effluent Pipeline Project (SEGEP). The SRGRP involves the Santa Rosa, Rohnert Park, Cotati, Sebastopol, and South Park sanitation districts. This pipeline delivers approximately 11 million gallons per day of tertiary-treated effluent. The SEGEP, which began construction in 1997 and finished in 2003, involves the Southeast Regional, Middletown, Clearlake Oaks, and Northwest Regional treatment plants in Lake County. It is a 29-mile pipeline that supplies 8 million gallons per day of secondary-treated effluent to The Geysers (Calpine 2014).

Smaller volumes of well water are used for drilling at the Geysers. However, no regional groundwater aquifers of significant yield have been reported in the surrounding Mayacamas Mountains. According to the final environmental assessment (EA):

> "The nearest groundwater basin is the Alexander Valley Groundwater Basin, Cloverdale Area Subbasin. Water quality where groundwater occurs in this basin is characterized as moderately-hard to hard (water that is high in minerals such as calcium and magnesium) and is generally suitable for all uses. Groundwater within the Cloverdale Area Subbasin has detectable total dissolved solids (TDS) levels between 130 and 304 milligrams per

liter (mg/L) and three wells have had boron levels exceeding 0.5 mg/L. Boron values are not expected to restrict uses of the water" (RMT 2010).

A Google Maps search indicates these two subbasins are approximately 20–30 miles from The Geysers project.

3.4.4 Newberry Volcano, Oregon

Newberry Volcano is part of the upper Deschutes Basin. Two caldera lakes nearby receive thermal spring discharge. There is significant interaction between the lakes and local groundwater. A regional aquifer underlies Newberry Volcano at depths of fewer than 100 to 500 feet and a local aquifer exists at depths of fewer than 50 feet. In addition, there is surface water at Paulina Lake and Creek and Little Deschutes River, but it is unclear whether water rights are available (Kleinfelder 2011). Existing groundwater wells at depths of 600 to 800 feet are currently being used to provide water for stimulation (Newberrygeothermal.com 2012).

3.4.5 Raft River, Idaho

Numerous geothermal springs and wells exist throughout the area surrounding the Raft River site. The depth to groundwater is in the range of 20 to 90 feet. Groundwater is elevated in total dissolved solids (TDS), with an average of 1,200 parts per million (ppm) for irrigation wells and 2,200 ppm for all wells (U.S. Geothermal 2010). There are two perennial creeks in the area, along with a reservoir used for irrigation. The well sites are also less than 2 miles from the Raft River. Groundwater in the area is managed by the Raft River Groundwater Quality Area; however, there are currently no areas of concern for groundwater use within 5 miles of the project site, so there should be no issues with the use of groundwater at Raft River (BLM 2010).

3.5 RESULTS

The water cost results from the AWCM for each of the five test sites are provided in Table 4. Costs range from as low as $113/acre-foot (ac-ft), representing a nearby surface water source at Raft River for a 50-MW high-temperature EGS flash plant, to over $10,000/ac-ft, denoting a municipal wastewater source piped 88 miles for a high-temperature EGS binary plant. Unsurprisingly, transportation distance was a major driver of water costs, with costs for municipal wastewater being nearly linear with the length of the pipeline. Economies of scale also play a large role in the cost of supplying water to a geothermal project. In all cases, costs for Scenario A (the high-temperature binary EGS plant requiring 387 ac-ft/yr) were higher on a per ac-ft basis than the costs for Scenario C (the high-temperature flash EGS plant requiring 1,940 ac-ft/ yr).

Table 5 shows the total annual water costs on a project basis. In general, the water costs per power plant ranged from a low of $140,000/year to a high of $2,800,000/year. These data

TABLE 4 Water Supply Cost Results (in 2012$ per ac-ft)

Water Source	Depth (ft)	Distance (mi)	Cost A	Cost B	Cost C	Notes
Brady's Hot Springs, NV[a]						
Fresh Groundwater	NA	NA	-	-	-	No fresh groundwater in the area
Surface Water	NA	NA	-	-	-	No surface water
Brackish Groundwater	500	1	358	192	148	Low-quality shallow groundwater appears to be available in the area
Newberry Volcano, OR						
Fresh Groundwater	800	1	451	271	225	Aquifer at 100 to 500 ft, wells used at 600–800 ft
Surface Water	0	5	808	384	241	Two nearby lakes and a stream near the site (exact distance only roughly determined)
Brackish Groundwater	3,000	1	812	539	473	Depth assumed
The Geysers, CA						
Fresh Groundwater	1,000	30	4,540	2,160	1,390	No groundwater aquifers of significant yield nearby, based upon farther distance
Surface Water	NA	-	-	-	-	None with available water rights
Brackish Groundwater	3,000	1	812	539	473	Depth assumed
WWTP, Nearest	0	34	4,630	2,060	1,200	
WWTP, Furthest	0	74	10,200	4,530	2,650	
Raft River, ID						
Fresh Groundwater	NA	-	-	-	-	Shallow groundwater is of low quality
Surface Water	0	2	382	181	113	Some surface water exists in the area, unclear if water rights are available
Brackish Groundwater	500	1	358	192	148	Shallow groundwater assumed to be brackish
WWTP Nearest	0	40	5,530	2,470	1,440	
WWTP Furthest	0	88	10,900	4,840	2,830	

[a] No data on water availability could be obtained for Desert Peak 2; however, costs for Brady's Hot Springs are likely applicable due to proximity

TABLE 5 Range of Estimated Total Annual Water Costs for EGS Projects (in $/year)

Location	20-MW EGS Binary High Temperature		10-MW EGS Binary Low Temperature		50-MW EGS Flash High Temperature	
Cost	Low	High[a]	Low	High[a]	Low	High[a]
Brady's Hot Springs, NV	$139,000	-[b]	$196,000	-[b]	$287,000	-[b]
Newberry Volcano, OR	$175,000	$314,000	$276,000	$550,000	$437,000	$918,000
The Geysers, CA	$314,000	$1,790,000	$550,000	$2,100,000	$918,000	$2,340,000
Raft River, ID	$139,000	$2,140,000	$185,000	$2,520,000	$219,000	$2,800,000

[a] High values presented only consider the nearest WWTP cost when wastewater is the highest cost option.
[b] No high value included since costs were only estimated for brackish groundwater.

include both a low and a high scenario based upon the lowest and highest water cost estimated per location (note that the high case does not consider the farthest WWTP scenario, because if wastewater was selected as the water source, the closest WWTP would be preferred, and already represents the highest cost of the alternatives. It can be seen that although the per ac-ft water costs may be higher for lower water consuming power plants, total water costs are actually lower.

As expected, nearby fresh surface or groundwater sources were identified as the cheapest water sources. However, these sources were only physically available for Newberry Volcano and Raft River sites. Furthermore, although surface water was physically available at Raft River, it is unclear whether water rights can be acquired to use this water for geothermal development. In general, the cost of acquiring fresh water rights, which ranges range from as low as $15/ac-ft in Idaho to as high as $164/ac-ft in Nevada (as shown in Table 6) is only a small portion of the overall cost (UCSB 2010).

TABLE 6 Cost of Acquiring Fresh Water (Surface and Groundwater), by State[a]

State	Fresh Water Acquisition Cost
California	$151
Idaho	$15
Nevada	$164
Oregon	$38

[a] Data from UCSB (2010); see Appendix A for more details.

However, it should be noted that these costs are based upon the limited data available on recent publicly reported water transactions, and may not be representative of all future water costs. Costs of acquiring water rights may rise in the future if water availability declines due to shifts in climate, or water demand increases resulting from growth.

The use of brackish groundwater appears to be a promising option in most locations, although there was little data on the depth and quality of brackish groundwater at Newberry Volcano and The Geysers, so depths had to be assumed. Municipal wastewater was available near The Geysers and Raft River, and may be available near others, although data could not be obtained for Desert Peak 2, Brady Hot Springs, or Newberry Volcano., For the two sites where data existed, municipalities with sufficient wastewater available were over 30 miles away, which results in high transportation costs.

3.5.1 Treatment Costs

All previous costs were estimated assuming no additional treatment was performed. This is likely an acceptable assumption for EGS projects utilizing water for supplementary injection to account for either below or above ground operational losses. However, there may be cases where various levels of water treatment could be required. These include the use of water for wet or hybrid cooling towers, and/or in cases where water sources may contain scale-forming compounds that must be removed before injection. Table 7 shows the incremental costs that treatment would add to the total cost of supplying water. These costs are directly additive to the appropriate water source costs presented in Table 4. For example disinfection may apply to all water sources, filtration may be required for surface or groundwater sources with high concentrations of suspended solids, while desalination is likely only to apply to brackish groundwater. All costs are based upon the LCOW.

TABLE 7 Water Treatment Costs (in 2012$ per ac-ft of water supplied)

Treatment	Scenario[a] A	Scenario[a] B	Scenario[a] C
Disinfection Only	$79	$34	$21
Groundwater Treatment	$579	$269	$176
Filtration	$1,340	$598	$372
Groundwater Treatment + Brackish Water Desalination	$1,680	$878	$637

[a] Detailed descriptions of the water treatment regimes can be found in Table A.5.

3.6 CONCLUSIONS

For all locations and plant sizes there appear to be water sources available with costs below the default value of $2000/ac-ft used in GETEM. Lower cost water sources vary across the locations and include surface water, groundwater, and brackish groundwater. The use of these lower values would result in slightly lower estimates of levelized cost of energy (LCOE) for most power plants. Estimated costs for WWTP effluent ranged below and above the GETEM default depending upon the scenario, which was driven by the distance from the field to the WWTP and the economies of scale of pipeline transport. Given the large impact of economies of scale, costs could potentially be reduced further, especially with respect to transportation from WWTPs, if multiple power plants are built in close proximity to these facilities within the same geothermal area. Additional treatment can add considerably to the cost of certain water types (particularly brackish groundwater) if water is used for purposes requiring desalination or filtration. Acquisition costs for water rights appear to add a small cost to the total cost of supplying water for geothermal; however these costs are based upon recent historical average water costs and may increase over time due to increases in water demand, decreases in water availability, or in times of drought.

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4 EGS ALTERNATIVE WATER POLICY ASSESSMENT

4.1 INTRODUCTION

To date, all active development of EGS projects in the United States is occurring in the western part of the country, within states and regions that have traditionally experienced water scarcity issues. Thus, the availability of water has the potential to significantly impact the long-term success of EGS development. Alternative waters represent a significant, but generally overlooked, source that could be used by geothermal energy projects for the replacement of the fluids lost during normal power plant operations.

Alternative water policies are examined for the four western states with active EGS development projects: California (The Geysers), Idaho (Raft River), Nevada (Desert Peak), and Oregon (Newberry Volcano). According to the U.S. Environmental Protection Agency (EPA), alternative waters include reclaimed water, grey water, and harvested storm water (EPA 2012). This report uses an expanded definition from a joint alternative waters project from ALL Consulting and the NETL, which includes treated wastewater effluent, produced water from oil and gas development, saline groundwater, and mine pool water (ALL Consulting 2010). While an effort was made to find regulations across all alternative water types included in the ALL Consulting and NETL database, regulations for treated wastewater dominated the findings in all four states.

4.2 STATE-LEVEL ALTERNATIVE WATER POLICIES

In general, the regulatory frameworks exist for geothermal projects to utilize recycled wastewater, although unseen barriers to this use could arise. The results of this analysis are presented by state and briefly summarized in Table 8. Overall, it is noted that regulations for the utilization of other alternative water sources (e.g., produced water from oil and gas development, saline groundwater, and mine pool water) could not be found in any state, however, Nevada has identified saline groundwater as a possible future source.

TABLE 8 Summary of Alternative Water Regulations and Regulatory Agencies

State	Types of Alternative Waters Regulated	Regulatory Agencies Involved
California	Treated Wastewater Effluent	California Department of Public Health (CDPH)
		California State Water Resources Control Board (SWRCB)
		Regional Water Quality Control Boards (RWQCBs)
		California Department of Water Resources (CDWR)

TABLE 8 (Cont.)

State	Types of Alternative Waters Regulated	Regulatory Agencies Involved
Idaho	Treated Wastewater Effluent	Idaho Department of Environmental Quality (IDEQ) Idaho Department of Water Resources (IDWR)
Nevada	Treated Wastewater Effluent; Saline Groundwater (proposed)	Nevada Department of Environmental Protection (NDEP) Nevada Division of Water Resources (NDWR)
Oregon	Treated Wastewater Effluent	Oregon Department of Environmental Quality (ODEQ)

4.2.1 California

Reclaimed water use in California is regulated under an intricate series of laws and regulations. It is perhaps the most complex set of such state laws in the country. Decision making related to recycled water use operates under an umbrella of regulatory agencies, and understanding how these agencies interact and which agency has regulatory authority for which actions is critical to navigating this process. The main regulatory instruments at play here include the California Water Code (Porter Cologne Water Quality Control Act), Basin Plan(s) adopted by the Regional Water Boards, applicable sections of Health & Safety Code Title 17, and California Code of Regulations (CCR) Title 22, Division 4, Chapter 3 pertaining to issuance of Recycled Water Permits. The California regulations, the applicable definitions contain within, the implementing agencies, and the permits specified are summarized in Table 9 and described in further detail below.

The SWRCB (or State Board) operates as the senior authority in the state for recycled water reuse. Created by the state legislature in 1967, the five-member State Board protects water quality by setting statewide policy, coordinating and supporting the RWQCBs (or Regional Boards) efforts (described below), and reviewing petitions that contest Regional Board actions. Together with the Regional Boards, the State Board is authorized to implement the federal Clean Water Act in California. The State Board also is solely responsible for allocating surface water rights. A Memorandum of Agreement (MOA) with the CDPH exists to implement CCR Title 22, water recycling criteria, and requirements to protect public health. These criteria detail permitted uses of recycled water and treatment requirements for its reuse.

The Water Recycling Criteria (WRC) are implemented throughout the state through water recycling orders issued by nine RWQCBs (or Regional Boards). The nine Regional Boards are semiautonomous and are comprised of seven part-time board members appointed by the governor and confirmed by the state senate. Regional boundaries are based on watersheds. Water quality requirements are based on the unique differences in climate, topography, geology, and hydrology for each watershed. Each Regional Board makes critical water quality decisions for its own region, including setting standards, issuing permits, determining compliance with requirements, and taking appropriate enforcement actions. The water recycling orders are of various types depending of project type, threat, and complexity related to water quality. Regional Boards may issue an individual waste discharge requirements order, master reclamation order, or water recycling requirements order. They may also enroll water recycling projects in the statewide General Order, if found applicable, for proposed recycled water reuse. In addition, each RWQCB has adopted a Water Quality Control Plan (Basin Plan) for its specific region to protect the water quality in that region, though the basin may be subject to additional water quality controls and limitations for water recycling projects within its jurisdiction.

Apart from the various Water Boards, the California Department of Water Resources (DWR) also reviews recycled water use. In addition, they update the "California Water Plan" every five years by evaluating the quantity of recycled water being used in the state and planning for future use. A Recycled Water Task Force oversees this entire process and published a report in 2003 entitled *Water Recycling 2030* (CRWTF 2003).

4.2.1.1 State Water Resources Control Board

The California SWRCB's Recycled Water Policy (Policy), which was published in 2013, is a policy document adopted to enhance and streamline recycled water use in California. From the document text, "The purpose of this Policy is to provide direction to the Regional Boards, proponents of recycled water projects, and the public regarding the appropriate criteria to be used by the State Water Board and Regional Water Boards in issuing permits for recycled water projects" (SWRCB 2013). The Policy describes permitting criteria that are intended to streamline the permitting process for recycled water use, so as to expedite these projects and increase the total amount of reclaimed water in use in California by at least 1,000,000 ac-ft by 2020 and by at least 2,000,000 ac-ft by 2030.

The Policy also details, among other things, appropriate conditions for the use of recycled water in groundwater recharge projects. Initially, it was thought that these types of conditions might be important to EGS projects looking to use recycled water for stimulation of their reservoir. However, after further inquiries with relevant stakeholders, it became clear EGS reinjection would occur far beneath a groundwater reservoir and would thus not be considered groundwater recharge. The Policy references the definition for recycled water for groundwater recharge found in the Water Code section 13561(c), which states, "the planned use of recycled water for replenishment of a groundwater basin or an aquifer that has been designated as a source of water supply for a public water system." Geothermal reservoirs exist far beneath groundwater reservoirs, and are generally hydrologically distinct. As such, they are not covered under this definition.

The Policy further details requirements applicable to recycled water producers for monitoring constituents of emerging concern (CECs) for recycled water. More importantly for this analysis, the Policy also applies to entities "that further treat or enhance the quality of recycled water supplied by municipal wastewater treatment facilities, as well as groundwater recharge reuse facilities" (SWRCB 2013). CECs regulated in the Policy include birth control hormones, caffeine, triclosan, sucralose, N,N-diethyl-meta-toluamide (DEET), and several others. In the thermoelectric power industry, although many facilities contract with their local municipal treatment plant to provide water of sufficient quality, if they plan to use recycled water, it is not uncommon for facilities to further treat water on site (assuming it is economically viable). Although upon initial reading one may be led to believe that EGS projects in California may fall under these regulations, this is not the case in practice. For example, it appears that the level of treatment used at The Geysers (i.e., the addition of hypochlorite to the water to prevent biofouling) is usually done at the recycled water producer, and not on-site; thus, the CEC monitoring rules do not apply.

Several other earlier resolution and policies from the SWRCB are also worth briefly mentioning. Resolution 75-58, the *Water Quality Control Policy on the Use and Disposal of Inland Water for Power Plant Cooling*, from 1975, was the first notable effort by the SWRCB to affirm the importance of recycled waters. It was a direct result of the Waste Water Reuse Law of 1974. The Resolution advises the RWQCBs that when considering issuance of a permit for power plant cooling, they should consider the reasonableness of the request "in the context of alternative water sources which could be used" (SWRCB 1975). The resolution also encourages the use of alternative waters and wastewater for power plant cooling when appropriate. Two years later, in 1977, the SWRCB issued another resolution, Resolution 77-1, the *Policy with Respect to Water Reclamation in California*. This later Resolution states that both the State Board and Regional Boards should encourage the reclamation and reuse of water in areas of the state where water is scarce so long as doing so does not interfere with vested rights and other beneficial uses (SWRCB 1977).

4.2.1.2 Regional Water Quality Control Boards

Although the nine RWQCBs in the state of California function independently, they implement SWRCB policies and issue permits relating to the Clean Water Act. The SWRCB is authorized to enact these policies and permits and has delegated authority to the RWQCBs to implement them. In addition to following the SWRCB's *Recycled Water Policy*, the RWQCBs also have the ability to impose further requirements and rules for a water recycling project if they deem it necessary to protect local water resources. These additional requirements are often outlined in the relevant Basin Plans.

Active geothermal areas in California are spread out geographically, but some important RWQCB zones for geothermal development include the North Coast RWQCB (Region 1), which contains part of the EGS site at The Geysers; the Lahontan RWQCB (Region 6), which includes the geothermal areas around Glass Mountain; and the Colorado River RWQCB (Region 7), which includes geothermal projects around the Salton Sea area. Basin Plans for these areas were analyzed in further detail. In general, the Basin Plans designate beneficial uses for water bodies and establish water quality objectives, waste discharge prohibitions, and other implementation measures to protect those beneficial uses.

The Regional Boards also typically cite and use Resolution 77-1; Resolution 75-58; CCR Title 22 Division 4 Chapter 3; the Recycled Water Task Force; and other relevant regulations for recycled water use from the SWRCB and CDPH. For example, Order 96-011, *General Water Reuse Requirements for Municipal Wastewater and Water Agencies*, is an order that was drafted by San Francisco RWQCB (Region 9) and serves "as a general water reuse order authorizing municipal wastewater reuse by producers, distributors, and users of non-potable recycled water throughout the region." The order applies to producers of secondary and tertiary water under CCR Title 22 and to any distributors who receive water, provide additional treatment to meet CCR Title 22 regulations, and then distribute it to users. This is a general water reuse order that can be used if a recycled water project meets certain conditions. It is meant to take the place of project-specific permits and to expedite recycled water use in the state of California. However, project-specific permits must still be obtained if a project is sufficiently complex, as EGS projects may be.

4.2.1.3 California Department of Public Health

The CDPH is charged with protection of public health and drinking water supplies, and therefore must develop uniform Water Recycling Criteria (WRC or Criteria) for particular water uses. RWQCBs rely on CDPH for the establishment of permit conditions needed to protect public health. Many of these regulations are detailed in *The Purple Book: California Health Laws Related to Recycled Water*, which is a guide to recycled water use in California that is published by the Drinking Water Program within the Department of Health Services Division of Drinking Water and Environmental Management (CDHS 2001). This guide includes excerpts from the Health and Safety Code, Water Code, and Titles 22 and 17 of the CCR all in one document.

The WRC are administered under the CDPH Drinking Water Program. The criteria are codified in the California Water Code Sections 13500 through 13583. In Section 13550, it defines *recycled water* as "water, which as a result of treatment of waste, is suitable for direct beneficial or controlled use that would not otherwise occur and is therefore considered a valuable resource." Section 13500, otherwise known as the Water Recycling Law, gives Regional Boards the authority to issue master reclamation permits and sets forth WRC for specific uses. Master reclamation permits, however, do not cover groundwater replenishment or surface augmentation projects that use recycled water, however. Instead, individual Waste Discharge Requirement (WDR) Orders are issued for these activities by the relevant Regional Boards.

Specific requirements for wastewater treatment type and levels are specified in Title 22, Division 4, Chapter 3 of the CCR, entitled "Water Recycling Criteria." Article 60306, "Use of Recycled Water for Cooling," states that recycled water used for industrial or commercial cooling that involves a cooling tower, evaporative condenser, or spraying mechanism must be tertiary treated recycled water. If none of the above, it must be disinfected secondary treated recycled water.

Wastewater treatment is generally divided into three stages: primary, secondary, and tertiary. Primary treatment is also known as mechanical treatment and includes mechanical processes such as filtering and sedimentation. Secondary treatment involves biological treatment of the waste effluent through activated sludge basins. Finally, tertiary treatment involves disinfection through chlorination or ozonation. In addition, if recycled water is being used for a cooling system with a cooling tower or that otherwise creates a mist, the facility must use a drift eliminator and chlorine or other biocide to minimize growth of *Legionella* and other micro-organisms. For any industrial processes that may come into contact with workers, the water must be tertiary treated and for industrial processes that do not come into contact with workers, such as for dust control, the water must be secondary treated. Terms like tertiary and secondary treatment are given specific water quality levels here under Article 60301.

In addition to the WRC, the California Health and Safety Code Division 104, Part 12, Chapters 4 and 5, deal mainly with site-specific physical safety requirements for recycled water use. Article 2.116800 says that local health officers may maintain programs for the control of cross-connections by water users, within the users' premises, where public exposure to drinking water may occur. Water users must comply with all orders and instructions from the local health official with respect to the installation, testing, and maintenance of backflow prevention devices. Article 2.116805 stipulates that local health officials can also collect fees to maintain programs to protect water. Finally, Article 2.116815 requires that all pipes that carry recycled water have to be purple so that they are readily identifiable as carrying recycled water.

The above regulations, the applicable definitions they contain, their implementing agencies, and the permits they specify are summarized in Table 9.

4.2.2 Idaho

The State of Idaho regulates water reuse from municipal (i.e., sewage) and industrial (i.e., other than sewage) sources through the IDEQ. This is accomplished primarily by the Idaho Administrative Procedures Act (IDAPA) 58.01.17, the *Recycled Water Rules*. These rules require anyone wishing to land-apply or otherwise use wastewater reuse to obtain a permit before constructing, modifying, or operating a reuse facility in the state. The rules do not apply to mining activities.

Permitting under IDAPA 58.01.17 is customized for each application. Two types of wastewater reuse permits are issued: industrial and municipal. All wastewater reuse permits specify both standard and site-specific conditions. Permits are applied for after a pre-application meeting with the IDEQ, which also reviews and approves applications. Applications must include site-specific information, facility and topographic maps, and wastewater reuse-specific information.

Municipal wastewater is classified A through E, depending on its level of treatment (i.e., what processes it has undergone) and measurements of certain water quality metrics such as turbidity, total coliform, maximum total nitrogen, 5-day biochemical oxygen demand (BOD5), and pH. Classes A and B must be oxidized, clarified, filtered, and disinfected. Classes C and D must be oxidized and disinfected. Class E must only meet primary effluent quality.

Industrial reuse and reuse for geothermal applications are not specified; however, "subsurface distribution and use" is provided for, and is limited to classes A through D. In general, the subsurface distribution and use of recycled water must be designed and located so that compliance with IDAPA 58.01.11, *Ground Water Quality Rule*, is maintained and pollutants cannot be reasonably expected to enter waters of the state in concentrations resulting in injury to beneficial uses. Water must be treated to Class A, B, C, or D. Authorization from the Idaho Department of Water Resources is required for groundwater injection wells.

Two other rules possibly impact the reuse of water for geothermal applications in Idaho: IDAPA 58.01.11, *Ground Water Quality Rule*; and IDAPA 58.01.16, *Wastewater Rules*. Both rules are administered through the IDEQ. The *Ground Water Quality Rule* establishes minimum requirements for protection of groundwater quality through standards and an aquifer categorization process. Although the requirements of this rule serve as a basis for administering ground water quality programs, the rule does not create a permit program. The *Wastewater Rules* are cited in the *Recycled Water Rules*. For all wastewater treatment and reuse facilities connected to groundwater, the requirements in IDAPA 58.01.11 must be followed. The Wastewater Rules set procedures and requirements for the planning, design and operation of wastewater facilities and the discharge of wastewaters and human activities that may adversely affect public health and water quality in the waters of the state. They refer specifically to IDAPA 58.01.17 and IDAPA 58.01.11 for situations involving water reuse and groundwater.

TABLE 9 California State Laws and Applicable Definitions for Water Reuse

California Law	Definitions	Regulatory Authority	Permits
California State Water Resources Control Board Resolution 75-58: Water Quality Control Policy on the Use and Disposal of Inland Waters Used for Powerplant Cooling	*Brackish Waters*—Includes all waters with a salinity range of 1,000 to 30,000 mg/L and a chloride concentration range of 250 to 12,000 mg/L. The application of the term "brackish" is not intended to imply that such water is no longer suitable for industrial or agricultural purposes.	California State Water Resources Control Board California Regional Water Quality Control Boards	None
California State Water Resources Control Board Recycled Water Policy	*Recycled Water*—Water that, as a result of treatment of waste, is suitable for a direct beneficial use or a controlled use that would not otherwise occur and is therefore considered a valuable resource (California Water Code Section 13050[n]).	California State Water Resources Control Board California Regional Water Quality Control Boards	General permit for irrigation projects using recycled water Permit for groundwater recharge using recycled water (CEC monitoring plan required)
California Regional Water Quality Control Board Basin Plans	*Recycled Water*—Water that, as a result of treatment of waste, is suitable for a direct beneficial use or a controlled use that would not otherwise occur and is therefore considered a valuable resource (California Water Code Section 13050[n]).	California Regional Water Quality Control Boards	NPDES permits

TABLE 9 (Cont.)

California Law	Definitions	Regulatory Authority	Permits
California Code of Regulations (CCR) Title 22 Division 4 Chapter 3, "Water Recycling Criteria"	*Coagulated Wastewater*—Oxidized wastewater in which colloidal and finely divided suspended matter have been destabilized and agglomerated upstream from a filter by the addition of floc-forming chemicals. *Filtered Wastewater*—Oxidized wastewater that has either (a) passed through undisturbed soils or a bed of filter media at a rate not to exceed 5 gal/min and that meets turbidity requirements of an average of 2 NTU in 24/h or (b) passed through a micro-, ultra-, nano-, or reverse-osmosis treatment membrane such that turbidity does not exceed 0.2 NTU more than 5% of the time in 24 hrs. *Conventional Treatment*—A treatment chain that utilizes a sedimentation unit process between coagulation and filtration and produces an effluent that meets the definition for disinfected tertiary recycled water. *Disinfected Secondary-2.2 Recycled Water*—Water that has been oxidized and disinfected so that the median concentration of total coliform bacteria in the disinfected effluent does not exceed a most probable number of 2.2 per 100 mL. *Disinfected Secondary-23 Recycled Water*—Water that has been oxidized and disinfected so that the median concentration of total coliform bacteria in the disinfected effluent does not exceed a most probable number of 23 per 100 mL. *Disinfected Tertiary Recycled Water*—Water that has been filtered and has been disinfected by either (a) a chlorine disinfection process with a CT (contact time) of not less than 450 mg-min per liter or (b) a disinfection process when combined with filtration that has been shown to inactivate 99.999% of the polio virus. *Recycling Plant*—An arrangement of devices, structures, equipment, processes, and controls that produce recycled water.	California State Water Resources Control Board	None

TABLE 9 (Cont.)

California Law	Definitions	Regulatory Authority	Permits
California Code of Regulations (CCR) Title 17, Section 7583, “Drinking Water Supplies”	*Reclaimed Water*—Wastewater that as a result of treatment is suitable for uses other than potable. *Water Supplier*—The person who owns or operates the public water system. *Water User*—Any person obtaining water from a public water supply.	Not Specified	None
California State Water Code Division 7, Section 13050, “Water Quality Definitions”	*Recycled Water*—Water that, as a result of treatment of waste, is suitable for a direct beneficial use or controlled use that would not otherwise occur, and is therefore a valuable resource. *Mining Waste*—All solid, semisolid, and liquid waste materials from the extraction, beneficiation, and processing of ores and minerals. It includes soil, waste rock, and overburden. *Injection Well*—Any bored, drilled, or driven shaft, dug pit, or hole in the ground into which waste or fluid is discharged and the depth of which is greater than the circumference.	Not Specified	None

Regulations were not found for the reuse of any other type of water in the State of Idaho. The Idaho regulations, the applicable definitions they contain, their implementing agencies, and the permits they specify are summarized in Table 10.

4.2.3 Nevada

The State of Nevada regulates water recycling through the Nevada Administrative Code (NAC) 445A.274 to 445A.280, which is entitled *Use of Treated Effluent* (NAC 2014). The NDEP administers the rule. Under the NAC 445A.275, *General Requirements and Restrictions*, in order to use treated effluent (1) the user must have received approval from NDEP of a plan for the management of effluent, (2) the user must have obtained a discharge permit pursuant to NAC 445A.228-263, and (3) the treated effluent has to have received at least secondary treatment, which is defined as a 5-day biological oxygen demand (BOD_5) test value of 30 mg/L or less, a TDS value of 30 mg/L or less, and a pH of between 6.0 and 9.0 (NAC 2014). Other ancillary requirements include the posting of signs (NAC 445A.2752) and adherence to additional rules if the treated effluent is to be used for irrigation (NAC 445A.2754). Finally, there are requirements for the bacteriological quality of the effluent. According to the rules, industrial processes, under which EGS would likely fall, are in Reuse Category B, which means there are specific targets must be adhered to for total coliform and fecal coliform.

For reclaimed water, users of reclaimed water must notify the NDWR and inform them of any plan to use reclaimed water in advance and to address any issues that may arise relating to water rights conflicts. Furthermore, local governments are also allowed to create additional rules on reclaimed water usage as they see fit, and these should also be consulted.

NDEP has created three water technical sheets (WTSs) that aid in following the regulations listed above. The first of these sheets, WTS-1A *General Design Criteria for Reclaimed Water Irrigation Use*, details usage guidelines for the irrigation use of recycled or reclaimed water (NDEP 2014a). The second sheet in the series, WTS 1-B *General Criteria for Preparing an Effluent Management Plan*, details the requirements and structure for an effluent management plan, the submission and approval of which is required for reclaimed water use (NDEP 2014b). Finally, the last sheet in the series, WTS-1C *Nutrient Management for Reuse and Biosolids Sites*, provides a general overview of wastewater nutrient reduction and management strategies that can be implemented at reclaimed water reuse sites and ranches fertilized with municipal biosolids (NDEP 2014c).

In Nevada, *treated effluent* is defined as "sewage that has been treated by a physical, biological, or chemical process" (NAC 2014). The term is specifically distinct from *graywater*, which is defined as "untreated household wastewater that has not come into contact with toilet waste. The term includes, without limitation, used water from bathtubs, showers and bathroom washbasins, and water from machines for washing clothes and laundry tubs, but does not include wastewater from kitchen sinks or dishwashers" (NAC 2014). Graywater reuse is illegal in parts of Nevada owing to the necessity of this water being returned to the Colorado River, because Nevada overdraws its legal allotment and must return a specific quantity of water to meet its

TABLE 10 Idaho State Laws and Applicable Definitions for Water Reuse

Idaho Law	Definitions	Regulatory Authority	Permits
Idaho Administrative Procedures Act 58.01.17	*Recycled Water*—Water that has been treated by a wastewater treatment system and is used in accordance with these rules. *Reuse*—The use of recycled water for irrigation, ground water recharge, landscape impoundments, toilet flushing in commercial buildings, dust control, and other uses. *Subsurface Distribution System*—Any system with a point of discharge beneath the earth's surface. *Wastewater*—Any combination of liquid or water and pollutants from activities and processes occurring in dwellings, commercial buildings, industrial plants, institutions, and other establishments, together with any groundwater, surface water, and stormwater that may be present; liquid or water that is chemically, biologically, physically, or rationally identifiable as containing blackwater, gray water, or commercial or industrial pollutants; and sewage.	Idaho Department of Environmental Quality	Wastewater Reuse Permit
Idaho Administrative Procedures Act 58.01.11	*Ground Water*—Any water of the state that occurs beneath the surface of the earth in a saturated geological formation of rock or soil.	Idaho Department of Environmental Quality	None
Idaho Administrative Procedures Act 58.01.16	*Reuse*—The use of reclaimed wastewater for beneficial uses including, but not limited to, land treatment, irrigation, groundwater recharge using surface spreading, seepage ponds, or other unlined surface water features. *Treatment Facility*—Any physical facility or land area for the purpose of collecting, treating, neutralizing, or stabilizing pollutants including treatment plants; the necessary collecting, intercepting, outfall and outlet sewers; pumping stations integral to such plants or sewers; disposal or reuse facilities; equipment and furnishing thereof; and their appurtenances. For the purpose of these rules, a treatment facility may also be known as a treatment system, a wastewater system, wastewater treatment system, wastewater treatment facility, or wastewater treatment plant.	Idaho Department of Environmental Quality	None

quota (SNWA 2009). Finally, *reclaimed water* is defined as "domestic wastewater that has been treated to secondary treatment standards and disinfected to levels necessary for the chosen method of reuse. Other terms for this water include treated effluent, reuse water, and recycled water" (NDEP 2014b).

Although no regulations were found for the reuse of any other type of water in the State of Nevada, the Nevada State Water Plan mentions the possibility of using saline groundwater, and other supplies of low-quality water, as a way to meet future water demand in the state (NDWP 1999). The Nevada regulations, the applicable definitions they contain, their implementing agencies, and the permits that they specify are summarized in Table 11.

4.2.4 Oregon

The State of Oregon regulates water reuse through the Oregon Administrative Rules, Chapter 340, Division 55 (OAR 340-055), *Recycled Water Use*. The ODEQ, which administers the rule, has issued internal guidance for the rule that covers recycled water from domestic water treatment facilities: *Internal Management Directive (IMD): Implementing Oregon's Recycled Water Use Rules*. OAR 340-055 sets forth requirements for classifying, permitting, transporting, monitoring, and reporting concerning the use of recycled water.

Permitting in the State of Oregon is a two-step process. First, a National Pollutant Discharge Elimination System (NPDES) or Water Pollution Control Facilities (WPCF) permit must be obtained for the reuse (or treatment for reuse) of recycled water at a facility. Then the facility must work with the ODEQ to develop a Recycled Water Use Plan (RWUP), which details the proposed use, including water quality classification and treatment standards. It also sets design parameters, such as setback distances, for protecting public health and the environment.

The IMD issued by the ODEQ provides detailed guidance for a number of aspects of OAR 340-055. Among other requirements, OAR 340-055 requires that for permits to be issued authorizing water reuse, the reuse must serve a beneficial purpose. Section 2.2 of the IMD specifies the allowable beneficial purposes. Geothermal applications are not specifically listed, but industrial cooling is identified. It is unclear what, if any, water use for EGS can be included in this category, but it is likely that at least water used for power plant cooling would qualify. However, in Section 2.2.2, the IMD provides a pathway for proposing other beneficial purposes and having them approved. The ODEQ will request from the applicant any information necessary to evaluate the proposal, which could include quantity and quality data, adjacent land uses, potential for offsite migration, epidemiological data, and other data. The ODEQ will evaluate proposals for additional beneficial uses based on the following criteria:

1. Is the use protective of public health?
2. Is the use protective of the environment?
3. Does the use provide a resource value?

TABLE 11 Nevada State Laws and Applicable Definitions for Water Reuse

Nevada Law	Definitions	Regulatory Authority	Permits
Nevada Administrative Code, Chapter 445A (NAC 445A), “Water Controls”	*Graywater*—Untreated household wastewater that has not come into contact with toilet waste. The term includes, without limitation, used water from bathtubs, showers and bathroom washbasins, and water from machines for washing clothes and laundry tubs, but does not include wastewater from kitchen sinks or dishwashers (NAC 445A.2743). *Treated Effluent*—Sewage that has been treated by physical, biological, or chemical processes. The term does not include graywater (NAC 445A.2748).	Nevada Department of Environmental Protection	Discharge permit required for use of reclaimed water, including effluent management plan
WTS-1B: General Criteria for Preparing an Effluent Management Plan	*Reclaimed Water*—Domestic wastewater that has been treated to secondary treatment standards and disinfected to levels necessary (NAC 445A.276) for the chosen method of reuse. Other terms for this water include treated effluent, reuse water, and recycled water.	Nevada Department of Conservation and Natural Resources, Bureau of Water Pollution Control	None

The IMD also establishes classes of recycled water based on level of treatment. Classes range in descending order of quality from A to D, as well as a lowest-quality class, *nondisinfected*. The classes are differentiated by level of treatment and standards for turbidity, total coliform, and *E. coli*. Class A must be oxidized, disinfected, and filtered. Classes B, C, and D must be oxidized and disinfected. The nondisinfected class need only be oxidized. Classes A through C are acceptable for use in industrial cooling. It is further noted that Oregon has changed terminology in its most current version of OAR 340-055. In the past, the term reclaimed was used. Now, Oregon uses *recycled*, because "recycled water emphasizes the value of treated effluent as a state water resource and as an important urban and rural sustainability activity" (ODEQ 2009).

Regulations were not found for the reuse of any other type of water in the State of Oregon. The Oregon regulations, the applicable definitions they contain, their implementing agencies, and the permits they specify are summarized in Table 12.

4.3 ANALYSIS

4.3.1 State Definitions

All four states reviewed in this report have codified definitions of recycled and/or reclaimed water (refer to Tables 9 through 12). For the most part, the definitions are consistent with each other. One notable difference is the distinction that California makes between recycled and reclaimed water. Reclaimed water is defined in the CCR Title 17, Section 7583, *Drinking Water Supplies*, as "wastewater which as a result of treatment is suitable for uses other than potable." Recycled water is defined in the California Water Code Section 13050(n) as "water which, as a result of treatment of waste, is suitable for a direct beneficial use or a controlled use *that would not otherwise occur* and is therefore considered a valuable resource" [emphasis added]. None of the other states make a distinction between the terms, and none of them specify that recycling only includes uses that would not otherwise occur.

Nevertheless, all of the reviewed states included in their definitions of recycled and/or reclaimed water the simple concept of treated wastewater used for another purpose. Interestingly, As mentioned previously, Oregon, in its revised *Recycled Water Use* rules (OAR 340-055), notes that it changed terminology from reclaimed to recycled water. California also codifies that recycled water is a "valuable resource" (CCR 17, Section 7583).

Despite these minor differences in definition, it does not appear that there is a noteworthy difference in the way that these four states view recycled or reclaimed water. Therefore, there is not a significant definitional barrier to widespread water reuse across these states—at least not with the primary terms. There are, however, differences in treatment standards and acceptable use.

TABLE 12 Oregon State Laws and Applicable Definitions for Water Reuse

Oregon Law	Definitions	Regulatory Authority	Permits
Oregon Administrative Rules, Chapter 340, Division 55 (OAR 340-055), "Recycled Water Use"	*Beneficial Purpose*—A purpose where recycled water is utilized for a resource value, such as nutrient content or moisture, to increase productivity or to conserve other sources of water. *Recycled Water*—Treated effluent from a wastewater treatment system that as a result of treatment is suitable for a direct beneficial purpose. Recycled water includes reclaimed water as defined in ORS 537.131. *Wastewater* or *Sewage*—The water-carried human or animal waste from residences, buildings, industrial establishments, or other places, together with such groundwater infiltration and surface water as may be present. The admixture with sewage of wastes or industrial wastes shall also be considered "wastewater" within the meaning of this division.	Oregon Department of Environmental Quality (Primary) Oregon Department of Human Services Oregon Water Resources Department	National Pollutant Discharge Elimination System (NPDES) or Water Pollution Control Facilities (WPCF) permit Recycled Water Use Plan (RWUP)
Internal Management Directive: Implementing Oregon's Recycled Water Use Rules	The revised water reuse rules substitute *recycled water* for *reclaimed water*. Recycled water emphasizes the value of treated effluent as a state water resource and as an important urban and rural sustainability activity.	Oregon Department of Environmental Quality (Primary) Oregon Department of Human Services Oregon Water Resources Department	None

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4.3.2 State Regulatory Comparison

All four states reviewed here all provide regulation for the reuse of treated wastewater effluent. None of the states specified geothermal energy production as an acceptable reuse, but none excluded it. Thus, the regulatory framework appears to be in place for geothermal projects to utilize recycled wastewater, although unseen barriers to this use could arise. Regulations for the utilization of other alternative water sources (e.g., produced water from oil and gas development, saline groundwater, and mine pool water) could not be found in any state; however, Nevada identified saline groundwater as a possible future source.

Some similarities among state regulations for wastewater reuse were found. While all four states required some form of planning and permitting, Nevada and Oregon specifically require plans of use for the wastewater to be filed along with the wastewater treatment permit application. All of the reviewed states also specify treatment standards. Idaho, Nevada, and Oregon include categorizations of reclaimed water based on treatment and quality levels, and specify the acceptable categories of water for particular uses (although none explicitly included geothermal power production as a use).

A few significant differences among the state regulations were found as well. California stands alone among the reviewed states in having passed laws emphasizing or requiring the use of reclaimed water when possible. Nevada is the only state where mention was found of saline groundwater as a possible future source. While Idaho, Nevada, and Oregon all categorized levels of reclaimed water, their classification systems and standards differed, albeit slightly in some cases.

Another important source of potential regulatory authority in this area worth mentioning is the U.S. Environmental Protection Agency's Underground Injection Control (UIC) program. From the UIC website, "The UIC Program is responsible for regulating the construction, operation, permitting, and closure of injection wells that place fluids underground for storage or disposal" (USEPA 2014). UIC wells are regulated under a series of classes, which describe their use and corresponding regulations, normally based on functional groupings such as mining, oil and gas, etc. While traditional geothermal wells are regulated as Class V wells, the injection of nontraditional waters discussed above might require a different class designation, and therefore, additional rules and regulations that the operator would need to be aware of. For example, produced water from oil and gas operations might be regulated under Class II, and mine pool water might be regulated under Class III. While three of the four states discussed here (Oregon, Nevada, and Idaho) have primacy under this program, California operates under a dual system where both the state and the EPA have regulatory authority.

4.3.3 Suggestions for Future Improvement

Although the pathways allowing for geothermal use of reclaimed wastewater appear to have been established in California, Idaho, Nevada, and Oregon, these pathways are not always clear. Additional clarification may be needed in these states to explicitly provide for geothermal use of reclaimed wastewater. The reuse of other alternative waters (as identified above) may require additional rulemaking or legislative efforts. Laws and regulations explicitly stating the need to reuse alternative water, such as the ones in California, may assist with opening up policy to allow, or even encourage, the use of alternative water for geothermal energy production.

4.4 ADDITIONAL REPORTS ON ALTERNATIVE WATERS

The Energy Policy Research Institute (EPRI), in conjunction with the California Energy Commission (CEC), published a guide to the use of reclaimed water for power generation entitled, *Use of Degraded Waters as Cooling Water in Power Plants* (EPRI 2003). The EPRI report is very detailed and extensively covers the technical aspects of using alternative water sources for cooling, such as necessary water quality requirements, technical feasibility, environmental impacts, and commercially available treatment technologies. Similar to this report's conclusions, the EPRI report recognized that treated municipal effluent has traditionally dominated the focus when looking at alternative waters for cooling. The report also called for the further use of other sources.

In 2009, the American Water Works Association (AWWA) Water Reuse Committee re-published an updated edition of an earlier technical guide, entitled *Planning for the Distribution of Reclaimed Water* (AWWA 2009). The committee also published a specific report on the technical requirements of using produced water as an alternative water supply. However, viewing these documents requires a paid membership to AWWA, and thus their use is limited for the general public.

Finally, the U.S. Department of the Interior's Bureau of Reclamation recently released a series of reports on produced water treatment and management for reuse (Reclamation 2011).

It is added that, with the exception of the above reports, the availability of documentation and guidelines for the use of alternative waters is extremely limited. Future work in this area should include in-depth analysis and discussion of requirements and availability of specific alternative water sources on a source-by-source basis.

5 SUMMARY AND CONCLUSIONS

Geologically speaking, it is a combination of thermal, tectonic, and hydraulic conditions that determines the productivity of an enhanced geothermal reservoir. Research has shown that high rock temperatures, a high degree of fracturing, high tectonic stresses, fluid saturation, and high intrinsic permeability all favor productivity. Geologic conditions common to the EGS projects analyzed represent those that make a reservoir a candidate for development, including high heat and a high degree of fracturing and crustal stress. In addition, these hotspots tend to occur in active hydrothermal (and tectonic) environments with igneous resource rock. However, the geology is unique enough from site to site that stimulation protocols must be tailored accordingly. At least three projects thus far, Desert Peak, Newberry Volcano, and Raft River have demonstrated effective stimulation leading to an increase in injectivity of between 3 and 11 times the initial injectivity. To date there is not sufficient data reported from these projects to allow estimation of potential below ground operational losses from these projects, although most of them are taking place within existing hydrothermal reservoirs and thus are expected to experience negligible losses.

Although the existing infield EGS projects have yet to show significant below ground water losses, data is still extremely limited on greenfield EGS projects which may have more significant blow ground reservoir losses. Given this, the cost of supplying both traditional and alternative water sources to EGS projects were examined. This analysis showed that there appear to be water sources available with costs below the default value of $2,000/ac-ft used in GETEM for all locations and plant sizes analyzed. The use of these lower values would result in slightly lower estimates of LCOE for most power plants. In addition, given the large impact of economies of scale, costs could potentially be reduced even further, especially related to for transportation from wastewater treatment plants if multiple power plants are built in close proximity within the same geothermal area. Although there is limited data on the availability of brackish water sources, if it is available, it appears to be a more promising alternative than municipal waste water in most cases given the more remote locations of at least the existing EGS projects. Transportation distances were a key driver of this difference.

Despite the potential cost advantage, state regulations in states with existing EGS projects are far clearer on the use of reclaimed municipal waste water than they are for the use of brackish groundwater. The four western states (i.e., California, Idaho, Nevada, and Oregon) with active EGS development all have codified definitions of recycled and/or reclaimed water and, for the most part, these definitions are generally consistent with each other. For example, all four states reviewed included within their definitions the concept of treated wastewater used for another purpose. And, despite minor variances, it does not appear that there is a meaningful difference in the way that any of the four states view recycled or reclaimed water. Furthermore, none of the states specified geothermal energy production as an acceptable reuse, however none excluded it. Therefore, there is not a significant definitional barrier to widespread water reuse across these states; although, there are some differences exist in treatment standards and acceptable use. Nevertheless, a regulatory framework appears to be in place for geothermal projects to utilize recycled wastewater, although unseen barriers to this use could arise. It is further noted that regulations for the acquisition and handling of other alternative water sources (produced water from oil and gas development, saline groundwater, and mine pool water) could not be found in any state, however, Nevada has identified saline groundwater as a possible future source. However, the injection of alternative fluids will almost certainly be regulated under the EPA's UIC program. Currently conventional geothermal fluids are regulated under Class V, produced water from oil and gas operations are regulated under Class II, and mine pool water are regulated under Class III. At this point it's unclear under which class some of these fluids would fall if they are injected for geothermal development. While three of the four states discussed here (Oregon, Nevada, and Idaho) have primacy under the UIC program, California operates under a dual system where both the state and the EPA have regulatory authority.

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APPENDIX A – WATER COST ESTIMATION APPROACH

The model presented estimates the costs associated with constructing and operating the infrastructure required to source water for geothermal power plants. The model is designed to improve water cost estimates for users of the Geothermal Electricity Technology Evaluation Model (GETEM). The goal of the model is to provide reasonable estimates for the costs associated with makeup water projects that are within a reasonable range of the actual costs (i.e., ±50%). The cost estimates that result from this model can be used as inputs into GETEM to aid in providing more accurate estimates of the levelized cost of electricity from geothermal facilities. It is noted that determining the exact costs of these types of projects requires detailed, project-specific engineering analyses, which would generally render the model too cumbersome to be used effectively by the typical GETEM user.

A.1 WATER COST MODELING FRAMEWORK

There are two main categories of inputs to the model from which the cost of water is calculated. The first category comes from GETEM, and the second category contains user-defined inputs necessary to calculate the cost of water (refer to Figure A.1).

Using the inputs from these two main categories, the model calculates five cost categories that are aggregated to compute the total cost of water: (1) acquisition, (2) well drilling, (3) pipeline, (4) pumping, and (5) treatment. For each of these cost categories, upfront construction costs and operation and maintenance (O&M) costs are calculated. The following subsections describe in further detail how each of these cost categories is calculated.

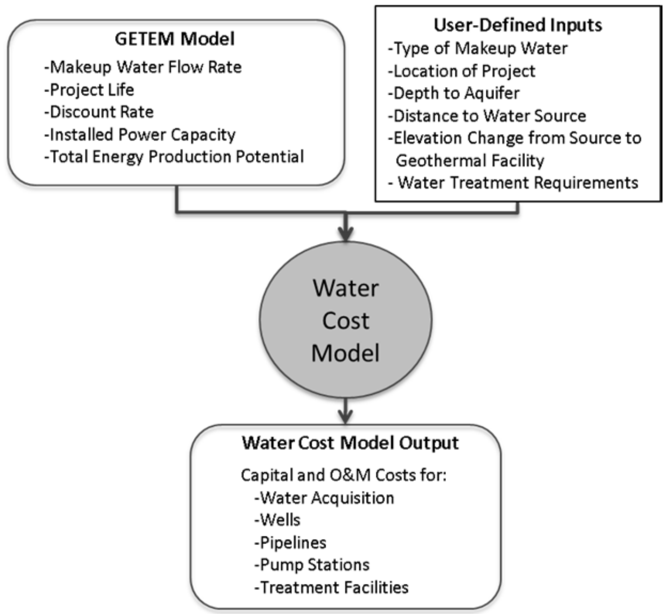

FIGURE A.1 Flow Diagram of the Inputs and Outputs of the Water Cost Model

A.2 WATER ACQUISITION COSTS

Water acquisition costs are applied to fresh groundwater, fresh surface water, and municipal fresh water only. These costs are presented below. The acquisition costs associated with saline/brackish groundwater, produced water, and effluent from wastewater treatment plants (WWTPs) were assumed to be zero. It is noted that, while these costs may not in fact be zero, sufficient data have not yet been obtained to accurately quantify them. However, the user is able to add into the model a user-defined acquisition cost for these water sources, assuming it is known; otherwise the default value of zero will be applied to the model calculation.

A.2.1 Fresh Groundwater and Surface Water

Fresh groundwater and fresh surface water acquisition costs were estimated from a database of Western U.S. water sales and transfers aggregated by the Bren School at the University of California Santa Barbara (University of California 2010). The dataset was obtained as one large, integrated file; thus, the first step was to divide the data into states and organize it chronologically. After yearly state-level water acquisition data were obtained, states that had geothermal energy reserves were selected for further review—Arizona, California, Colorado, Idaho, Montana, Nevada, New Mexico, Oregon, Utah, Washington, and Wyoming.

Further analysis was conducted based on the category of sale. Therefore, the data were organized according to 12 broad categories based on both the point of origin and point of use of the water: agriculture (Ag) to Ag, Ag to municipal or industrial purposes (Urban), Ag to the environment (Enviro), Urban to Ag, Urban to Urban, Urban to Enviro, Enviro to Ag, Enviro to Urban, Enviro to Enviro, Combination, Recycled, and Unknown. Because the primary concern was related to water purchases that could be used by a large-scale commercial or industrial facility, the categories of interest were narrowed down to five: (1) Ag to Urban, (2) Urban to Urban, (3) Enviro to Urban, (4) Combination, and (5) Recycled.

Next, the dataset was analyzed to obtain a cost figure for an inflation-adjusted acre-foot (AF) of water on a state-by-state basis. The costs for all water sales and transfers within the state were then averaged, resulting in a single value for each state that represented the long-term, inflation-adjusted average water acquisition prices (in $/AF). The original database used the Consumer Price Index for All Urban Consumers (CPI-U) to normalize all prices in 1987 dollars. The CPI-U also was used to convert 1987 dollars into 2012 dollars (the most recent data available) for use in the makeup water model (BLS 2013).

Upon detailed examination, it was observed that the price data included data points for certain years that appeared to be outliers when compared to the long-term trend. Thus, as a quality assurance effort, a simple statistical analysis was used to test for outliers within the data. The first step in the statistical analysis was to calculate *z*-values for each water transaction. The *z*-value is a common statistic used to measure deviation from the mean and is calculated using Equation A.1:

$$z = \frac{(mean - value)}{standard\ deviation} \quad \text{(A.1)}$$

A *z*-value of 1 or −1 indicates that the value being measured is 1 standard deviation away from the mean. If the data are normally distributed, then roughly 68% of all the values within the data set will fall within 1 standard deviation of the mean. As the *z*-value increases, in both the positive and negative direction, the values get farther and farther away from the mean and are therefore more likely to be outliers. For this project, all data points that were greater than 3 standard deviations away from the mean were excluded; that is, those that had a *z*-value greater than 3 or less than −3. Again, assuming a normal distribution, this exclusion applies to less than 2% of all the data; that is, ±3 standard deviations is inclusive of greater than 98% of the total dataset. Once the outliers were excluded from the data, the average long-term price for water acquisition for each state was calculated. Table A.1 lists the average long-term price data used in this model for fresh groundwater and fresh surface water.

A.2.2 Municipal Water

A dataset containing municipal water rates and charges for 2012 from a variety of U.S. cities was purchased from the American Water Works Association (AWWA) (AWWA 2013).; however, only data included pricing information for a variety of system sizes, only data from the largest system size classification (Class A, more than 75 million gallons per day sold) were included for further analysis. This was done to better estimate the acquisition of large volumes of water for commercial and industrial users, namely, geothermal energy facilities. More specifically, the cost of municipal water was calculated by averaging the monthly water costs for Class A systems utilizing an 8-in metered pipe (the largest category) for cities in the

Western U.S. For use in the water cost model, the average cost per acre foot ($/AF) was needed and because of the limited number of data points in any given state, the average for all western cities was used ($1,090 per AF). Table A.1 indicates the average long-term price data used in this model for municipal water.

TABLE A.1 Long-Term Water Acquisition Costs per Category and State Used in the Water Model

	Average Cost of Water in 2012 U.S. Dollars per Acre-Foot				
State	Fresh Ground-/ Surface Water	Municipal Water	Saline/Brackish Groundwater	Produced Water	WWTP Effluent
Arizona	149	1,090	0	0	0
California	151	1,090	0	0	0
Colorado	220	1,090	0	0	0
Idaho	15	1,090	0	0	0
Montana	65	1,090	0	0	0
Nevada	164	1,090	0	0	0
New Mexico	280	1,090	0	0	0
Oregon	38	1,090	0	0	0
Utah	86	1,090	0	0	0
Washington	186	1,090	0	0	0
Wyoming	80	1,090	0	0	0

A.3 WATER WELL DRILLING COSTS

Well costs are calculated as a function of the required water flow and depth of the well, as presented in Table A.2. The data in Table A.2 represent the capital costs of water well construction, including pumps and other associated facilities, according to a South Central Texas Regional Water Planning Group (SCTRWPG) report (SCTRWPG 2011). To calculate the costs from this information, the model first uses the Makeup Water Flow Rate (in gallons per minute [gpm]) from the GETEM inputs to select the appropriate cost column in Table A.2. Each column in Table A.2 corresponds to the appropriate cost curve in Figure A.2. Once the appropriate cost curve is selected from Figure A.2, the model then calculates the cost of the well according to a linear equation, as depicted in Equation A.2:

$$y = mx + b \tag{A.2}$$

Where

y = cost of drilling the well ($),
x = depth of the well (ft),
m = slope of the cost line, and
b = intercept.

TABLE A.2 Well Costs According to the Capacity and Depth of the Well (in 2008$)

Well Depth (ft)	Well Capacity (gpm)					
	100	175	350	700	1,000	1,800
150	$111,207	$168,820	$288,065	$325,581	$405,971	$593,548
300	$150,062	$214,374	$342,998	$392,572	$485,021	$687,337
500	$194,276	$267,968	$407,311	$468,943	$577,470	$799,883
700	$234,472	$316,202	$464,924	$538,615	$660,540	$899,031
1,000	$308,163	$404,631	$572,111	$665,899	$814,621	$1,083,929
1,500	$431,428	$553,353	$748,969	$878,934	$1,069,190	$1,389,412
2,000	$554,693	$700,735	$925,828	$1,091,968	$1,325,099	$1,696,235

Source: SCTRWPG (2011).

For example, if the required water for a project was 1,000 gpm and the well was 1,000 ft deep, the model would calculate the cost of the well by inputting the well depth as variable x in the 1,000 gpm cost curve. If the required well capacity exceeds 1,800 gpm, the model will calculate the cost of drilling multiple wells to meet the required capacity.

The SCTRWPG report also estimates the project annual O&M costs to be 1% of the capital costs of water well construction, including pumps and other associated facilities, according to the SCTRWPG report (SCTRWPG 2011). The annual O&M costs of the project are calculated by multiplying 1% by the total capital costs and then calculating the current value of all the future costs according to the discount rate and project life specified in the GETEM inputs. The cost of lifting the water from the bottom of the well to the surface was then added to these O&M costs.

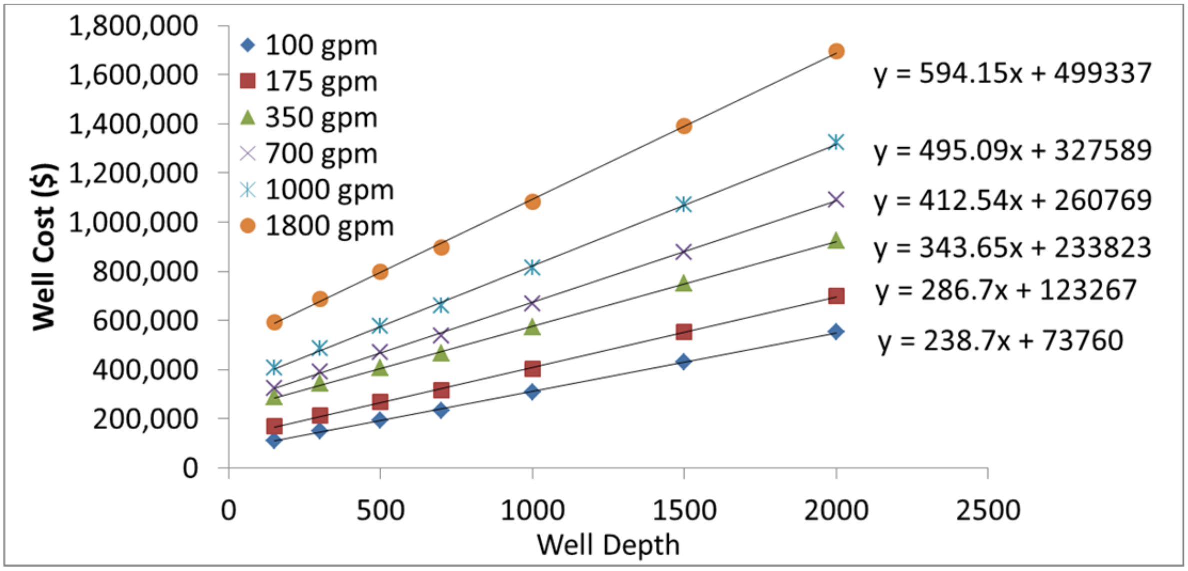

FIGURE A.2 Cost Curves for Wells over Varying Water Flow Rates

The cost of energy for groundwater pumping is determined by first calculating the horsepower (hp) requirements from Equation A.3.

$$hp = \frac{wp}{E_p} = \frac{Q \cdot TDH}{K \cdot E_p} \tag{A.3}$$

Where

Q = required flow rate of makeup water (gpm) (from GETEM),

TDH = total dynamic head of the fluid to be pumped (ft),

E_p = mechanical efficiency of the pump (assumed to be 75%), and

K = conversion factor equal to 3,960 gal-ft/min/hp (National Pump Company 2012).

To simplify the groundwater pumping calculation, *TDH* in this case is assumed to be the depth of the well. This assumption ignores the piezometric head in the well, any change in head due to drawdown, and friction losses that may occur along the well. These simplifications generally have opposing impacts on the pumping power requirement; thus, they will at least partially cancel each other out.

The annual energy cost of operating the groundwater pump is then calculated assuming the pumps are operated continuously and powered by electricity. This calculation is shown in Equation A.4.

$$Annual\ Cost = C_e \cdot \frac{hp \cdot 0.746 \cdot 8760}{E_m} \tag{A.4}$$

Where

C_e = cost of electricity with a default value of 0.07 \$/kWh (EIA 2013), and

E_m = electrical efficiency of the pump motor (assumed to be 93% based upon efficiencies of large electric motors [Geankoplis 1993]).

The remaining numbers in Equation A.4 are constants for the conversion of units from hp to kW (i.e., 0.746) and to account for the number of hours per year (i.e., 8.760).

A.4 WATER PIPELINE COSTS

Regardless of the water source, most makeup water projects will require some sort of pipeline construction. Data on pipeline costs are dependent on pipeline diameter and are based on the values reported by SCTRWPG (2011), which details three cost categories with different price per mile data for pipeline construction. These categories include urban, urban/rural, and rural. Rural costs were used in the water cost model because it was assumed that large-scale geothermal projects would be located away from urban areas.

The cost of pipeline, therefore, changes as a function of both the required pipeline diameter and the total length of the pipeline. The pipeline diameter is determined according to the Equation A.5:

$$D = \sqrt{\frac{4Q_f}{\pi \cdot v_{max}}} \tag{A.5}$$

Where

D = pipeline diameter (ft),

Q_f = flow rate of makeup water (ft^3/s), and

V_{max} = maximum allowable velocity of the water in the pipe (assumed to be 3, 6, or 10 ft/s depending upon input).

In order to determine the appropriate pipeline cost per mile, the model uses the makeup water flow rate from the GETEM inputs as the value for Q_f, calculates D via Equation A.5, and then selects the appropriate cost data from the values listed in Table A.3. The V_{max} variable in the equation is set through an input value that allows the user to select a low-, medium-, or high-pressure pipeline, which results in values of 3, 6, or 10 ft/s, respectively. As an example, a required makeup water flow rate (Q_f) of 2.2 ft^3/s (1,000 gpm) would require a pipeline of 11 in., assuming a maximum flow rate of 10 ft/s. The model would round this to the closest cost category above the actual value, which, in this case, is a 12-in. pipe costing $327,360 per mile. The total construction cost for this pipeline would then be calculated by multiplying $327,360 per mile by the distance from the water source to the facility, which involves data that are part of the user-defined data inputs section of GETEM.

TABLE A.3 Pipeline Costs as a Function of Pipeline Diameter (in 2008$)

Pipeline Diameter (in.)	Rural ($/mi)	Pipeline Diameter (in.)	Rural ($/mi)
12	327,360	72	2,840,640
16	422,400	78	3,194,400
20	496,320	84	3,680,160
24	554,400	90	4,155,360
30	707,520	96	4,672,800
36	939,840	102	5,179,680
42	1,182,720	108	5,728,800
48	1,462,560	114	6,283,200
54	1,774,080	120	6,900,960
60	2,106,720	132	8,701,440
66	2,476,320	144	10,332,960

Source: SCTRWPG (2011).

As before, annual O&M costs for pipelines were estimated by the SCTRWPG (2011) report as 1% of total construction costs. These values were calculated for each year of the project, and the current value of all costs was calculated according to the discount rate specified in the GETEM data inputs section.

A.5 WATER PUMPING STATION COSTS

Pumping costs are calculated according to Table A.4. The horsepower required for a particular project is calculated from Equation A.3, presented in Section A.3 on water well costs. However, for water pumping related to transportation, the total dynamic head is calculated as follows:

$$TDH = Friction\ Loss + Minor\ Losses + Static\ Lift \qquad \text{(A.6)}$$

Static lift is defined as the height (ft) that the water will rise (or fall) before arriving at the pump, and this value is input by the model user. Minor losses are assumed to be 5% of friction losses. Friction loss (or head loss) occurs along the pipeline length, and for water pipe systems this can be determined by using the Hazen-Williams presented in Equation A.7:

$$H_f = \frac{3.022 \cdot v_{max}^{1.85} \cdot L}{C^{1.85} \cdot D^{1.166}} \qquad \text{(A.7)}$$

Where

v_{max} = maximum allowable velocity (set to 3, 6, or 10 ft/s),

L = pipeline length (ft),

C = pipeline roughness coefficient (assumed to be 130; C typically varies between 90 and 150, although values can be outside that range), and

D = pipeline diameter (ft) (determined from Q_f and V_{max} according to Equation A.5).

TABLE A.4 Pumping Station Costs according to Horsepower

Pump Station (hp)	Pump Station Cost ($ millions)	Pump Station (hp)	Pump Station Cost ($ millions)
<300	2,070,000	6,000	11,290,000
300	2,070,000	7,000	12,270,000
400	2,620,000	8,000	13,190,000
1,000	4,290,000	9,000	14,050,000
2,000	6,240,000	10,000	14,870,000
3,000	7,760,000	15,000	18,510,000
4,000	9,070,000	20,000	21,630,000
5,000	10,230,000	>20,000	NA[a]

[a] NA = not applicable.
Source: SCTRWPG (2011).

Equations A.5 through A.7 are used to calculate the hp required by a specific project depending on the water flow (gpm), elevation change (ft), distance of the pipeline (mi), and the diameter of the pipe (ft). The total amount of hp is then divided evenly by the number of pump stations required. The number of pump stations is calculated by dividing the total mileage of the pipeline by 12; that is, it is assumed that a pump station is required every 12 mi of pipe. For example, if the project required 6,000 hp and had 20 mi of pipe, the model would calculate that two 3,000-hp stations would be required rather than one 6,000-hp station. The cost of a pump station is then determined from the Equation A.8:

$$y = 94899x^{0.5492} \tag{A.8}$$

Where

y = cost of a pump station ($), and

x = pump station power (hp).

The cost curve represented by Equation A.8 was calculated by regressing the data presented in Table A.4 and Figure A.3. The cost per station calculated by Equation A.8 is then multiplied by the number of pump stations required to calculate the total pumping construction cost.

Annual O&M costs were estimated as 2.5% of the total construction costs (SCTRWPG 2011), and the present value of these costs over the life of the project was used as the total O&M cost. The electricity costs of running the pumps were added to these O&M costs and were calculated assuming continuous operation and powered by electricity as described in Equation A.3.

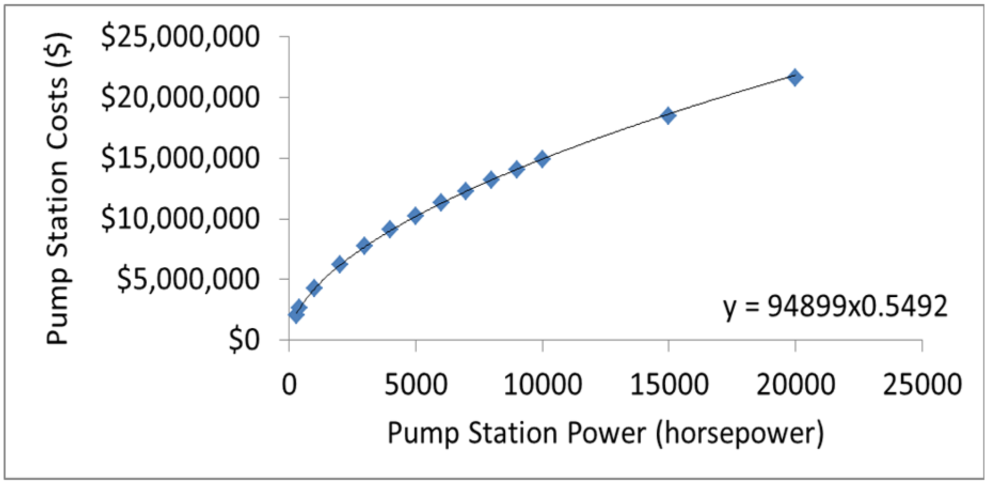

FIGURE A.3 Cost Curve for Calculating Pump Station Construction Costs (in 2008$)

A.6 WATER TREATMENT COSTS

Capital and O&M water treatment costs are primarily estimated based on two factors: (1) the level of treatment required, and (2) the volume of water being treated. Similar to the well costs, treatment costs are determined using cost curves developed from the data that report the construction and O&M costs, respectively, for treatment facilities (SCTRWPG 2011). Treatment construction costs are specifically calculated using a linear equation similar to that presented in Equation A.2 above, where *y* is the cost of constructing the treatment facility and *x* is the capacity required in gpm. The cost curves used in this model are differentiated by the type of treatment required and range from Level 0 to Level 6 as presented in Table A.5. The model allows for the stacking of up to two different treatment levels to create treatment trains. The capital and O&M costs for the two levels of treatment are added together to determine the total treatment costs. Figures A.4 and A.5 show the cost curves for treatment construction.

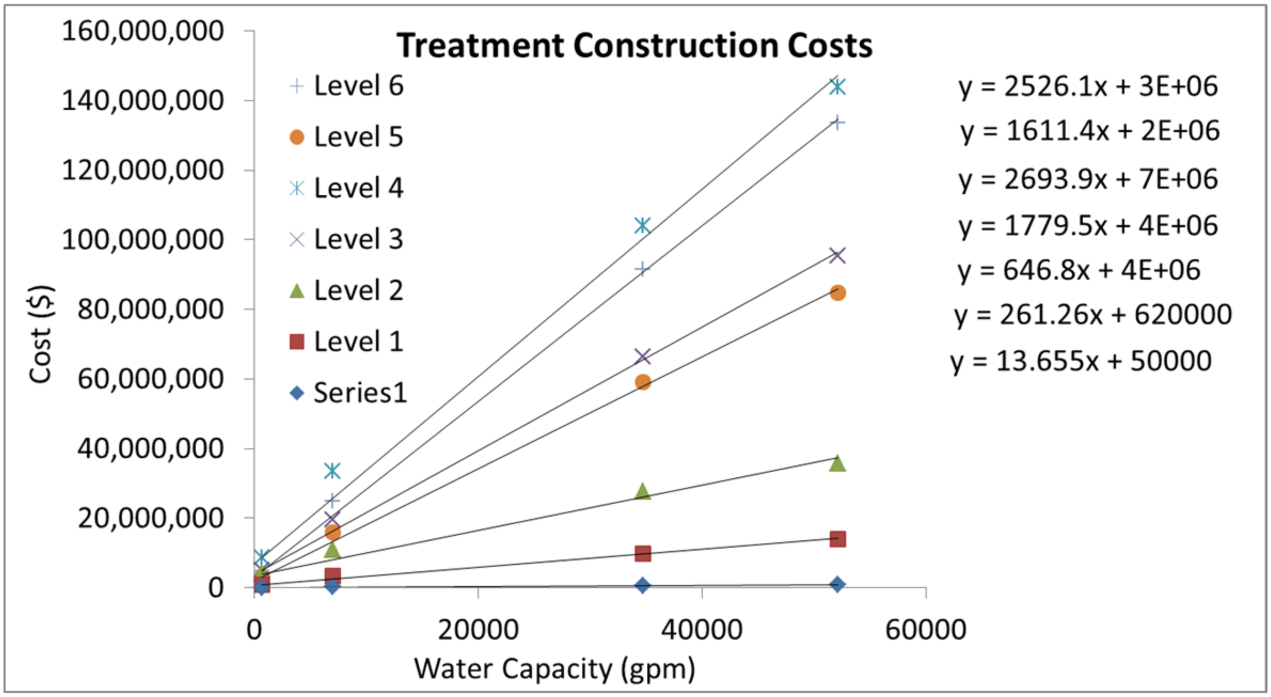

FIGURE A.4 Cost Curves for Construction Costs of Treatment Plants of Varying Treatment Level and Capacity (in 2008$)

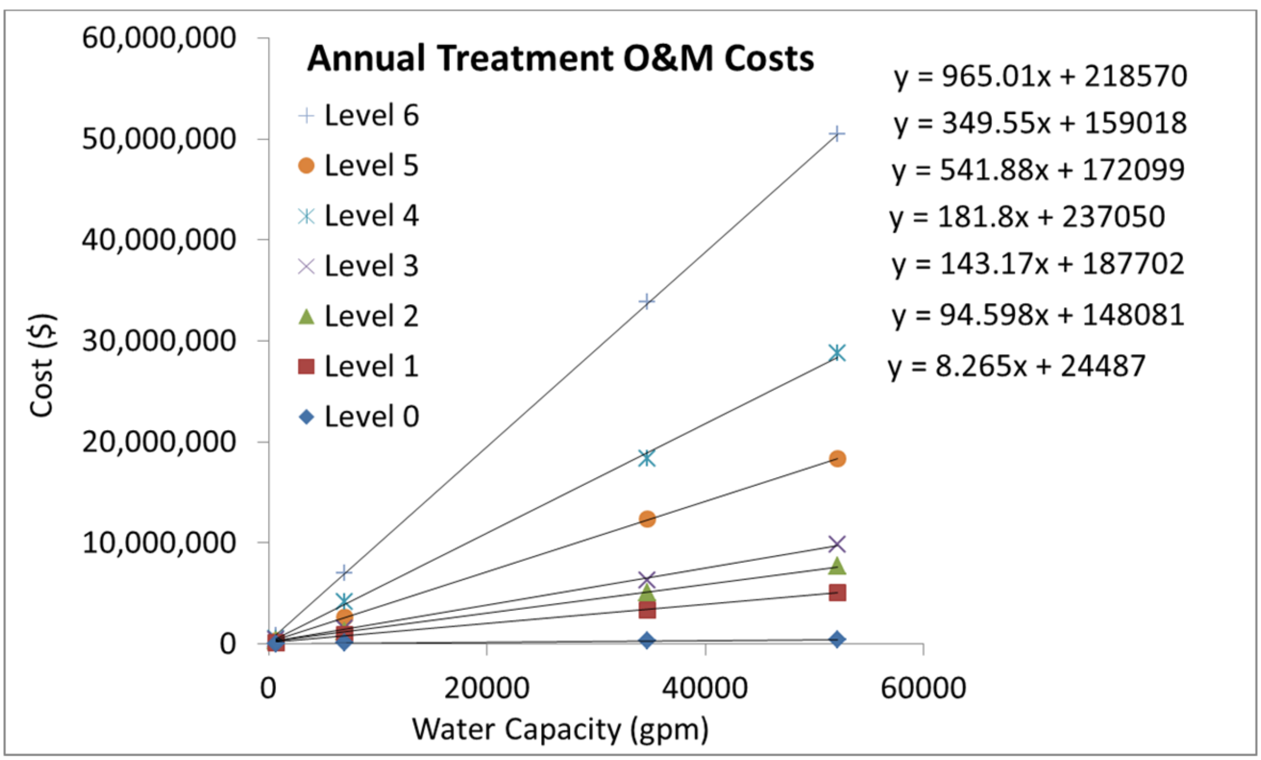

FIGURE A.5 Cost Curves for O&M Costs of Treatment Plants of Varying Treatment Level and Capacity (in 2008$)

TABLE A.5 Treatment Levels

Level	Treatment Process Description
Level 0	Disinfection Only: For groundwater with no contaminants that exceed regulatory limits.
Level 1	Groundwater Treatment: For groundwater to lower the iron and manganese content and to disinfect.
Level 2	Direct Filtration Treatment: For treating groundwater from sources where iron, manganese, or other constituent concentrations exceed the regulatory limit and require filtration for solids removal.
Level 3	Surface Water Treatment: For treating all surface water sources to be delivered to a potable water distribution system.
Level 4	Reclaimed Water Treatment: For treatment where wastewater effluent is to be reclaimed and delivered to a supply system or injected into an aquifer.
Level 5	Brackish Groundwater Desalination: For desalination of a surface water or groundwater containing high solids concentrations, additional solids removal treatment should be included in addition to desalination. Cost does not include pretreatment for solids removal prior to reverse osmosis membranes.
Level 6	Seawater Desalination: For desalination of a surface water or groundwater containing high solids concentrations, additional solids removal treatment should be included in addition to desalination. Cost does not include pretreatment for solids removal prior to reverse osmosis membranes.

Source: SCTRWPG (2011).

A.7 CALCULATING TOTAL COSTS

All capital and O&M costs are summarized in the model output (presented in Table A.6). Each of the capital costs are summed to form the capital cost subtotal (a + b + c + d + e = f), and the O&M costs are summed to form the O&M cost subtotal (g + h + i + j + k = l). Both of these subtotals are then summed to form the total present value cost of water (f + l = m). It should be noted that there are some minor discrepancies between the years for which each cost estimate is based. The majority of the costs are presented in constant 2008 dollars as that is what was presented in the source, however the water acquisition costs are in constant 2012 dollars. This discrepancy is recognized, but the error is expected to be minimal relative to the inherent uncertainty in generating high level cost estimates as this model is designed to do. Future versions may be refined to include inflation curves and allow users to adjust costs to a specific year.

TABLE A.6 Organization of the Model Output

Model Output	Value ($)
Capital costs	
Upfront water acquisition cost	a
Well costs	b
Pipeline costs	c
Pumping costs	d
Treatment costs	e
Capital cost subtotal	a + b + c + d + e = f
Present value O&M costs	
Annual water acquisition fees	g
Well costs	h
Pipeline costs	i
Pumping costs	j
Treatment costs	k
Present value O&M subtotal	g + h + i + j + k = l
Total present value cost	f + l = m

A.7.1 Time Value of Money Calculations

Present value calculations are performed for all O&M costs that occur in the future; all construction costs are assumed to occur in the present, and therefore do not require discounting. Future O&M costs are calculated by summing the discounted annual O&M values over the life of the project (see Sections A.2 through A.6 for information regarding the annual O&M costs for each of the five categories). The discount rate used in the calculation of present values enters this model from the GETEM input section.

A.7.2 Levelized Cost of water (LCOW)

The LCOW is based upon the methodologies for calculating the levelized cost of energy (LCOE), as presented by Short et al. which is the standard method used by Short et al. (1995). The modified equation is shown below:

$$\text{LCOW} = \frac{\text{Total Present Value Cost}}{\text{Qf}} \cdot UCRF \tag{A.9}$$

$$UCRF = \frac{r(1+r)N}{(1+r)N-1} \tag{A.10}$$

Where:

Q_f = total annual water requirement (ac-ft),

r = discount rate, and

N = total project lifetime (years).

A.8 WATER COST MODEL VALIDATION

Dellinger and Allen (1997) list the construction and O&M costs related to the Southeast Effluent Pipeline Project that brought water from regional WWTPs to The Geysers geothermal facility. Project data reported in Dellinger and Allen (1997) were used to parameterize the model developed in this research to calculate total project costs. Total costs and other project-specific calculations were then validated against the actual project data. Table A.7 lists the input data used to parameterize the model, and Table A.8 lists both the project data and the model output used for validation.

TABLE A.7 Data from the Southeast Effluent Pipeline Project Used to Parameterize the Model

Parameter	Value
Pipeline length (mi)	29
Total water volume (gpm)	5,416
Elevation change (ft)	1,600

Source: Dellinger and Allen (1997).

The validation simply calculates the simple difference between the project data and the model calculations for three cost categories and three project parameters. Two sets of model calculations are made. The first set of calculations assumes a fixed maximum velocity for the pipeline velocity of 10 ft/s for sizing the pipeline and pumps. The second set of calculations modifies the maximum velocity parameter until the model calculated a pipeline diameter that matched the diameter used in The Geysers project. The value of the parameter in this case was 5.5 ft/s.

In the fixed velocity assumption case, the model calculates a narrower pipeline diameter. This results in a less expensive pipeline but more expensive pumps and much higher O&M costs due to high energy consumption. These much higher O&M costs result in an overestimate of the total cost by around 40%, even though the capital costs are underestimated by about 20%.

TABLE A.8 Data from the Southeast Effluent Pipeline Project and Model Calculations for Validation

	Model Validation				
Parameter	Geysers Data[a]	Model Calculations[b]	% Difference	Model Calculations[c]	% Difference
Pipeline diameter (in.)	20	16	–26%	20	0
Total pumping power (hp)	7,370	8,914	21%	4,318	–41%
Number of pumping stations	6	3	–50%	3	–50%
Capital costs (10^6 \$)	45	35	–21%	32	–30%
Annual O&M costs (10^6 \$)	2	5.2	158%	2.8	38%
Total cost (10^6 \$)	68	95	39%	63	–7%

[a] Source: Dellinger and Allen (1997).
[b] Results assume a 10 ft/s maximum velocity in the pipeline.
[c] Results after modifying maximum velocity to match Geysers pipeline diameter (5.5 ft/s).

In the fixed diameter case, the model underestimates the pumping requirements by about 40% and capital costs by 30%. The operational costs are much closer to estimates for the Geysers project although still higher despite the lower estimated pumping power. The overestimated O&M costs and underestimated projects combine to result in a total cost that is within 7% of the reference case.

Possible sources of discrepancy between the cost estimates include but are not limited to the following:

- Omission of various overhead and contingency costs associated with project development;
- Uncertainty over the actual elevation changes along the pipeline;
- Reduced capital costs for pumps resulting from economies of scale due to underestimating the number of pump stations;
- Different assumptions of electricity costs for O&M; and
- Specific parameters used in the actual pipeline project, such as desired pipeline pressure, that can alter, for example, pipeline diameters and number of pump stations.

As a result of this analysis, and to account for the potential for different pipeline design conditions, a user input for pipeline pressure which allowed for selecting a maximum velocity of 3 ft/s, 6 ft/s, or 10 ft/s was added. This new input results in a direct tradeoff between pipeline capital cost and operational costs. Lower velocities require larger diameter pipelines, but operate at lower pressures, resulting in less pumping power. Higher velocities result in smaller pipelines and higher pressures, more pumping power.

A.9 REFERENCES

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