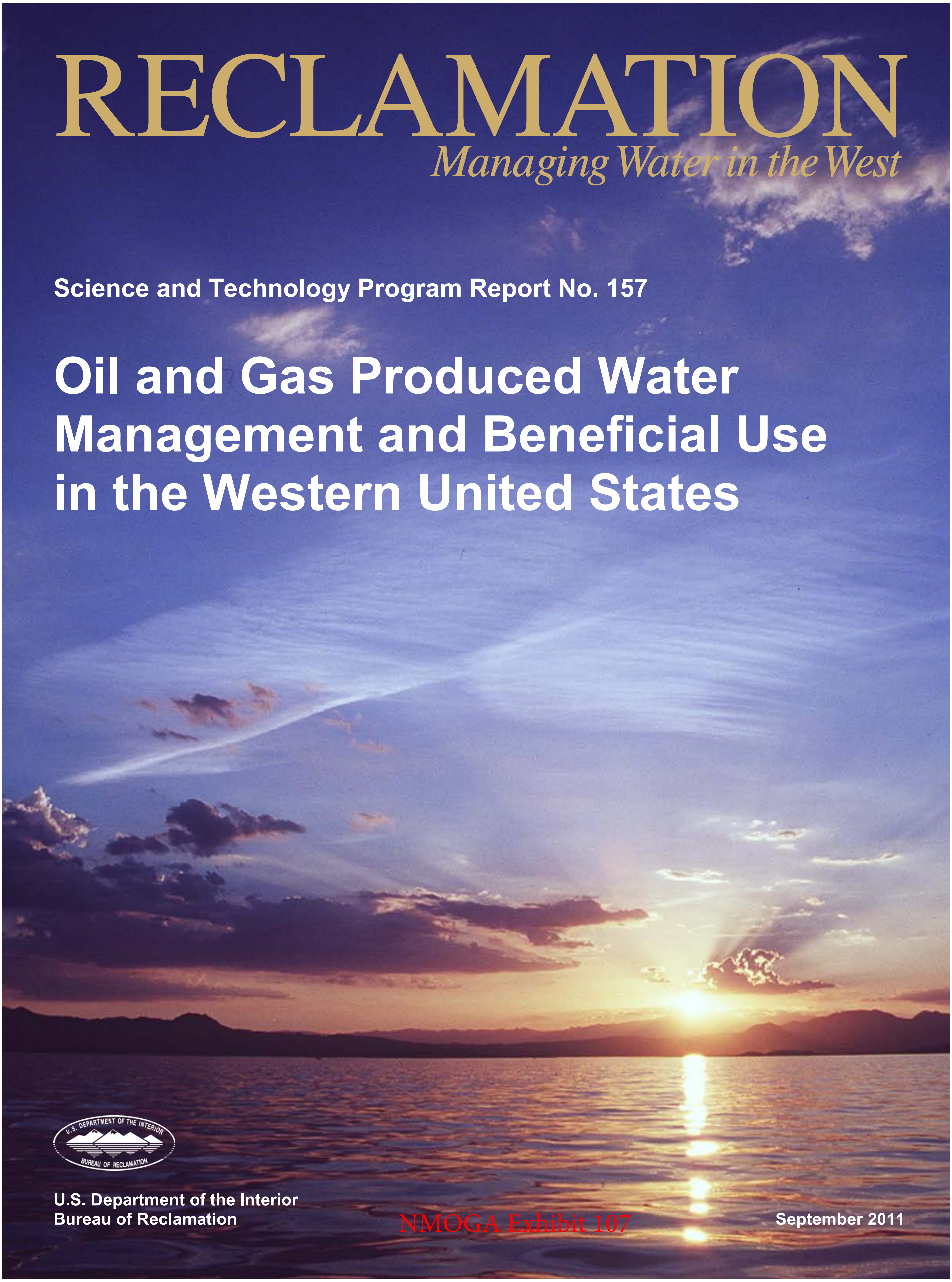

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Managing Water in the West

Science and Technology Program Report No. 157

Oil and Gas Produced Water Management and Beneficial Use in the Western United States

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Produced water from oil and gas operations is currently handled as a waste product. The quality of produced water varies significantly based on the geochemistry of the producing formation, the type of hydrocarbon produced, and the characteristics of the producing well. If produced water meets appropriate water quality criteria, it may be used beneficially for purposes such as irrigation, livestock watering, aquifer storage, streamflow augmentation, and municipal and industrial uses. Treatment may be required to improve the quality of produced water so that it can be put to beneficial use.

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Oil and Gas Produced Water Management and Beneficial Use in the Western United States

Prepared for Reclamation Under Agreement No. A10-1541-8053-381-01-0-1

by

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The mission of the Bureau of Reclamation is to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American public.

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Acronyms

acre/lb	acres per pound
AFY	acre-feet per year
AOC	assimilable organic carbon
AWWA	American Water Works Associations
BAF	biological aerated filter
bbl/MCF	barrels per million cubic feet
bpd	barrels per day
BAC	biologically active carbon
BOD	biological oxygen demand
BOE	barrels of energy
BTEX	benzene, toluene, ethylbenzene, and xylene
CBM	coal bed methane, also coal bed natural gas
CIP	clean in place
COD	chemical oxygen demand
COGCC	Colorado Oil and Gas Conservation Commission
DBP	disinfection byproduct
DGF	dissolved gas flotation
EC_w	electrical conductivity
EOR	enhanced oil recovery
DAF	dissolved air flotation
DO	dissolved oxygen
DOE	U.S. Department of Energy
dS/m	decisiemens per meter
ED	electrodialysis
EDI	electrodeionization
GAC	granular activated carbon
gpd	gallons per day
IGF	induced gas flotation
kgal	kilogallon
kWh/day	kilowatthours per day

Acronyms (continued)

m^2/gram	square meters per gram
MCF	million cubic feet
meq/L	milliequivalent per liter
MF	microfiltration
mrem/yr	millirem per year
MFL	magnetic flux leakage
mg/L	milligrams per liter
NOM	natural organic matter
NORM	naturally occurring radioactive materials
O&M	operation and maintenance
OPUS	optimized pretreatment and unique separation
pCi/L	picocuries per liter
ppm	parts per million
psi	pounds per square inch
Reclamation	Bureau of Reclamation
SAR	sodium absorption ratio
S/cm	siemens per centimeter
TDS	total dissolved solids
THMs	trihalomethanes
TN	total nitrogen
TOC	total organic carbon
TSS	total suspended solids
UF	ultrafiltration
USEIA	U.S. Energy Information Administration
USEPA	U.S. Environmental Protection Agency
USGS	U.S. Geological Survey
UV	ultraviolet
VOC	volatile organic chemicals
WAC	weak acid cation
ZLD	zero liquid discharge
°F	degree Fahrenheit
μg/L	microgram per liter

Acronyms (continued)

µm	micrometers
>	greater than
<	less than
%	percent

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Figures (continued)

1. Executive Summary

Due to increasing demand on fresh water sources, there is a need to develop new water supplies in the Western United States. Large volumes of water produced during oil and gas extraction, called produced water, are generated in drought prone locations that are also experiencing an increase in population. Produced water is a waste byproduct of the oil and gas industry; however, with appropriate treatment and application to beneficial use, produced water can serve as a new water supply in the Western United States.

The Bureau of Reclamation (Reclamation) Technical Service Center gathered data from publically available sources to describe the water quality characteristics of produced water, performed an assessment of water quality in terms of geographic location and water quality criteria of potential beneficial uses, identified appropriate treatment technologies for produced water, and described practical beneficial uses of produced water.

Produced water quality varies significantly based on geographical location, type of hydrocarbon produced, and the geochemistry of the producing formation. In general, the total dissolved solids concentration can range from 100 milligrams per liter (mg/L) to over 400,000 mg/L. Silt and particulates, sodium, bicarbonate, and chloride are the most commonly occurring inorganic constituents in produced water. Benzene, toluene, ethylbenzene, and xylene (BTEX) compounds are the most commonly occurring organic contaminants in produced water. The types of contaminants found in produced water and their concentrations have a large impact on the most appropriate type of beneficial use and the degree and cost of treatment required.

Many different types of technologies can be used to treat produced water; however, the types of constituents removed by each technology and the degree of removal must be considered to identify potential treatment technologies for a given application. For some types of produced water, more than one type of treatment technology may be capable of meeting the contaminant removal target; and a set of selection criteria must be applied to narrow down multiple treatment options.

Beneficial uses of produced water include crop irrigation, livestock watering, streamflow augmentation, and municipal and industrial uses. Produced water also can be placed in aquifer storage for future use. The type of beneficial use most appropriate for a produced water application depends on the geographical location of the produced water generation, the location of the beneficial use, and the constituent concentrations in the produced water.

Given the large volumes of produced water generated in the Western United States and the growing need for new water supplies, produced water has the potential to augment conventional water supplies. Produced water, if managed as a resource rather than a waste for disposal, has the potential to be used beneficially.

2. Background

Produced water is defined as the water that exists in subsurface formations and is brought to the surface during oil and gas production. Water is generated from conventional oil and gas production, as well as the production of unconventional sources such as coal bed methane, tight sands, and gas shale. The concentration of constituents and the volume of produced water differ dramatically depending on the type and location of the petroleum product. Produced water accounts for the largest waste stream volume associated with oil and gas production.

2.1 Petroleum Resource Formation and Production

2.1.1 Conventional Oil and Gas

Oil is formed from plant and animal material that accumulates at the bottom of a water supply such as an ocean, river, lake, or coral reef. Over time, this material is buried by accumulating sediment and is pushed deeper into the earth's surface where the pressure increases from the weight of the overlying sediment and the temperature increases due to heat from the earth's core. Oil and gas reservoirs are created when hydrocarbon pyrolysis occurs in a confined layer of porous reservoir material. The confined material restrains the fossil fuel in the subsurface, while the permeable and porous reservoir material allows for accumulation. Oil exists underground as small droplets trapped inside the small void spaces in rock. When a well is drilled into an oil reservoir, the high pressure that exists in the reservoir pushes oil out of the small voids and to the surface.

2.1.2 Unconventional Petroleum Resources

Oil shale, gas shale, tight sands, and coal bed methane are considered unconventional petroleum resources. Oil shale reservoirs are confined in sedimentary formations. Oil shale formations do not convert hydrocarbons into crude oil. Oil shale commonly is refined to produce a cleaner energy product for high grade fuel use. Tight sedimentary formations retain the hydrocarbons requiring energy and water intensive well development. Fracturing polymers in combination with water are injected at high pressures into the reservoir formation. Fracturing is necessary to produce sufficient effective aquifer conductivity to allow the production of economical quantities of oil and gas. The United States has the largest oil shale deposits. The Green River formation in Wyoming, Colorado, and Utah contains the largest oil shale deposit in the United States. Seventy percent of the commercially attractive resource in the Green River formation resides on land managed by the United States Federal Government.

Gas shale also is produced naturally from the shale formation. Gas is stored in fractures, pore space, and adsorbed to the organic reservoir material. Gas shale was first developed by producing it from large fractures in the formations that provided sufficient gas flow for economic development. Recent advances in well completion technology and artificial fracturing have increased the exploration of this resource. Shale gas has been produced for extend periods in the United States in the Illinois and the Appalachian basins. Due to recent advances in technology, the Barnett Shale in Texas also has been highly economical.

Tight sands gas are an unconventional natural gas resource produced from low permeability compacted sediments. Similar to gas shale, advancements in technology have increased the development of tight sands into an economic resource. Gas is tightly contained in the low permeability reservoir formation, and wells must be stimulated to produce from the reservoir formation. Tight sands basins in the United States overlap certain gas shales basins, but there is no coincidence of tight sands in shale gas basins. Tight sands production occurs in the Great Plains, Rocky Mountains, the Four Corners region, onshore gulf coast, and in Arkansas/Oklahoma.

Coal bed methane or coal bed natural gas is an unconventional natural gas resource extracted from coal beds. Methane (CH_4) is formed in the coal seam as a result of both the bacterial processes (biogenic) and the chemical reactions that occur with high temperature and pressure during the bituminization phase (thermogenic). Methane from higher ranking coals is formed by thermogenic production, and lower rank coals produce methane by biogenic production. Additionally, the volume of gas increases with coal rank, depth, and reservoir pressure. Coal has a large surface area per volume, so that coal seams can contain large volumes of gas. Coal seams are capable of containing six to seven times more gas than conventional gas reservoirs of comparable size (Taulis 2007).

Because of the way in which coal is formed, large amounts of coal bed methane exist at shallow depths. The shallow depths make drilling wells for coal bed methane production relatively inexpensive. At greater depths, higher pressure causes fractures in the coal seam to close, making the formations less permeable and more difficult for gas to move through the coal. Many of the coal bed methane basins in the Rocky Mountain region, including the Powder River and the San Juan basins contain subbituminous coals. Subbituminous coal is soft enough that conventional well bores can be used, and the well is drilled to the top of the target coal seam.

The Energy Information Administration publishes estimates of the proved reserves of coal bed methane. The proved reserves represent estimated quantities of coal bed methane (CBM)[1] that analysis of geological and engineering data demonstrate, with reasonable certainty, to be recoverable in future years from known reservoirs under existing economic and operating conditions (United States Energy Information Administration 2007). Actual coal bed methane production data, formation testing, coal core analyses, and other data are used to

[1] Also known as coal bed natural gas.

determine the economic production capacity of the coal formations. It is not necessary that production, gathering, or transportation facilities be installed or operative for a reservoir to be considered proved. Table 1 contains estimates of total and proved reserves for the major coal bed methane producing basins in the Western United States. In general, as more data becomes available and technology advances, the estimated recoverable reserves of CBM increase. Between 2002–2007, the estimated total United States reserves increased by 18 percent (%) based on historical data provided by the U.S. Energy Information Administration (USEIA).

Table 1. CBM recoverable gas reserves and water quality

Basin	Cumulative Production (BCF)[1]	Proved CBM Reserves (BCF)[1]	2008 Average Water Production (million barrels)[2]	Water to Gas Ratio (bbl/MCF)[2]
Powder River	2,314	2,418	718	2.75
Raton	625	2,486	131	1.34
San Juan	13,147	8,446	46	0.031
Uinta	758	1,995	31	0.42
Piceance	41	NA	0.30	1.2

NA – information not available

[1] United States Energy Information Administration 2007; BCF = billion cubic feet.

[2] National Research Council (NRC) Committee on Management and Effects of Coalbed Methane Development and Produced Water in the Western United States 2010; bbl/MCF = barrels per million cubic feet.

2.2 Produced Water Generation and Production

2.2.1 Conventional Oil and Gas

On average, about 7 to 10 barrels, or 280 to 400 gallons, of water are produced for every barrel of crude oil. Formation water (or connate water) exists naturally in the porous aquifer with the hydrocarbons. Formation water generally reflects the water quality associated with the depositional environment for the reservoir—marine, brackish, or continental fresh water. Oil reservoirs commonly contain larger volumes of water then gas reservoirs. This is due to the higher compressibility and sorption capacity of gas. Gas is stored and produced from less porous reservoirs that contain source rock with a lower water capacity. Produced water generation commonly increases over time in conventional reservoirs as the oil and gas is depleted during hydrocarbon production.

2.2.2 Unconventional Resources

Produced water from most unconventional resources is minimal due to tighter reservoir formations, such as in tight sands, oil shale, and gas shale reservoirs. Producers commonly import water to these operations for onsite use in drilling, fracturing, and production. Fresh water used in drilling applications and reservoir fracturing is contaminated by the saline terrestrial water associated with the reservoir depositional environment. Fresh water brought onsite for use in operations, such as flow back or frac water returning from fracturing applications, also is managed as a waste stream. This waste stream commonly is associated with the initial phase of well development and production. In most unconventional oil and gas operations, frac water is considered the largest waste stream of production.

Alternatively, coal bed methane produces the largest volumes of water during gas production as compared to other unconventional hydrocarbon production. The water in coal beds contributes to the pressure in the reservoir that keeps methane gas adsorbed to the surface of the coal. The water must be removed by pumping to lower the pressure in the reservoir and stimulate desorption of methane from the coal. Generally, as the gas production increases, the water production decreases; therefore, the volume of CBM-produced water generated decreases over time. Figure 1 shows the typical water and gas production profile for CBM producing gas wells.

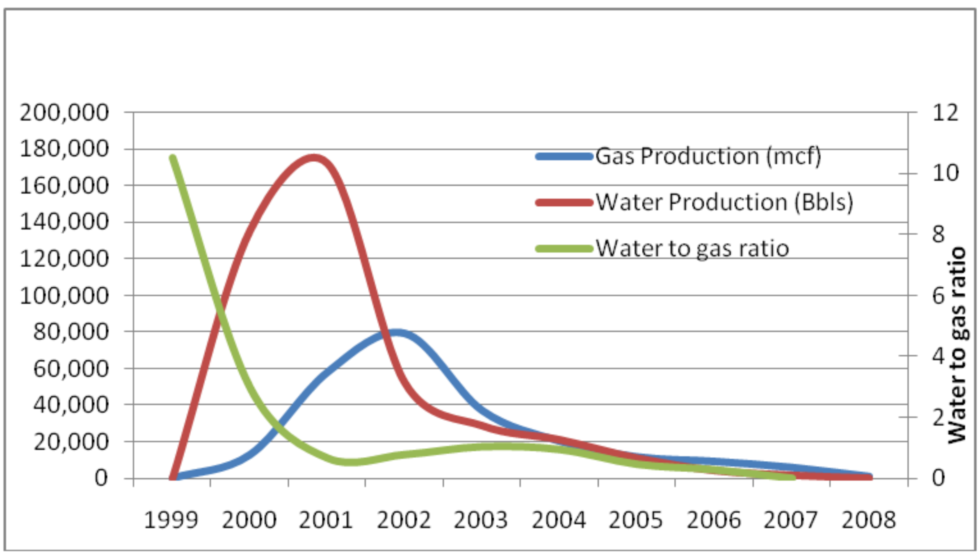

Figure 1. Typical water and gas production for CBM.

Coal beds contain fractures and pores that can transmit large volumes of water. In some areas, coal beds may function as local or regional aquifers and are important sources for ground water (Rice and Nuccio 2000). The volume of water varies significantly from basin to basin. These variations can occur for many different reasons depending on the part the CBM development cycle plays, the rank of the coal, the depth of the coal, and the hydrologic connectivity to other water bearing aquifers. Generally, deeper coal seams will contain less water, but the salinity of the water will be higher. Water to gas ratios are used to describe the volume of water produced per million cubic feet of natural gas. Water to gas ratios are used, along with the estimated recoverable reserves of natural gas, to predict the volume of water that will be generated in each producing basin.

2.3 Current Produced Water Management Practices

Water is considered a byproduct of oil and gas production and generally is treated by the oil and gas industry as a waste for disposal. Produced water management practices are driven by the cost of the hydrocarbon resource. Produced water is the largest volume waste stream associated with oil and gas production. Because produced water is viewed as a waste byproduct to the oil and gas industry, historically, the most commonly practiced management strategies are aimed at disposal rather than beneficial use. The most common practices for produced water disposal include land application or discharge, subsurface injection, and offsite trucking.

- Land application or discharge is a relatively inexpensive method of disposal for produced water. However, this is only an option for relatively high quality produced waters. If the water is of poor quality, contamination of the surrounding soil, water, and vegetation can occur. Regulatory guidelines also must permit land applications.

- Subsurface injection is the industry preferred alternative to produced water disposal. In some cases, re-injection of produce waters is not feasible because the subsurface formation does not have the capacity to receive the water.

- In the event that land application or re-injection is not feasible, the water may be trucked to offsite, re-injection facilities. Re-injection facilities commonly are located around a feasible accepting geologic formation for injection. These facilities sometimes include minor treatment applications aimed at lowering the scaling potential of the reinjection water or modify the chemistry of the water to aid in disposal.

Typically, producers have limited water treatment experience and are hesitant to employ produced water treatment technologies given their negative past experiences. From an oil and gas producer's perspective, the primary concern of beneficial use of produced water as a management strategy is liability; therefore, re-injecting the water into the subsurface formation is the preferred disposal/ management method. However, in some areas, disposal is not possible because the geology of the subsurface formation cannot accommodate the water, or re-injection may cause contamination of other subsurface water supplies. Offsite trucking is another water management strategy preferred by producers from a liability standpoint; however, it is very costly.

2.4 Environmental Impacts Caused by Produced Water

Environmental impacts caused by the disposal of produced water have been reported since the mid-1800s when the first oil and gas wells were drilled and operated. The most commonly reported environmental concerns are as follows: degradation of soils, ground water, surface water, and ecosystems they support (Otton 2006). Because many produced waters contain elevated levels of dissolved ions (salts), hydrocarbons, and trace elements, untreated produced water discharges may be harmful to the surrounding environment.

Large water volumes also can cause environmental impacts through erosion, large land area disposal basins, and pipeline and road infrastructure. Water hauling spills and unplanned discharges are all risks when managing produced water. The volume of the receiving body is critical in determining environmental impacts as ocean discharge offers substantive dilution, while small streams offer low dilution capacity. Physical water properties of concern include temperature, effervescence, low dissolved oxygen concentrations, as well as high and low pH depending on the well type.

Sodium is the most commonly occurring dominant cation in produced water. High sodium levels compete with calcium, magnesium, and potassium for uptake by plant roots; therefore, excess sodium can prompt deficiencies of other cations. Elevated levels of sodium also can cause poor soil structure and inhibit water infiltration in soils (Davis, Waskom et al. 2007). Infiltration into shallow ground water sources is also a concern when water is applied for irrigation use. Mineral accumulation due to subsurface ion exchange can change the water quality of shallow, underlying aquifers.

Trace elements, including boron, lithium, bromine, fluorine, and radium, also occur in elevated concentrations in some produced waters. Many trace elements are phytotoxic and are adsorbed in the soil. These elements may even remain in soils after the saline water has been flushed away. Radium-bearing scale and sludge found in oilfield equipment and discarded on soils pose additional hazards to human health and ecosystems. Meteoric water applied to contaminated soils has the potential to solubilize metals and transport them through the subsurface. Precipitation of metals and metal solubility are important considerations in applying these constituents to soils.

2.5 Study Objectives

The objectives of this project are as follows:

(1) Describe the characteristics of produced water: constituent concentration and volumes produced.

(2) Identify potential beneficial uses of produced water and the geographical relationship between produced water generation and potential beneficial uses. Three case studies are presented.

(3) Identify constituents in produced water that exceed water quality requirements of beneficial uses and constituents that will be problematic for treatment of produced water

(4) Evaluate produced water treatment technologies (organic/particulate removal technologies, desalination, brine management technologies, and post-treatment or stabilization technologies) and describe benefits and limitations of each technology based on produced water specific design requirements.

3. Conclusions and Recommendations

Produced water is generated in large volumes across the Western United States from both conventional and unconventional petroleum production with the majority of the water produced in Texas, Oklahoma, Kansas, California, and the Rocky Mountain region including Montana, Wyoming, Utah, Colorado, and New Mexico. Given the large volume of water generated during operations, produced water could be considered an alternative water resource in locations experiencing water shortage.

Produced water could be used to augment conventional water supplies for use in irrigation and livestock watering, streamflow augmentation, and industrial applications. Water quality issues may need to be addressed for produced water to be used for these beneficial uses. For agricultural purposes, most produced water sources contain elevated levels of sodium and high conductivity that require treatment to eliminate the possibility of damage to crops and livestock. In some states, produced water volumes are large enough to make a significant contribution to the water demand for irrigation and livestock.

Numerous treatment technologies have been suggested for produced water. This document provides a qualitative comparison of the different technologies and provides guidance on the benefits and limitations of each technology. Water quality constraints and site-specific design criteria should be used to select the most appropriate treatment technology for a given produced water source and desired beneficial use.

Three case studies were presented, which illustrate the large potential for beneficial use in the Western United States for different types of applications: agriculture, stream low augmentation, and industrial use. Appropriate management techniques will allow produced water to be used as a resource rather than treated as a waste to meet the growing water demand in the Western United States.

This work, along with research conducted by others (through the Department of Energy, National Energy Technology Laboratory, and the Research Partnership to Secure Energy for America), has thoroughly evaluated produced water occurrence, quality, quantity, beneficial uses of produced water, and produced water treatment technologies. Future work should focus on simultaneously considering all of this information to develop site-specific produced water management strategies that are both environmentally and economically efficient.

4. Geographical Occurrence of Produced Water

4.1 Conventional Oil and Gas Resources

Conventional oil and gas resources are explored across the United States. In 2008, the U.S. Energy Information Administration estimated that 363,107 oil wells and 460,261 gas wells were producing in the United States. Of the wells in operation, 78% of the oil wells and 65% of the gas wells produced 10 barrels of energy (BOE) per day or less. Conventional resources are not commonly produced by a few wells with excellent production numbers. Instead, since a majority of wells produce less energy per day, production is compensated by drilling dense well populations to increase production in a field. The large quantity of wells also contributes to a large volume of produced water generated. The geographic location of oil and gas wells within the United States is shown in the context of the major producing basins and the top producing oil and gas wells; see figure 2.

Conventional oil and gas wells in the Western United States represented 86% of the total oil and 72% of the total gas wells nationwide in 2008. States in the Western United States containing more than 25,000 oil wells include California, Kansas, Oklahoma, and Texas, while States containing more than 25,000 gas wells include Colorado, Kansas, New Mexico, Oklahoma, Texas and Wyoming. Conventional oil and gas wells in the Western States are presented in figures 3 and 4. As mentioned previously, oil reservoirs commonly contain larger volumes of water then gas reservoirs. For conventional wells, States with the largest volumes of produced water quantities should include California, Kansas, Oklahoma, and Texas.

Conventional well fields across this Western United States are tabulated in table 2. The 22 basins recognized are included based on the number of wells associated with each basin. This table is not comprehensive to all oil and gas basins, which exist in this region. Idaho, Nevada, Oregon, and Washington are not included in the State distribution in table 2, due to the absence or small number of oil and gas wells in these locations. The USEIA does report that 20 gas wells exist in the State of Oregon and 73 oil wells in the State of Nevada. It also should be noted that oil and gas operations also exist off shore in the Gulf of Mexico, off of Texas-Louisiana, and the Pacific Ocean off the coast of California. These wells and basins are not included in this assessment of Western State resources; however, information on these coastal basins and wells is available through the USEIA.

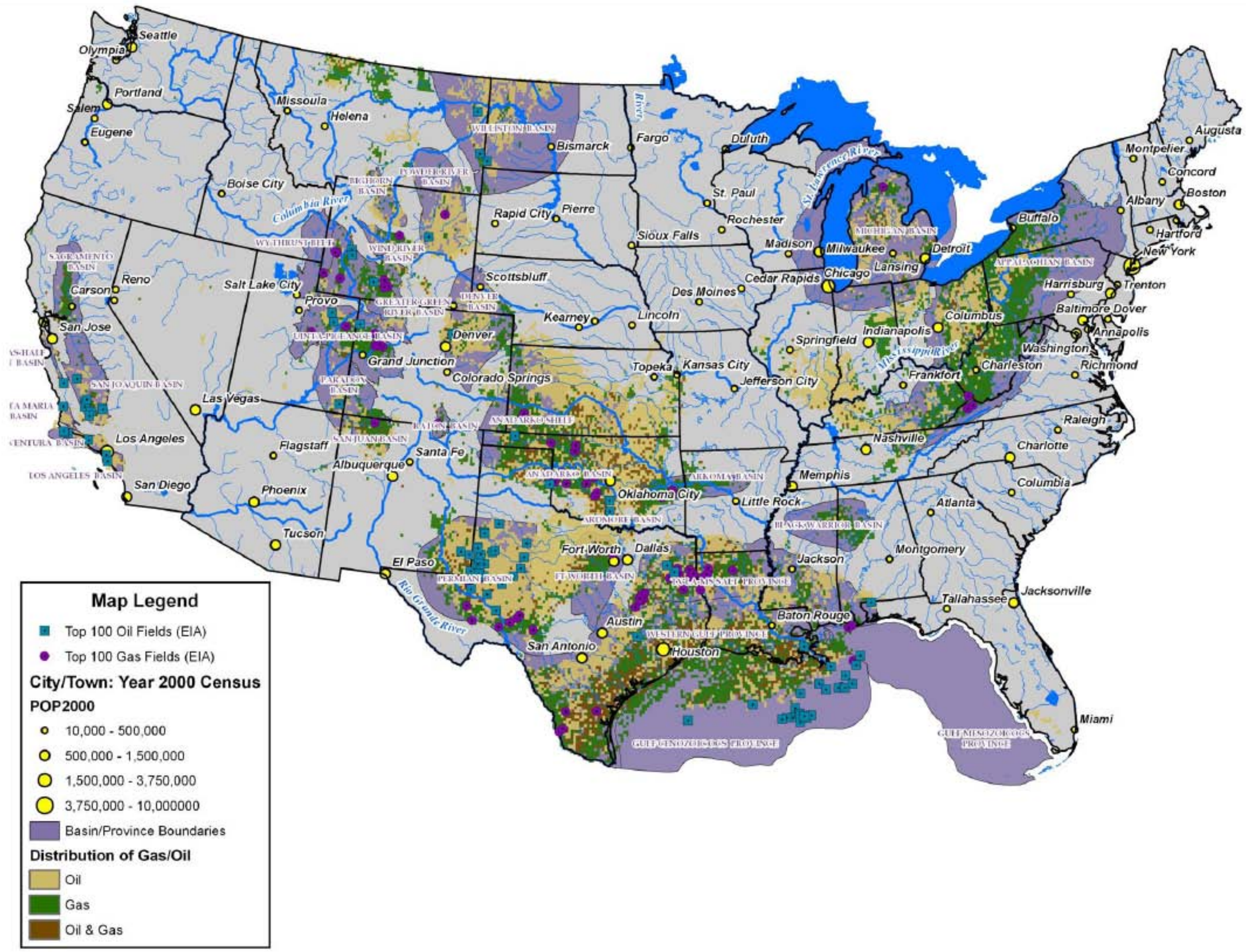

Figure 2. Geographic location of major oil and gas producing wells and basins in the United States.

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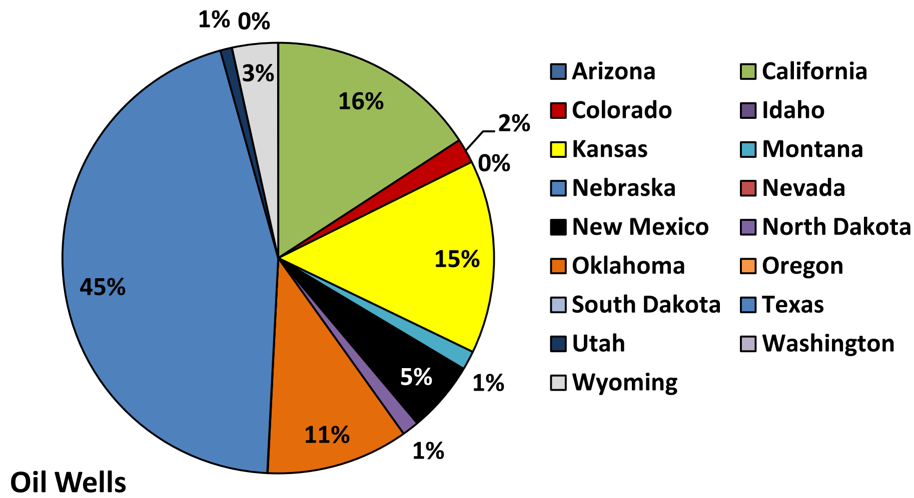

Figure 3. Geographic distribution of oil wells in the Western United States.

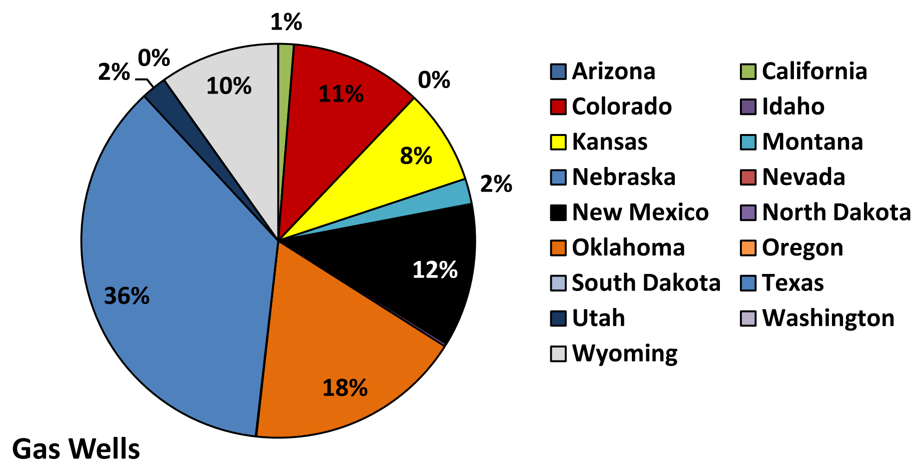

Figure 4. Geographic distribution of conventional gas wells in the Western United States.

Table 2. Geographic location of conventional oil and gas resources in the Western United States

Basins	AZ	CA	CO	KS	MT	NE	NM	ND	OK	SD	TX	UT	WY
Anadarko			X	X					X		X		
Ardmore									X				
Bighorn					X								X
Denver			X			X			X			X	
Forest City-Cherokee-Arkoma						X			X				
Greater Green River			X									X	X
Los Angeles		X											
Montana Thrust Belt					X								
Palo Duro											X		
Paradox			X									X	
Permian							X				X		
Piceance			X										
Powder River					X								X
Raton			X				X						
Sacramento		X											
San Juan	X		X				X					X	
Uinta												X	
Ventura		X											
Western Gulf											X		
Williston					X			X		X		X	
Wind River													X
Wyoming Thrust Belt												X	X

4.2 Unconventional Oil and Gas Resources

Unconventional oil and gas resources are produced nationwide. The unconventional resources focused upon in this report include oil shale, gas shale, tight sands gas, and coalbed methane. Table 3 summarizes the locations of 5 oil shale, 16 gas shale, 8 tight sands gas, and 6 coalbed methane basins in the Western United States. Again, Idaho, Nevada, Oregon, and Washington are not included in the State distribution in table 3, due to the absence or small number of wells in these locations. General summaries of the geographic distribution of unconventional wells are provided by unconventional resource in the following text.

4.2.1 Oil Shale

Oil shale basins in the Western United States are limited to Colorado, Utah, and Wyoming. The large water volumes associated with oil shale production originate from fracture watering. Fracturing water is primarily used during well development. This water represents a large volume over a small period of time, which is often difficult to manage.

4.2.2 Gas Shale

Basins occur in the Western United States in 10 states. Texas, New Mexico, Oklahoma, Montana, and Utah contain the largest number of individual basins. Gas shale basins commonly overlap other unconventional resources such as coalbed methane. Gas shale layers commonly act as aquitards and confining layers to coal seams. The Raton, San Juan, Uinta, and Piceance all contain both resources. Specific gas plays are recognized in table 3 to differentiate these unconventional resources.

4.2.3 Tight Sands Gas

Basins are located in eight Western States and do not extend north of Wyoming or west of Utah. Colorado and Texas include the greatest number of basins. Specific gas plays are recognized in table 3 for tight sands gas as well. Similar to oil shale and gas shale, water production during gas production in this resource is low. Water is primarily associated with well development during artificial reservoir fracturing.

4.2.4 Coalbed Methane

Western basins are located along the Rocky Mountain regions of the United States in Colorado, New Mexico, Utah, Wyoming, and Montana. The coal formations are commonly associated with conventional oil and gas as well as unconventional

Table 3. Geographic location of unconventional oil and gas resources in the Western United States

Oil Shale

Basin	AZ	CA	CO	KS	MT	NE	NM	ND	OK	SD	TX	UT	WY
Great Divide													X
Green River			X									X	X
Piceance			X										
Uinta			X									X	
Washakie			X										X

Gas Shale

Basin	Specific Gas Plays	AZ	CA	CO	KS	MT	NE	NM	ND	OK	SD	TX	UT	WY
Anadarko	**Woodford**									X				
Arkoma	**Woodford-Caney, Fayetteville**									X				
Big Horn	**Mowry**					X								X
East Texas Salt	**Haynesville**											X		
Forest City-Cherokee-Arkoma	**Excello-Mulky**				X					X				
Ft. Worth	**Barnett**											X		
Greater Green River	**Hillard-Baxter-Mancos**			X									X	X
Maverick-Rio Grande Embayment	**Pearsall-Eagle Ford**											X		
Montana Thrust Belt	**Cody**					X								
Palo Duro	**Bend**											X		
Paradox	**Hermosa**												X	
Permian-Marfa	**Barnett-Woodford**							X				X		
Raton	**Pierre**			X				X						
San Juan	**Lewis**							X						
Uinta-Piceance	**Mancos**												X	
Williston	**Gammon**					X			X		X			

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Table 3. Geographic location of unconventional oil and gas resources in the Western United States (continued)

Tight Sands Gas

Basin	Specific Gas Plays	AZ	CA	CO	KS	MT	NE	NM	ND	OK	SD	TX	UT	WY
Anadarko	Cleveland, Red Fork, Granite Wash									X		X		
Denver	Muddy J, Niobrara Chalk			X	X		X							X
Ft. Worth	Davis											X		
Permian	Abo, Penn-Perm Carbonate, Morrow, Thirty-one, Ozona Canyon							X				X		
Piceance	Mesaverde, Mancos-Dakota			X									X	
San Juan	Mesaverde, Pictured Cliffs, Dakota			X				X						
Uinta	Wasatch-Mesaverde, Mancos-Dakota			X									X	
W. Gulf Coast	Wilcox Lobo, Olmos, Stuart City-Edwards, Vicksburg											X		
W. Gulf Coast-Texas-Louisiana-Mississippi Salt	Austin Chalk, Travis Peak, Bossier, Cotton Valley, Gilmer Lime											X		

Coalbed Methane

Basin	Coal Formations	AZ	CA	CO	KS	MT	NE	NM	ND	OK	SD	TX	UT	WY
Piceance	Mesaverde Group			X										
Powder River	Wasatch, Fort Union					X								X
Raton	Vermejo, Raton			X				X						
San Juan	Fruitland			X				X						
Sand Wash	Iles, Williams Fork, Fort Union, Wasatch			X										X
Uinta	Mancos Shale, Mesaverde Group			X									X	

resources such as gas shale. Coal formations specific to coalbed methane production are provided in table 3. Coalbed methane represents the largest water contributor over a well lifetime of all the unconventional resources. Produced water volumes from unconventional resources are primarily from coalbed methane well production. In further sections, produced water from unconventional resources will be limited to coalbed methane.

4.3 Geographic Distribution of Produced Water Generation

Over 80% of the produced water generated nationwide is produced in the Western United States. Conventional and unconventional resources contribute to produced water volumes. Figure 5 relates conventional and unconventional well numbers to one another by State locations. The geographic distribution of water volumes should follow a similar trend the well population of each State. It is expected that conventional oil wells will have a larger impact than conventional gas wells on produced water volumes. Therefore, it is expected that California, Kansas, Oklahoma, and Texas will produce large amounts of produced water due to the number of conventional wells present in these States.

Coalbed methane wells in Wyoming, Montana, New Mexico, and Colorado also contribute to the produced water volumes generated by each State.

Figure 6 summarizes the produced water quantities by State. Wyoming is associated with the second highest volumes for produced water in the Western United States. Wyoming generates substantial quantities of water due to the large number of coalbed methane wells in the Powder River basin. Conventional oil and gas wells supplement this volume; however, the unconventional wells represent a significant contribution. Texas dominates total well numbers in conventional resources with 45% of the gas and 36% of the oil wells in the Western United States. Texas also dominates the produced water generation at 44% or 236,914 thousand acre-feet per year. This is a significant water volume for the State. If produced water is managed as a water resource instead of a waste product, the volumes generated annually in each State could supplement the water supply required.

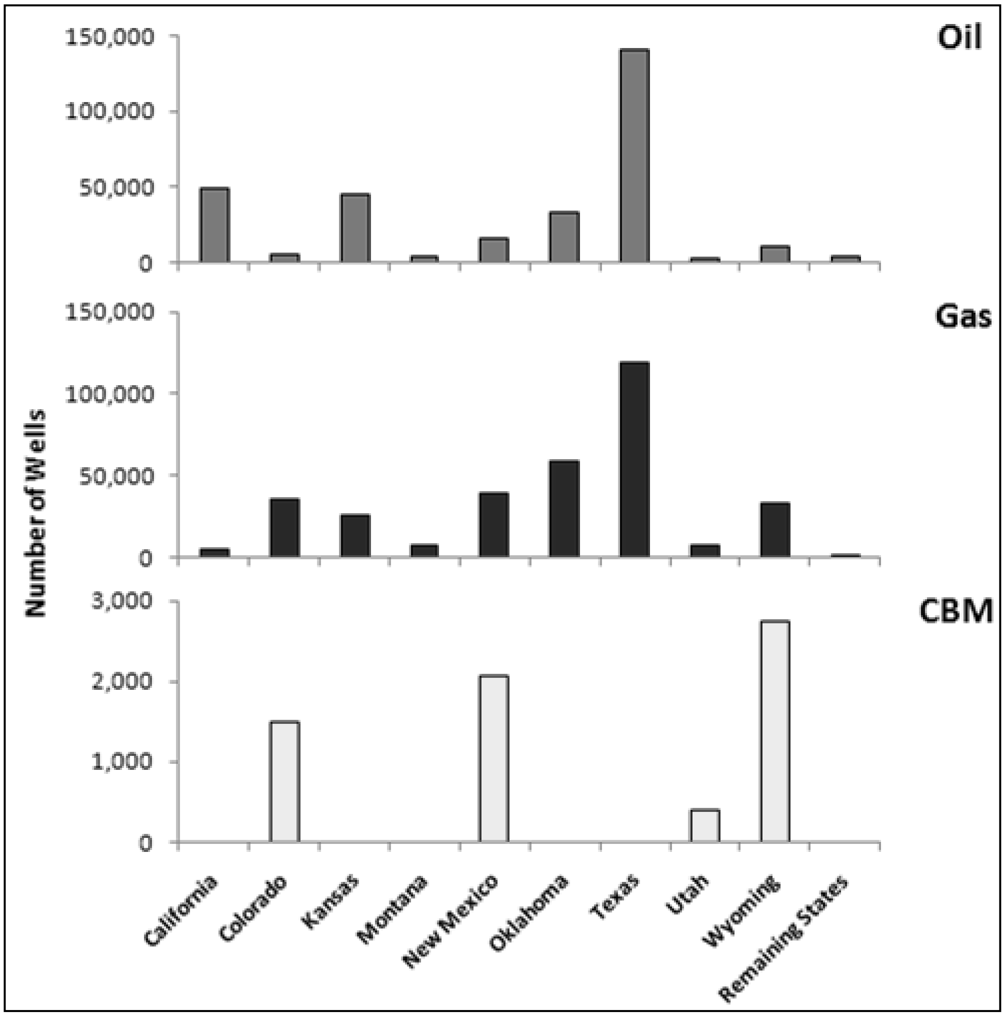

Figure 5. Conventional and unconventional well distribution by State.

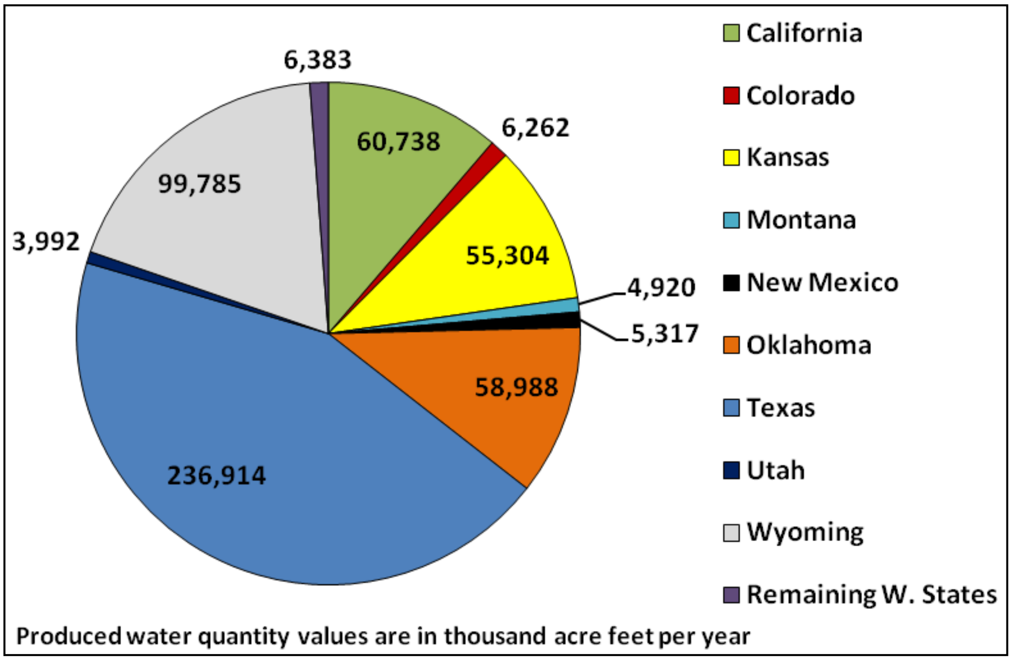

Figure 6. Produced water quantities by State in the Western United States.

5. Beneficial Uses of Produced Water

The Nation faces an increasing set of water resource challenges: aging infrastructure, rapid population growth, depletion of ground water resources, impaired water quality associated with particular land uses and land covers, water needed for human and environmental uses, and climate variability and change. All play a role in determining the amount of fresh water available at any given place and time (WaterSMART). Figure 7 shows the areas of the Western United States that have the potential for conflict over water. With appropriate treatment and management strategies, produced water has the potential to augment conventional water supplies.

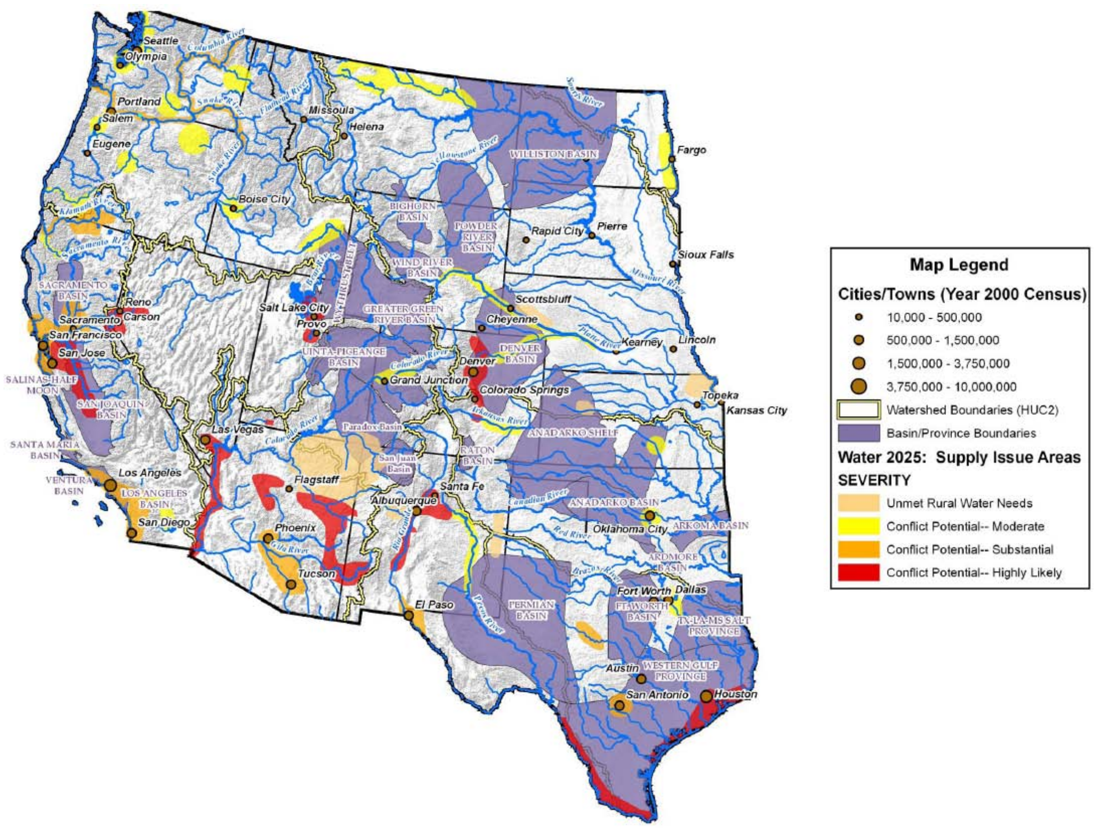

Figure 7. Overlay of oil and gas producing basins and areas with a potential for water conflict.

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5.1 Produced Water Use

Although produced water from oil and gas wells commonly is considered a high volume, high salinity waste stream, produced water has the potential to be used to offset water demands and over allocation of water supplies. Waste stream management is necessary to continue hydrocarbon production from oil and gas wells. Therefore, for use of produced water for beneficial purposes to be effective, the value of produced water must be assessed in each use scenario. The value of treating and managing produced water to be used for beneficial purposes will, therefore, depend on the specific situation including the water volume, water characteristics, and proposed use.

Produced water operators include extensive costs in the handling and management of produced water. Costs include bringing the water to the surface, re-injecting the water into the formation for disposal, and transporting the large amounts of water to injection wells. Often, transportation of large water volumes is so expensive that produced water may be treated onsite, including desalination, for less cost. Treatment onsite, even with the creation of a brine or concentrate waste stream, minimizes the total waste volume that requires injection. Furthermore, treatment creates a product of sufficient quality to alleviate dependences on local fresh water sources for many applications. Water volumes available from oil and gas production and potential beneficial uses of produced water are outlined in this chapter.

5.2 Produced Water Volumes Compared to Use Demands

To determine how produced water volumes compare relative to water use in the United States, information from two studies was used. The first study provided comprehensive information on produced water in a report from the U.S Department of Energy (DOE), entitled "A White Paper Describing Produced Water from Production of Crude Oil, Natural Gas, and Coal Bed Methane." This publication estimated the annual onshore U.S. produced water volumes for 1985, 1995, and 2002. The U.S. Geological Survey (USGS) also has done comprehensive studies on water use in the United States for 2000 and 2005. Combining the data provided in those studies, the following information was extracted for the Western United States.

Volumes of fresh water used annually in the Western States range from an estimated 600 thousand acre-feet per year (AFY) in South Dakota to 43,000 thousand AFY in California. Water supply uses are presented by State in figure 8. Water usage in the Western United States is dominated by irrigation in most States. State specific trends in water use include elevated water consumption for thermoelectric power generation in Kansas, Nebraska, and

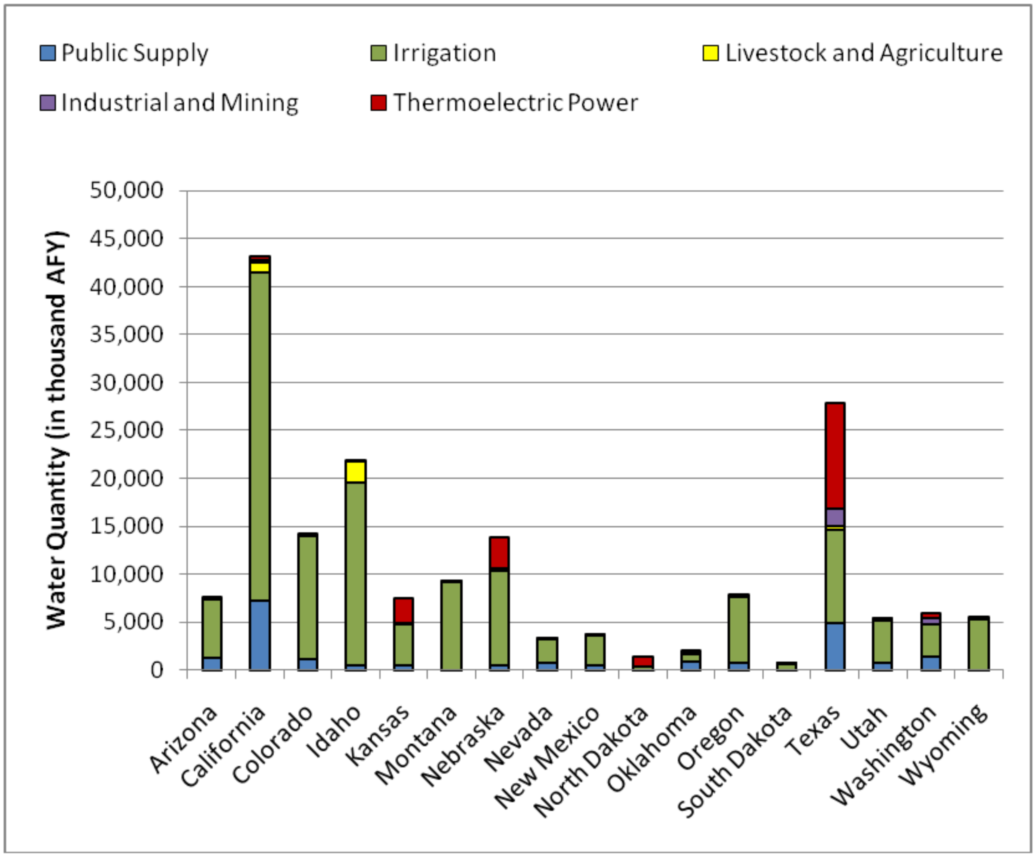

Figure 8. Fresh water usage in the Western United States.

Texas. Texas also uses significant water quantities for mining applications. California and Texas, meanwhile, use more water for public supply and consumption than Western States such as Nevada, New Mexico, North Dakota, Oklahoma, and South Dakota, use annually.

Significant oil and gas production takes place in the arid regions of the Western United States, consequently, producing large annual quantities of produced water. In the Western United States, produced water volumes have the potential to contribute to the overall water supplies utilized by each State. Produced water production was estimated in 2002, to be 1,487 AFY in the Western United States. The largest produced water production, in Texas, is almost double the quantity used in the state for livestock and agriculture (table 4). Due to arid to semi arid climates in these regions, there is an increased value for new water sources.

Although a potential value exists for treated water sources, in the United States, more than 98% of produced water from onshore wells is re-injected (Clark and Veil 2009). A number of options are available locally as potential uses of this water. The following section outlines potential beneficial uses of produced water and includes information on water quantities and quality requirements.

Table 4. Water use and produced water generation in the Western United States

State	Public Supply	Irrigation	Livestock and Agriculture	Industrial, Mining, Thermo-electric	Total Water Use	Produced Water Generated
Arizona	1,242	6,060		230	7,533	0.01
California	7,180	34,200	1,061	632	43,073	168
Colorado	1,085	12,800		290	14,174	17
Idaho	370	19,100	2,249	62	21,781	0
Kansas	490	4,160	130	2,628	7,409	153
Montana	188	8,920		192	9,300	14
Nebraska	424	9,860	105	3,347	13,737	7
Nevada	730	2,360		53	3,143	0.4
New Mexico	367	3,210		75	3,652	15
North Dakota	85	163		1,031	1,278	10
Oklahoma	786	804	187	196	1,972	163
Oregon	720	6,810		236	7,765	0
South Dakota	116	418	47.1	12	592	0.4
Texas	4,887	9,680	346	12,880	27,793	654
Utah	733	4,330	130	147	5,340	11
Washington	1,280	3,400		1,229	5,909	0
Wyoming	126	5,050		368	5,544	276
TOTAL	20,808	131,325	4,256	23,608	179,996	1,487

Note: Water volumes are in 1,000 AFY.

5.3 Beneficial Uses of Produced Water

The following outlined beneficial uses of produced water do not represent a comprehensive list but are provided as examples of application scenarios for produced water. These examples were chosen due to the variable nature of the consumer, water quantity requirements, and water quality criteria. Although not discussed in detail within this report, ownership of produced water first must be assessed, and proper permitting must be acquired to execute a beneficial use of produced water. Information on regulatory guidelines and permitting is available through the DOE's National Energy Technology Laboratory online Web site

"Produced Water Management Information System" created by Argonne National Laboratories as a resource for technical and regulatory information for managing produced water, including current practices, State and Federal regulations, and guidelines for optimal management practices (Veil).

5.3.2 Livestock Watering

In 2000, it was estimated that livestock water use represented for livestock watering, feedlots, dairy operations, and other on-farm needs such as cooling of facilities for the animals and products, dairy sanitation and wash down of facilities, animal waste-disposal systems, and incidental water losses constituted 1,760 million gallons per day of fresh water (USGS 2005). This represented less than 1% of the total water use in the United States in 2000; however, 50% of that consumption was used by California, Texas, and Oklahoma (USGS 2005). These states represented 53% of the produced water production in 2002 nationally (Clark and Veil 2009).

Livestock water requirements depend on the animal and are influenced by several factors such as activity, feed intake and environmental temperature (Lardy, Stoltenow et al. 2008). Table 5 is a summary of water volumes required for different species. Water requirements vary throughout the year; and the gender and size of an animal also impacts the estimated water consumption. To encompass these variations, table 5 provides an estimated range of daily water consumption for each livestock species. For grazing species, such as cows and horses, water sources throughout grazing land are important in ranching regions.

Table 5. Water intake volumes for livestock

Livestock	Water Intake	Units
Cattle	3.5 to 23.0	Gallons per day
Sheep	1.5 to 3.0	Gallons per day
Swine	0.5 to 5.5	Gallons per day
Horses	6.0 to 18.0	Gallons per day

While livestock can tolerate water of a lesser quality than humans, some important considerations must be made evaluating a potential water source. High levels of specific ions and salinity can harm the animals. The National Academy of Sciences offers upper limits for toxic substances in water (see table 6). Additional constituent concentrations and maximum levels that should be noted include sulfate and alkalinity not to exceed 2,000 mg/L and pH ranging between 5.5–8.5 for livestock watering.

Table 6. National Science Foundation recommended levels of specific constituents for livestock drinking water

Constituent	Upper Limit (mg/L)
Aluminium	5
Arsenic	0.2
Beryllium	No data available.
Boron	5.0
Cadmium	0.05
Chromium	1.0
Cobalt	1.0
Copper	10.5
Fluorine	2.0
Iron	No data available
Lead	0.1
Manganese	No data available
Mercury	0.01
Molybdenum	No data available
Nitrate + nitrite	100
Nitrite	10
Selenium	0.05
Vanadium	0.10
Zinc	24
Total dissolved solids	10,000

The total dissolved solid (TDS) cutoff concentration listed in table 6 of 10,000 mg/L is the maximum concentration in water above which it is not recommended for livestock watering use. Table 7 includes additional information on TDS levels for livestock (Lardy, Stoltenow et al. 2008). Specific TDS categories are outlined in table 7 because TDS requirements vary between species, with certain species being more susceptible to the impacts of saline water consumption than others. Also, table 7 notes the relative time periods water of certain quality may be utilized. It is important to consider not only the water quality but also the duration of consumption when predicting adverse effects.

Table 7. TDS categories for livestock water

TDS Category	TDS Range[1]	Description
Level 1	< 1,000	Satisfactory
Level 2	1,000 to 2,999	Satisfactory, slight temporary illness
Level 3	3,000 to 4,999	Satisfactory for livestock, increased poultry mortality
Level 4	5,000 to 6,999	Reasonable for livestock, unsafe for poultry
Level 5	7,000 to 10,000	Unfit for poultry and swine, acceptable short term for livestock
Level 6	> 10,000	Not recommended

[1] < = less than; > = greater than.

Water quality is an important consideration for livestock watering. Meeting limits for specific constituents is necessary to provide protection of livestock consuming produced water, and treatment is often necessary to meet requirements. Although water requirements for livestock watering are relatively low, oil and gas wells drilled on property leased from farmers and ranchers represent a local source of water available for use. The use of produced water for livestock watering is convenient, given large ranching areas in areas producing large volumes of produced water. These overlapping areas include States such as Oklahoma, Wyoming, Texas, and California.

5.3.3 Irrigation

In most States, irrigation represents the majority of fresh water use. In estimates for the Western United States in 2000, irrigation represented over 70% of total state water usage (USGS 2005). Water used for irrigation is less easily recovered than water used for public consumption. Water loss occurs through transpiration from plants and through evaporation, while irrigating or during transport. Nationally, 59% of irrigation water is supplied from surface water sources; while in the Western United States, 64% is supplied from surface water resources. Almost a quarter of the 5% discrepancy between the Western United States and the Nation reliance on surface water sources could be supplied by produced water resources discharged into streams and channels to be used downstream for uses such as irrigation.

Irrigation not only requires large water volumes, but also has stringent water quality criteria. Specifically for produced water, parameters such as the sodium adsorption ratio are important criteria for ensuring that the water quality is sufficient to not damage crops. The sodium absorption ratio (SAR) is a calculation of the suitability for a water source for irrigation. The equation for the calculation is:

$$SAR = \frac{[Na^+]}{\sqrt{\frac{[Ca^{+2}]+[Mg^{+2}]]}{2}}} \qquad (1)$$

The concentrations of sodium (Na^+), calcium (Ca^{+2}), and magnesium (Mg^{+2}) are in milliequivalents per liter. When irrigation water has high SAR values, above three, then much more control of salt accumulation is needed. Water with high SAR can be used if enough water is applied to wash the salts down below the root zone of the crops.

The SAR and electrical conductivity (EC_w) of the water must be considered together to determine the probable affect of using the water for irrigation (Ayers and Westcot 1994) (see figure 9). When the source water has a higher conductivity, then there is a greater potential for salt damage at lower SAR levels. EC_w normally is expressed as decisiements per meter (dS/m), which is the same as siemens per centimeter (S/cm). Given the saline nature of produced water with high sodium content the SAR and EC_w are both important parameters to consider before use.

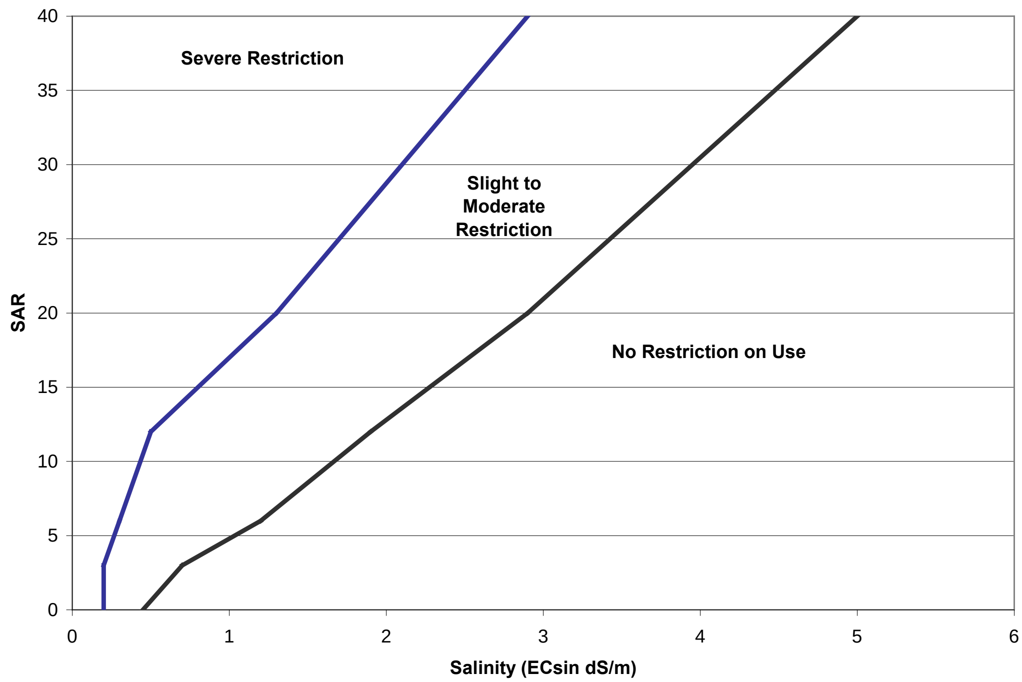

Figure 9. Suitability of water for irrigation (adapted from Ayers and Westcot 1994).

Boron is also important to consider when identifying the healthy range for most plants. The Food and Agriculture Organization publication, Water Quality for Agriculture, outlines boron concentration considerations for various types of crops (Ayers and Westcot 1994). Boron concentration limits are summarized in table 8.

Table 8. Crop tolerance to boron in irrigation water

Tolerance Level	Range of Boron Concentration	Crops
Very Sensitive	< 0.5 mg/L	Lemon, blackberry
Sensitive	0.5–0.75 mg/L	Avocado, grapefruit, orange, apricot, peach, cherry, plum, persimmon, fig, grape, walnut, pecan, cowpea, onion
Sensitive	0.75–1.0 mg/L	Garlic, sweet potato, wheat barley, sunflower, mung bean, sesame, lupine, strawberry, jerusalem artichoke, kidney bean, lima bean, peanut
Sensitive	1.0–2.0 mg/L	Red pepper, pea, carrot, radish, potato, cucumber
Moderately tolerant	2.0–4.0 mg/L	Lettuce, cabbage, celery, turnip, kentucky bluegrass, oats, maize, artichoke, tobacco, mustard, sweet clover, squash, muskmelon
Tolerant	4.0–6.0 mg/L	Sorghum, tomato, alfalfa, purple vetch, parsley, red beet, sugarbeet
Very tolerant	60–15.0 mg/L	Cotton, asparagus

Specific constituent criteria for irrigation waters are outlined in table 9. The table outlines minor constituents that may be prohibitive to plant growth used at concentrations above those listed for short- and long-term applications. In addition to these constituents, the following constituents and parameters also are identified as potentially detrimental at high concentrations to crops (Texas Coorperative Extension 2003):

- pH normal range 6.5–8.4
- Chloride < 70 parts per million (ppm) generally safe for all plants
- Nitrate < 10 ppm nitrate nitrogen (NO_3-N), 45 ppm nitrate (NO_3)

5.3.4 Stream Flow Augmentation

Although previously discussed in the context of irrigation, the discharge of produced water into streams provides more benefits than just the use of a surface water body as a conduit. Streamflow augmentation is the addition of waters to surface bodies to supplement low flows, thereby sustaining the surface body ecosystem. When not provided by precipitation or runoff, surface bodies are primarily derived from ground water. Urbanization has lead to changes in the ground water gradient, which may result in streams shifting from perennial, biologically rich streams to ephemeral streams (Shaver, Horner et al. 2007). Additionally, climate variations also affect surface water flows. Produced water may be used to sustain stream flow levels during low flow periods.

Table 9. Constituent limits for irrigation water (adapted from Rowe and Abdel-Magid, 1995)

Constituent	Long-term Use (mg/L)	Short-term Use (mg/L)
Aluminum (Al)	5	20
Arsenic (As)	0.1	2
Beryllium (Be)	0.1	0.5
Boron (B)	0.75	2
Cadmium (Cd)	0.01	0.05
Chromium (Cr)	0.1	1
Cobalt (Co)	0.05	5
Copper (Cu)	0.2	5
Fluoride (F)	1	15
Iron (Fe)	5	20
Lead (Pb)	5	10
Lithium (Li)	2.5	2.5
Manganese (Mn)	0.2	10
Molybdenum (Mo)	0.01	0.05
Nickel (Ni)	0.2	2
Selenium (Se)	0.02	0.02
Vanadium (V)	0.1	1
Zinc (Zn)	2	10

The quantity of water required to augment low stream flows is specific to the water body of application and the natural variations in water flow. For instance, creation of a perennial stream from a historically ephemeral stream using produced water flows may create an unsustainable ecosystem, because, as wells are abandoned, water sources will no longer be available. Over allocated water resources, where water taken from a surface body exceeds the flow or water sources where downstream users are in need of additional flow when available, are ideal situations for produced water augmentation. Produced water could be used to offset water use in surface bodies downstream from production, resulting in cheap transport of the water along a watershed and further dilution of the water through mixing with existing flow.

Important parameters to consider for this water management technique include impacts of elevated flows, which may include adverse affects such as erosion, total quantity losses due to evaporation, and impacts on the ecosystem based on water quality and physicochemical characteristics. Physical characteristics of the water that have potential to impact the ecosystem and aquatic life in a surface water body include temperature and dissolved oxygen (DO) levels resulting in high biological and chemical oxygen demand (BOD and COD). Depending on the species and application, water is expected to have DO levels from 3.0 to above 7.0 mg/L prior to discharge (Shaver 2007, #88). Additionally, salinity and specific constituents also must be managed to protect the ecosystem. Table 10 outlines constituents for aquatic life requirements and includes values for both chronic and acute toxicity, which are commonly dictated by the water hardness (Colorado Department of Public Health and Environment 2010).

5.3.5 Rangeland Restoration

Rangelands consist of shrubs and grasses and covers approximately 50% of the land surface in the United States. The most common use for rangelands is livestock grazing. Overstocking and drought are two of the causes of rangeland degradation. Degradation of rangeland also is caused by improper use of vehicles and other industrial activity and changing weather patterns resulting in drought.

Produced water can be applied to rangeland to help the natural biotic community to reestablish vegetation and to increase the response of the native species (Fox and Burnett 2002) . SAR is an important criterion for using produced water for rangeland restoration. Similarly to irrigation water, high SAR values can further damage soils; therefore, treatment may be required for some produced water sources to be used for rangeland restoration.

5.3.6 Industrial Uses

5.3.6.1 Reuse in Oil and Gas Operations

Reuse of produced water on site at oil and gas operation includes multiple applications, such as well drilling, hydraulic fracturing, secondary oil recovery, and sustaining aquifer pressure, which require large water volumes. Use of fresh water supplies in these practices may be minimized by treating and recycling produced water resources. Well head generation makes the resource available on site lowering transportation and trucking costs. Therefore, the market for treating produced water on site to meet water quality standards for use becomes economical as costs are compared to the cost of trucking fresh water on site at the volumes required for these operations. Water treated at a produced water collection point in a well field represents a local source of water commonly in closer proximity to most wells than fresh water sources. Although many onsite uses exist, two uses, well development through hydraulic fracturing and secondary recovery through enhanced oil recovery techniques, are described here in more detail.

Fracturing Water.—Unconventional resources commonly exist in subsurface formations with low permeability. Stimulation, in the form of hydraulic fracturing, is required to enhance permeability and allow for commercial production of the hydrocarbon resource. Hydraulic fracturing is the creation or extension of natural fractures in the formation material. Fractures increase the formation permeability as gas may flow unabated through these conduits to the wellhead. To create or extend naturally occurring fractures, pressurized hydraulic

Table 10. Acute and chronic concentration levels by hardness

	Mean Hardness in mg/L Calcium Carbonate									
	25	**50**	**75**	**100**	**150**	**200**	**250**	**300**	**350**	**400**
Aluminum										
Acute	512	1,324	2,307	3,421	5,960	8,838	10,071	10,071	10,071	10,071
Chronic	73	189	329	488	851	1,262	1,438	1,438	1,438	1,438
Cadmium										5.7
Acute	0.8	1.5	2.1	2.7	3.9	5	6.1	7.1	8.1	9.2
Chronic	0.15	0.25	0.34	0.42	0.58	0.72	0.85	0.97	1.1	1.2
Chromium										
Acute	183	323	450	570	794	1,005	1,207	1,401	1,590	1,773
Chronic	24	42	59	74	103	131	157	182	207	231
Copper										
Acute	3.6	7	10	13	20	26	32	38	44	50
Chronic	2.7	5	7	9	13	16	20	23	26	29
Lead										
Acute	14	30	47	65	100	136	172	209	245	281
Chronic	0.5	1.2	1.8	2.5	3.9	5.3	6.7	8.1	9.5	11
Manganese										
Acute	1,881	2,370	2,713	2,986	3,417	3,761	4,051	4,305	4,532	4,738
Chronic	1,040	1,310	1,499	1,650	1,888	2,078	2,238	2,379	2,504	2,618

Table 10. Acute and chronic concentration levels by hardness (continued)

	Mean Hardness in mg/L Calcium Carbonate									
	25	**50**	**75**	**100**	**150**	**200**	**250**	**300**	**350**	**400**
Nickel										
Acute	145	260	367	468	660	842	1,017	1,186	1,351	1,513
Chronic	16	29	41	52	72	94	113	132	150	168
Silver										
Acute	0.19	0.62	1.2	2	4.1	6.7	9.8	13	18	22
Chronic	0.03	0.1	0.2	0.32	0.64	1	1.6	2.1	2.8	3.5
Uranium										
Acute	521	1,119	1,750	2,402	3,756	5,157	6,595	8,062	9,555	11,070
Chronic	326	699	1,093	1,501	2,346	3,221	4,119	5,036	5,968	6,915
Zinc										
Acute	45	85	123	160	231	301	368	435	500	565
Chronic	34	65	93	121	175	228	279	329	379	428

Source: Colorado Department of Public Health and Environment 2010.

fluid is pumped into the geologic formation through the well bore into the target formation. When the pressure exceeds the rock strength, the fluids open or enlarge fractures that can extend several hundred feet away from the well. Current fracturing processes use “Slick Water” or “Light Sand” fracturing, which uses larger volumes of water than historically used to complete the process (R.W. Harden & Associates 2007).

This hydraulic fluid is composed mainly of water and a proppant material, such as sand or ceramic beads, and is used to maintain openings after fracturing has concluded (R.W. Harden & Associates 2007, #8). Fracturing fluids can be up to 99% water (USEPA 2010). Water used for fracturing (frac water) is usually fresh water containing low salt concentrations and low concentrations of sparingly soluble salt products such as barium and silica. Lower soluble salts are important considerations because precipitation of these salts in the formation would block fractures and lower formation permeability. Numerous chemical additives also are present in the hydraulic fluid mixture at low volume percentages as compared to the water/proppant mixture. Specific chemical additives can include friction reducers, biocides, and scale inhibitors.

Frac water is usually trucked onsite to the well head. Limited fresh water reservoirs are available onsite that provide sufficient quality and volume for the frac water mixture. Deep horizontal wells can require anywhere from 2–10 million gallons of frac water to complete the well hydraulic fracturing (ProchemTech, 2008 #3). In the Barnett Shale in Texas, wells require 1.2 to 3.5 million gallons of water for hydraulically fracturing, usually spanning an interval of about one month per gas well (R.W. Harden & Associates 2007). After frac water is injected, the internal pressure of the geologic formation causes the injected fracturing fluids to rise to the surface and recovered fracturing fluid is referred to as flowback water (USEPA 2010). Not all fracturing fluids injected during hydraulic fracturing are recovered. Estimates of the fluids recovered range from 15–80% of the volume injected depending on the site (USEPA 2010).

Hydraulic fracturing can occur repeatedly throughout the well lifetime. Some companies reuse flowback to hydraulically fracture more than one well as a way of conserving water and recycling the fluids (USEPA 2010). Flowback water represents only a portion of the water injected into the formation, making this option sustainable only as long as the water quantity is sufficient for continued fracturing. Unlike the intermittent production of flowback water from fracturing operations, produced water is generated continuously as long as gas production is occurring. Treated produced water used to supplement water quantities for hydraulic fracturing lowers the use of fresh water sources for well development and creates a more sustainable water use cycle within the well drilling operation.

Enhanced Oil Recovery.—Enhanced oil recovery (EOR) is used to extract additional oil in place in a reservoir, since only 20–40% of the total amount of oil in place can be recovered by standard extraction methods (Petroleum Technology Transfer Council). A number of EOR techniques exist as secondary recovery