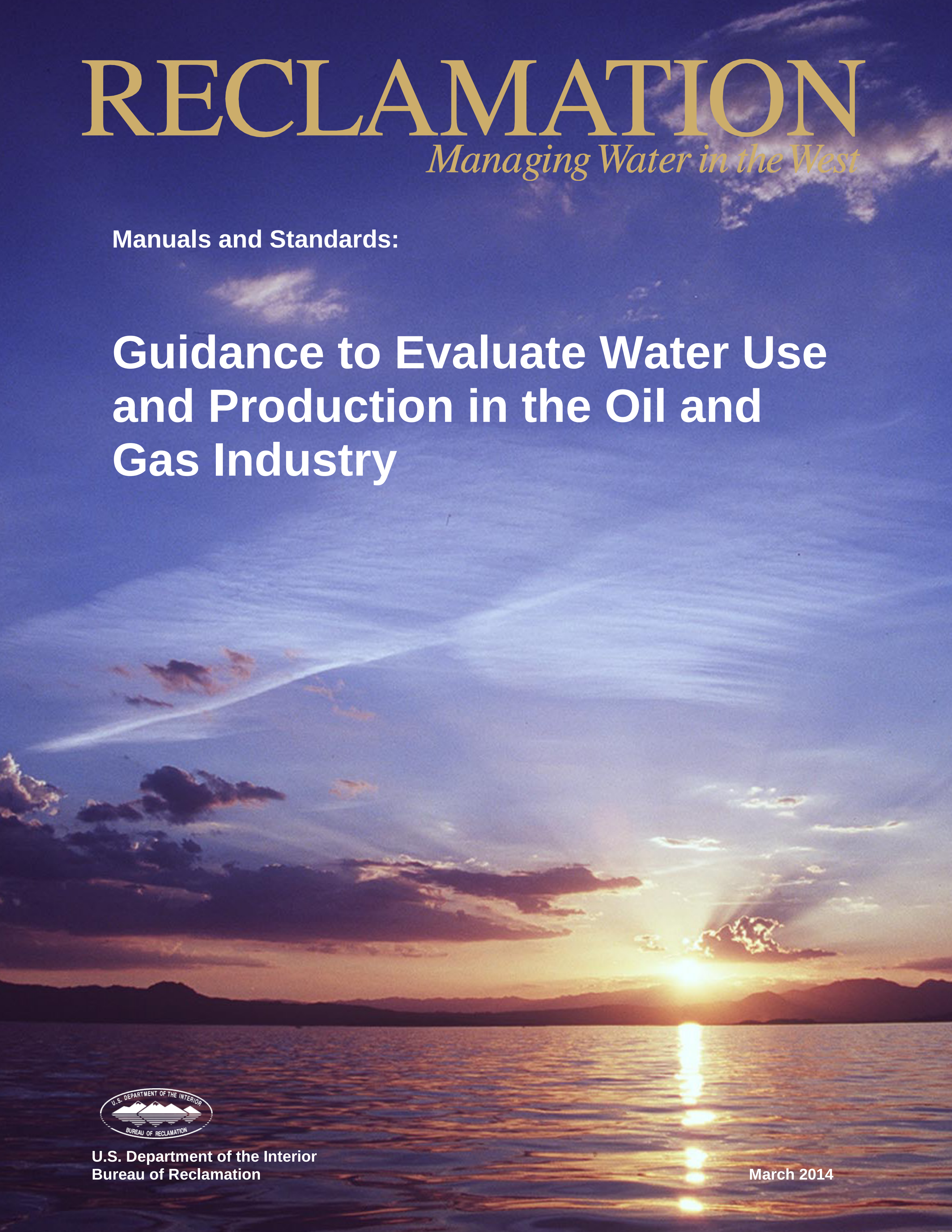

RECLAMATION

Managing Water in the West

Manuals and Standards:

Guidance to Evaluate Water Use and Production in the Oil and Gas Industry

U.S. Department of the Interior
Bureau of Reclamation

March 2014

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Oil and gas production requires large amounts of water to stimulate subsurface formations for petroleum production. In arid areas of the western U.S., meeting water demands for hydraulic fracturing poses challenges for local and regional water managers. Water that naturally exists in subsurface formations and is brought to the surface with hydrocarbon resources is termed "produced water." Produced water is considered the largest by-product of oil and gas generation and is generally managed as a waste product. This document provides guidance to water managers on evaluating water use and production in the oil and gas sector of the energy industry. Water management strategies that highlight tradeoffs in water management options to reduce demand and increase water supply are discussed.

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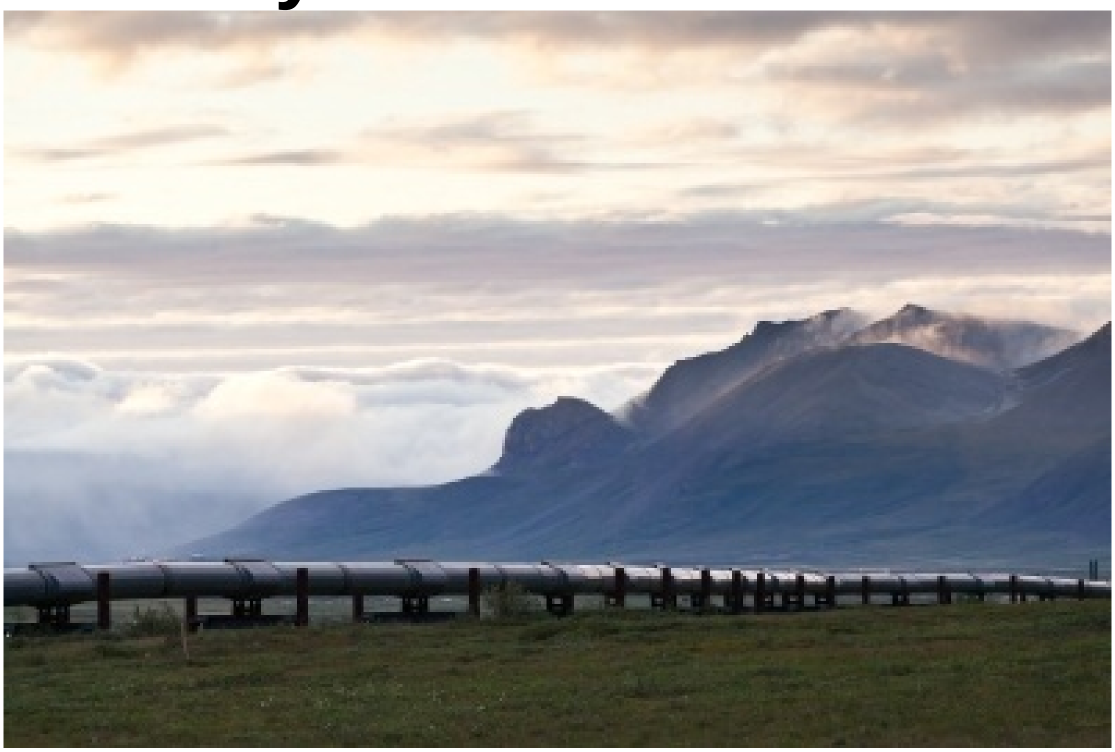

by:

Bureau of Reclamation
Technical Service Center
Water Treatment Group

U.S. Department of the Interior
Bureau of Reclamation

March 2014

Mission Statements

The U.S. Department of the Interior protects America's natural resources and heritage, honors our cultures and tribal communities, and supplies the energy to power our future.

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.

Disclaimer

Preface

Oil and gas production in the United States (U.S.) continues to increase as exploration and production of unconventional supplies, such as oil and gas shale resources becomes more prominent. Certain oil and gas recovery techniques, such as hydraulic fracturing, require large amounts of water to stimulate subsurface formations for petroleum production. In arid areas of the western U.S., meeting water demands for well development poses challenges for local and regional water managers. Conversely, oil and gas wells also produce a significant amount of water after well development. Water that naturally exists in subsurface formations and is brought to the surface with hydrocarbon resources is termed "produced water." Produced water is considered the largest by-product of oil and gas generation and is generally managed as a waste product. In the western U.S., most of the water produced during oil and gas production is disposed of, using methods such as deep well injection or evaporation.

This document provides guidance to water managers on evaluating water use and production in the oil and gas sector of the energy industry. Water management strategies that highlight tradeoffs in water management options to reduce demand and increase water supply are discussed. Options highlighted include:

- Using alternative water sources to develop wells
- Providing on-site industrial water reuse or recycling
- Using produced water post-well completion in beneficial ways

This guidance includes formula to calculate the amounts of water use and production using these various management strategies. This document also provides a standard assessment method for determining supply and demand with a focus on consumptive use calculations associated with energy production. Examples of formula calculations are provided in three scenarios. Considerations to factors impacting water use and production are also included.

Acknowledgements

Contributions and suggestions from industry, scientists, engineers, and water planners throughout and outside of Reclamation were invaluable in preparing this guidance. The effort of all those who contributed to this work, both past and present is greatly appreciated.

Acronyms and Abbreviations

AFY	acre-feet per year
API	American Petroleum Institute
BG	billion gallons
EERC	Energy and Environmental Research Center
EPA	U.S. Environmental Protection Agency
gpm	gallons per minute
MG	million gallons
mg/L	milligrams per liter
TDS	total dissolved solids

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Introduction

Water Demand and Production

Advances in oil and gas recovery techniques to produce energy from unconventional resources, such as oil and gas shale, have resulted in increased national energy production. Certain recovery techniques, such as hydraulic fracturing, can require large amounts of water to stimulate subsurface formations for petroleum production. In arid areas of the Western U.S., finding water sources for well development poses challenges for local and regional water managers, as water sources are limited, or stressed (Figure 1). In the Western U.S., water supplies are commonly allocated to historic water users, and excess supplies may be unavailable. The oil and gas industry commonly purchases water as a part of landowner agreements for well development to acquire water supplies. In the Western U.S., agreements to transfer rights from agricultural and municipal sources may also be made through state water management agencies to overcome limitations in water availability. Short-term needs and temporary locations further complicate tracking water transfers at regional or statewide scales.

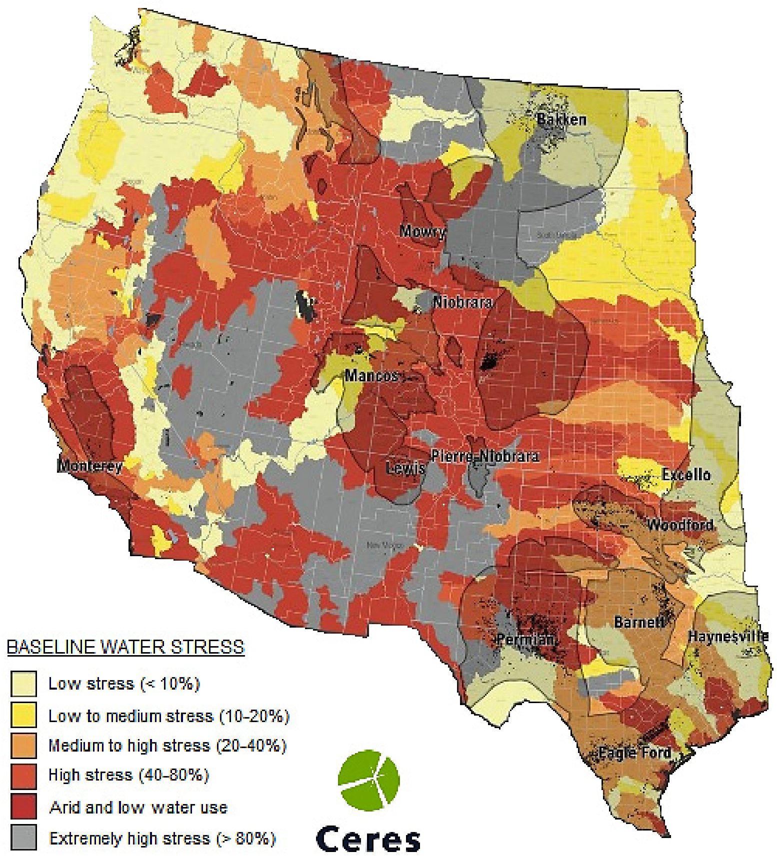

Figure 1. Competition for water in U.S. shale energy development (adapted from Freyman and Salmon, 2013, all rights reserved).

Water use for the energy industry is an important consideration when assessing regional water demands. Although the quantity of water used by the oil and gas industry for well development (including the volume injected for hydraulic fracturing), is small compared to agricultural, municipal and other industrial demands, the total water balance is affected—since water generally must be acquired from existing users. The well development process, particularly for unconventional gas shale wells, results in water consumption in the geologic formation during the fracturing process (Figure 2a.).

Hydraulic fracturing fluid, a mixture of water, sand, and fracturing chemicals, is injected into the formation during well development and typical return to the surface. This returning water, termed “flowback water,” can range from 15 to 80 percent of injected volumes depending on the formation (U.S. Environmental Protection Agency [EPA], 2010). Water is also consumed through management practices that dispose of flowback water in deep subsurface formations. The use of water treatment processes to reuse flowback water offset the consumptive volumes.

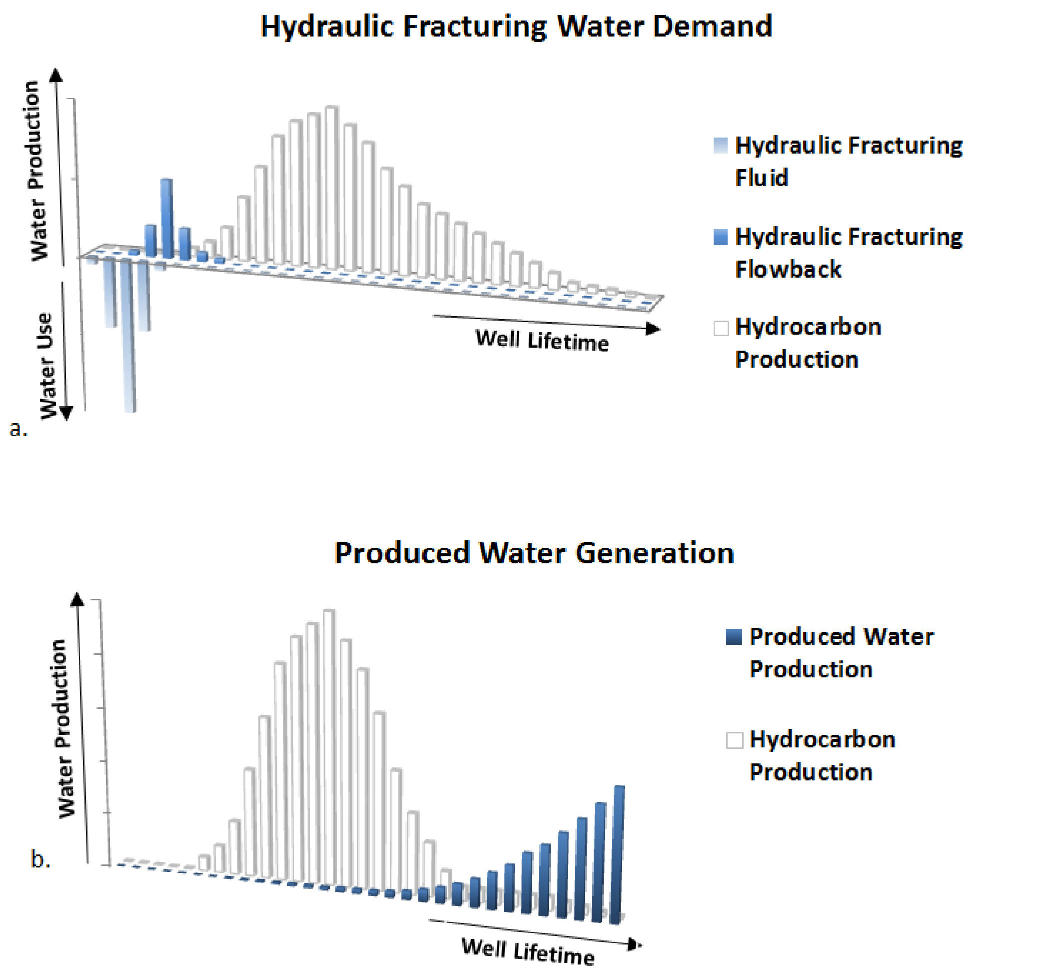

Figure 2. Conceptual representation of water use for hydraulic fracturing and water production over the well lifetime.

Oil and gas wells also produce a significant amount of water after the well is developed and during production. This water, termed “produced water,” is considered the largest by-product of oil and gas generation (Figure 2b.). Produced water exists naturally in subsurface formations with hydrocarbon resources. It is brought to the surface as a byproduct during of oil and gas production. Produced water is generally managed as a waste product, with most of the water disposed of through injection or evaporation. Transporting water and disposing through deep injections wells can be costly. Furthermore, in certain areas adequate disposal formations are not available for deep well injection.

Using this produced water as an alternative water supply, however, could benefit communities in oil and gas producing regions. A number of studies have focused on treating and using produced water for beneficial purposes, such as stream flow augmentation and agriculture including a Reclamation Science and Technology Program Report No. 157, “Oil and Gas Produced Water Management and Beneficial Use in the Western United States (Guerra et al., 2011).” Understanding the ultimate fate of water in the oil and gas industry is necessary to assess industry demand on water resources.

Objectives

This guidance for water use and production assessment in the oil and gas industry is meant to provide general information to water planners to improve projects of industry demand and production in regional water planning. This guidance’s objective is to present a standard method of water assessment to determine regional water use and production in the oil and gas industry. To develop this guidance, various water management practices for the oil and gas industry in the Western U.S. were evaluated to calculate water use and demand, produced water, and water reuse. This guidance focuses on evaluating water supply sourcing strategies, water consumption estimates, and water production formulas. The document is organized into three sections:

Section 1: Water Supply and Demand. The water supply and demand section focuses on defining water use, water production, and water reuse or beneficial use options for the oil and gas industry.

Section 2: Water Management Alternatives. The water management alternatives section focuses on strategies to reduce water consumption, including:

- **Non-traditional supplies:** This management strategy uses alternative water supplies for hydraulic fracturing to reduce fresh water consumption.
- **On-site water reuse and recycling:** This management strategy employs on-site water reuse technologies for the oil and gas industry to reduce water use requirements and generate water supplies at locations of need.

- **Off-site beneficial use of flowback or produced water:** This management strategy uses flowback and produced water generated from oil and gas operations for beneficial purposes outside of the industry (for example, stream flow augmentation, agriculture, and aquifer recharge).

Section 3: Water Assessment. The water assessment framework establishes formula for calculating general water supply use and production. This section integrates water supply and demand estimates into variables in water balance formulas for oil and gas development.

Water Supply and Demand

This section identifies and suggests available data sources to estimate both water use and production in the oil and gas industry. Data presented on water use and production vary based on source. For instance, water use data for hydraulic fracturing may be presented to show total water use to compare water demands for development in different areas and regions (Freeman and Salmon, 2013). Alternatively, water demand is also commonly compared between water demands in other categories, such as agriculture and municipalities to understand usage percentages (Colorado Division of Water Resources et al., 2010). Finally, Federal water production information is periodically queried and reported (Clark and Veil, 2009). Data are presented by state.

Generally, water production far outweighs water use, especially in the Western U.S., where large numbers of historical wells are already producing in basins where now unconventional oil and gas resources, such as gas shale, are being developed. Figure 3 presents a comparison of water use and production data for that were reported in Salmon and Freeman (2013). Apart from estimations of water use for fracturing in the Marcellus (Pennsylvania), water use is generally less than 10 percent of the total state water production from oil and gas operations. In other words, for every acre-foot of water used for well development, nine acre-feet of produced water are generated over the well's lifetime. The critical difference is that water is required for well development over a short period of time (months) and generated over a longer period (years).

Both water use and production data exist, but these are rarely recorded together. When evaluating data on a local or regional scale, a multifaceted approach to data collection is best for comparing sources and filling gaps. Tables 1, 2, and 3 include a number of suggested sources for water use, production, and beneficial use data for the oil and gas industry. These tables are not meant to be a comprehensive list of sources but suggest potential databases and contacts. Industry participation in water assessment studies is also a reliable source of data and, if possible, collaboration with industry to collect data is preferable.

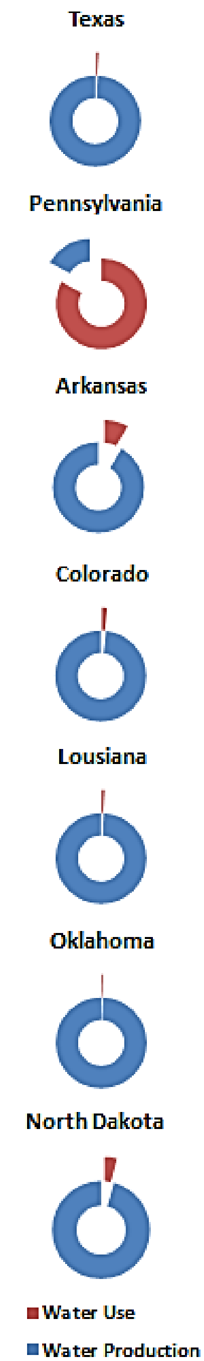

Figure 3. Estimated water use and production volumes by state (Sources: Freeman and Salmon, 2013 and Clark and Veil, 2009).

Table 1. Recommended Water Use Data Sources for Hydraulic Fracturing

Data	Description	Sources and Reference Studies
National Assessments and Volunteered Datasets	Industry-volunteered data on hydraulic fracturing fluids, includes water volumes, sources, and fracturing chemicals.	Groundwater Protection Council FracFocus – Chemical Disclosure Registry
	National water assessment on water use by water user category.	United States Geologic Survey Water Census
	Fracturing mapping site that maps well development by state.	FracTracker – FracMapper State-by-State Maps
State Assessments	State assessment and projection of water use for fracturing with comparisons to total state water use.	Colorado Division of Water Resources et. al. -- Water Sources and Demand for the Hydraulic Fracturing of Oil and Gas Wells in Colorado from 2010 – 2015
Research Studies	Research summary of hydraulic fracturing information. Includes estimations of water requirements per well by shale play.	Pacific Institute -- Hydraulic Fracturing and Water Resources: Separating the Frack from the Fiction
	Research paper focuses on potential water use/water supply conflicts in basins with hydraulic fracturing activity and water supply constraints.	Freeman and Salmon 2013 -- Hydraulic Fracturing & Water Stress: Growing Competitive Pressures for Water

Note: This table is meant to suggest resources and is not a comprehensive list of all available data sources.

Table 2. Recommended Water Production Data Sources for Oil and Gas Produced Water

Data	Description	Sources and Reference Studies
National Assessments	National databases on well production used to estimate water production based on estimations of oil to water or gas to water ratios.	Energy Information Administration – Natural Gas Data
State Assessments	State data on water production for the oil and gas industry.	Interstate Oil and Gas Compact Commission
	Inquiries for water production data from state oil and gas agencies.	Compilation of State contacts from the Railroad Commission of Texas
Online State Database Examples	**Colorado:** State oil and gas water production database. Colorado also maintains water quality records available upon request.	Colorado Oil and Gas Conservation Commission
	Utah: State oil and gas water production database.	Utah Department of Natural Resources Oil and Gas Program Division of Oil, Gas, and Mining
	Wyoming: State oil and gas water production database. Wyoming database also includes water quality.	Wyoming Oil and Gas Conservation Commission
Research Studies	National data collection of produced water production by state.	Argonne National Labs – Produced Water Volumes and Management Practices in the United States

Note: This table is meant to suggest resources and is not a comprehensive list of all available data sources. Sites were accessed 3/7/2014.

Table 3. Recommended Beneficial Use Management and Data Sources

Data	Description	Sources and Reference Studies
Management Options, Assessments and Handbooks	Comprehensive management and impact reports on beneficial use of produced water, management options, beneficial use categories, analysis tools, and case studies.	The National Academies Press -- Management and Effects of Coalbed Methane Produced Water in the Western United States
		Guerra et al., 2011. -- Oil and Gas Produced Water Management and Beneficial Use in the Western United States
		Colorado School of Mines – Produced Water Treatment and Beneficial Use Information Center
		ALL Consulting -- Handbook on Coal Bed Methane Produced Water: Management and Beneficial Use Alternatives
Management Experiences	Management experiences in beneficial use categories.	Interstate Oil and Gas Compact Commission
State Discharge Permits and Reuse Information	**Colorado:** State surface water discharge permitting for produced water treatment facilities.	Colorado Department of Public Health and Environment
	Wyoming: State environmental reports on reuse applications.	Wyoming Environmental Quality Council
Research Workshops	Produced Waters Workshop.	Colorado Water Resources Institute -- Colorado State University

Note: This table is meant to suggest resources and is not a comprehensive list of all available data sources. Sites were accessed 3/4/2014

Water Management Alternatives

Assessing water use and production requires a general understanding of industry water management practices. For instance, in the Western U.S., water sourcing commonly relies on groundwater supplies purchased as part of land lease agreements. The use of brackish groundwater supplies to offset fresh water consumption is also increasing. Brackish groundwater is generally considered an alternative non-traditional supply, and it may not be considered in a regional water portfolio. Meanwhile, produced water is considered the largest by-product of oil and gas generation and is generally managed as a waste product. Regulatory requirements for release or disposal of water from the oil and gas industry commonly dictate water management options. Specific regulatory guidelines for beneficial use options are outlined in Guerra et al., 2011.

This section introduces some water management concepts for meeting water demands and working with produced water. These concepts are not meant to replace comprehensive studies of suggested water management practices. There are a number of studies available with in depth information on water use and minimization in the oil and gas industry. A few select studies with additional information include:

- **Modern Shale Gas Development in the United States: A Primer**. U.S. Department of Energy Office of Fossil Energy National Energy Technology Laboratory. April 2009.

- **Water Management Associated with Hydraulic Fracturing**. American Petroleum Institute (API) Guidance Document HF2 1st Edition, June 2010.

- **Handling Produced Water from Hydraulic Fracturing**. Pam Boschee, Oil and Gas Facilities Editor, February, 2012.

- **Water Resources and Shale Gas/Oil Production in the Appalachian Basin—Critical Issues and Evolving Developments**. Pam Boschee, 2012, U.S. Geological Survey. August 2013.

This section focuses primarily on methods to reduce water consumption and increase water supply generation.

Non-traditional Supplies

This management strategy uses alternative water supplies for hydraulic fracturing. Hydraulic fracturing requires using a fluid to apply pressure to expand natural fractures in the hydrocarbon formation, allowing oil or gas to be produced economically. Fracturing may be accomplished using a number of liquid carriers, including water or liquefied gases, such as nitrogen or carbon dioxide. Gel fracturing uses water and polymers to create a higher viscosity fluid in the form of a gel to carry proppant and fracture the formation. Water supply options depend on the amount of water that will be required for long-term, area-wide development programs (API, 2010). Table 4 summarizes common water supplies and considerations for supply use.

Table 4. Water Sourcing and Considerations for Water Use

Water Sources	
Surface water—Using surface water may require pipelines or impoundments.	*Groundwater*—Groundwater wells may be developed on site.
Municipal water suppliers—Municipal water supplies may be useful for facilities near a town.	*Power plant cooling water*—Reuse of cooling water by nearby power generation facilities
Treated wastewater from municipal and industrial treatment facilities—Water rights may be purchased	*Recycled produced water and/or flow back water*—Industry recycling of water on-site in the locations it is generated and used
Consideration for Use	
Ownership, allocation, or appropriation of existing water resources—Ownership issues may include water rights procurement and working with State Engineers, particularly in areas where water resources are stressed or over allocated.	*Impacts to downstream habitats and users*—Reduction in flows due to surface and municipal water supply use may reduce allocates to downstream users and impact fish and wildlife.
Degradation of a stream's designated best use—Reduction in stream flows below levels necessary to support environmental habitat may limit water availability from surface streams.	*Water volume available for other needs, including public water supply*—Purchase of water supplies from municipal sources requires competition with public use and commonly raises public attention.
Aquifer volume diminishment—Extensive pumping of groundwater supplies may exceed recharge rates and prove unsustainable for the industry over long term development.	*Mitigation to prevent transfer of invasive species from one surface water body to another*—Pumping, transportation, and impoundments have the potential to move invasive species to sensitive areas.

Source: API, 2010

A regional water plan must determine the total volume of water used for fracturing. For instance, using treated municipal wastewater for fracturing subsequently reduces the volume of treated municipal wastewater discharged into surface water bodies. In areas where streams and rivers depend on treated municipal wastewater to maintain stream flow volumes, the effect of periodic supply reductions may impact downstream users or environmental flow requirements. Using brackish groundwater or other naturally impaired supplies may not influence the overall water budget for a region if brackish groundwater is not considered in the regional water plan. It is important to consider not only the volume of sourcing water, but the impact on regional supplies.

On-site Water Reuse and Recycling

This management strategy employs on-site water recycling and reuse to reduce water use requirements and generate water supplies where they are used for oil and gas production. Initial flowback water recovered in the first 30 days following well development and hydraulic fracturing may vary in volume from less than 10 to more than 70 percent of the fracturing fluid volume (API, 2010).

Flowback water quality is a mixture of the original fracturing fluid and natural water present in the formation. Mobile treatment units are commonly employed to treat and recycle water on-site. These mobile systems improve water quality for use as fracturing fluid. On-site treatment reduces transportation costs and makes water available for reuse in areas of development.

Water treatment systems are used to reduce concentration of constituents that are detrimental to equipment and incompatible with fracturing chemicals. Reuse of flowback for fracturing purposes requires less extensive treatment then most beneficial uses. The flowback water quality mixture is compatible with the formation, so treatment processes focus on reducing problematic constituent concentrations. Constituents of concern for fracturing include total dissolved solids (TDS), hydrocarbons, suspended solids, organic compounds, iron, manganese, and sparingly soluble salts. Advancements in fracturing chemicals also improve compatibility with recycled flowback. The reuse of water onsite for fracturing make-up water reduces water requirements from other sources, but rfeuse is limited to the flowback water returning from the formation during the initial flowback period.

Off-site Beneficial Use of Flowback or Produced Water

This management strategy uses flowback and produced water generated from oil and gas operations for beneficial purposes inside and outside the industry. Water for beneficial purposes, such as stream flow augmentation, agriculture, and aquifer recharge require more extensive treatment to meet water quality standards than reuse for fracturing fluid. Reclamation's 2011 report on beneficial use of produced water provides extensive information on regulatory requirements for beneficial uses, treatment technologies, and a case study example of centralized treatment for water supply generation for agricultural uses (Guerra et al., 2011).

These facilities are commonly located at centralized locations in the well field operation. These treatment plants generally operate as a centralized facility for one large company or a cooperative for many medium to small producers.

Centralized facilities offer more permanent operations to accommodate treatment processes that can achieve the range of water qualities that may be needed for multiple uses. Centralized facilities also offer on-site amenities, such as power, chemical storage, accessibility, and operator oversight.

To treat flowback and produced water for reuse in hydraulic fracturing, these treatment facilities are commonly designed with tiered treatment processes that produce multiple water qualities. In the Western U.S., these facilities are commonly designed to provide treated water with sufficient quality for reuse in hydraulic fracturing and/or water that meets requirements for surface water discharge. These facilities are an investment for initial flowback water treatment during well development, as well as long-term produced water disposal facilities. The prolonged life of these facilities offers an investment towards future water management in the area. By serving multiple wells over longer time periods, this management option uses treatment technology to create new supplies from the industry.

Water Assessment Framework

The following section describes a water assessment framework to define variables and boundaries in the industry to assess water use and production. This section takes into account data available from industry to define a water use scenario with three management aspects: water sourcing, on-site water recycling, and off-site beneficial use. Figure 4 displays a flowchart for these alternatives in the oil and gas industry.

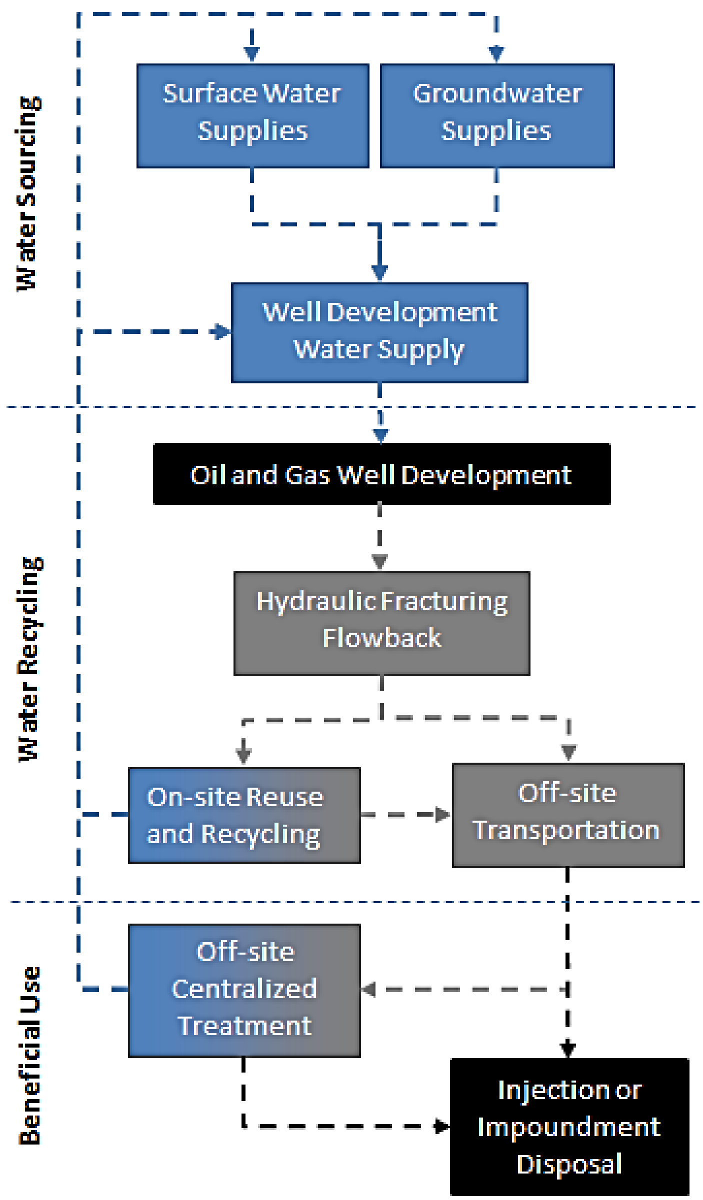

Figure 4. Water supply and production assessment framework for oil and gas.

Variables are assigned to the assessment framework shown in Figure 4 to define and describe water use in the industry. These variables include water volumes for hydraulic fracturing requirements collected from industry data and information on water sourcing. Inputs are also included for water consumption, such as the percentage of water lost to the formation during fracturing and volumes of water disposed of through deep well injection. Treatment efficiencies for both onsite and offsite facilities are also included to describe water reuse and beneficial use volumes. These variables, their definitions, and common values are included in Table 5.

Table 5. Assessment Framework Variables and Descriptions.

Water Sourcing or Water Use		
Equation	**Variables**	**Descriptions**
1	**$Wells_{Total}$** Estimated number of wells developed annually in a basin	Historic or projected number of wells developed annually in a basin or region.
	HF_f Fracturing frequency	Number of fracturing events per well development.
	HF_V Hydraulic fracturing water volumes	Water use in fracturing mixture make-up per well fracturing event.
	V_{Use} Total annual water volume required	Water volume per fracturing event (HF_V) times the number of events (HF_f) and number of wells ($Wells_{Total}$).
2	**V_{NTS}** Non-traditional supplies	Non-traditional or unconventional water supplies used for hydraulic fracturing make-up water on an annual basis.
	V_{RS} Recycled water from the industry	Estimated recycled water use for hydraulic fracturing make-up water on an annual basis.
	V_{TS} Traditional supplies	Traditional or conventional water supplies used for hydraulic fracturing make-up water on an annual basis.

Table 5 (continued). Assessment Framework Variables and Descriptions

On-site Water Reuse and Recycling		
Equation	**Variables**	**Descriptions**
3	**$HFF_{\%}$** Flowback percent	Percentage of water returned from the formation during fracturing.
	$T_{Off\ HFF}$ Percentage of flowback water transported directly off-site	Depending on the size of the operation, only a certain percentage may be stored and recycled on-site. This value is the percent of water transported off site.
	$E_{OnRecyc}$ On-site water recycling efficiency	Water recycling process are not 100 percent efficient. This value is the percent of recycled on-site. Water not recycled is transported off-site.
	V_{RSOn} Volume recycled on-site	Total volume of water recycled on-site based on treatment process sizing and efficiency.
4	**$V_{OffTotal}$** Total off-site transportation	Total volume of water transported off-site includes volumes transported directly ($T_{Off\ HFF}$) and waste volume from treatment process based on process efficiency ($E_{OnRecyc}$).
Off-site Beneficial Use of Flowback or Produced Water		
5	**T_{OffDis}** Percentage of water sent directly to disposal	This percentage represents the water transported directly to disposal management facilities.
	$V_{PWTotal}$ Volume transported off-site for treatment	Volume of flowback or produced water transported to off-site treatment facilities for the basin or region annually.
	$E_{Off\ BU}$ Off-site treatment facility efficiency	Water recycling process are not 100 percent efficient, this value is the percent of water that is recycled for reuse off-site.
	V_{BU} Volume of water for beneficial use	Total annual volume of water recycled off-site for beneficial purposes.
6	**V_{SW}** Surface discharge	Water discharged via permit to surface water streams and rivers after treatment.
	V_{GW} Aquifer recharge	Water injected for groundwater recharge and stored in subsurface systems.
	V_{RSOff} Industry reuse	Total volume of water recycled off-site based on treatment process sizing and efficiency.

The following formulas use these variables to estimate water use and production for oil and gas operations in a region.

Water Sourcing or Water Use

Depending on data available, water use may be estimated directly with Equation 1. The volume of water supply from traditional sources is determined in Equation 2.

$$V_{Use} = Wells_{Total} x\ HF_f\ x\ HF_V \qquad \textbf{[Equation 1]}$$

where: $Wells_{Total}$ = total annual well development, wells/year
HF_f = number of fracturing events per well, event/well
HF_v = volume of water required in fracturing mixture, million gallons (MG)/event
V_{Use} = total annual volume of water used for oil and gas development, MG/year

and

$$V_{Use} - V_{NTS} - V_{RS} = V_{TS} \qquad \textbf{[Equation 2]}$$

where: V_{Use} = total annual volume of water used for oil and gas development, MG/year
V_{NTS} = volume of non-traditional supplies, MG/year
V_{RS} = volume of recycled water from the industry, MG/year
V_{TS} = volume of traditional supplies, MG/year

On-site Water Reuse and Recycling

Water supply generated through on-site reuse for subsequent fracturing events is estimated through Equation 3, which takes into account formation consumption through flowback percentage, off-site transport, and on-site water recycling process efficiencies. Subsequently off-site transport is calculated with Equation 4.

$$V_{RSOn} = [(V_{Use} x\ HFF_{\%}) - (V_{Use} x\ HFF_{\%})\ x\ T_{Off\ HFF}]\ x\ E_{OnRecyc}$$

[Equation 3]

where: V_{Use}= total annual volume of water used for oil and gas development, MG/year
$HFF_{\%}$ = percentage of water returned from the formation, %
T_{OffHFF} = percentage of water transported directly off-site, %
$E_{OnRecyc}$ = water recycling process efficiency, %
$V_{RS\ On}$ = total annual volume of water recycled on-site, MG/year

and

$$V_{OffTotal} = (V_{Use}\ x\ HFF_{\%}) - V_{RSOn}$$ **[Equation 4]**

where: V_{Use} = total annual volume of water used for oil and gas development, MG/year
$HFF_{\%}$ = percentage of water returned from the formation, %
$V_{RS\ On}$ = total annual volume of water recycled on-site, MG/year
$V_{OffTotal}$ = annual volume of flowback transported off-site, MG/year

Off-site Beneficial Use of Flowback or Produced Water

Water supply generated from off-site treatment and beneficial use of flowback water from fracturing and produced water over the well lifetime is calculated with Equation 5. Subsequent end uses for treated water are broken down in Equation 6.

$$V_{BU} = [(V_{OffTotal} + V_{PWTotal}) - (V_{OffTotal} + V_{PWTotal})\ x\ T_{OffDis}]\ x\ E_{OffBU}$$

[Equation 5]

where: $V_{OffTotal}$ = annual volume of flowback transported off-site, MG/year
$V_{PWTotal}$ = annual volume of produced water transported off-site, MG/year
T_{OffDis} = water transported directly for off-site disposal, %
E_{OffBU} = water recycling process efficiency, %
V_{BU} = total annual volume of water recycled off-site, MG/year

and

$$V_{SW} + V_{GW} + V_{RSOff} = V_{BU}$$ **[Equation 6]**

where: V_{BU} = total annual volume of water recycled off-site, MG/year
V_{SW} = volume of water used beneficially used for surface water applications, MG/year
V_{GW} = volume of water used beneficially used for groundwater applications, MG/year
V_{RSOff} = volume of water recycled off-site for industry use, MG/year

In the Appendix, three scenarios are provided as an example to demonstrate the use of Equations 1 through 6. The scenarios are based on industry information to provide common values and context, but are hypothetical.

Considerations

In conclusion, a number of considerations are given to relate equation variables to water use and production impacts. These considerations are meant to provide context for values input into equations:

Comparing volumes required for use (V_{Use}) to the beneficial products created (V_{BU}) requires considering alternative water sourcing, on-site reuse, and off-sire beneficial use.

Using non-traditional supplies (V_{NTS}) and industry produced water (V_{RS}) is the most direct way to offset water requirements from traditional supplies (V_{TS}) for oil and gas development. Technologies and advances in fracturing chemical compatibility make reusing flowback, produced water, and other naturally impaired supplies possible. Non-traditional supplies may be limited in volume, so traditional supplies may need to contribute to total volumes (V_{Use}) required for development.

- The flowback percentage ($HFF_{\%}$) is an indication of industry consumption use based on this assessment. Water lost to the formation during fracturing is considered a consumptive loss to regional water balances. These losses vary by location and formation, but they must be taken into account to understand the fate of water production.

- On-site water recycling facilities may be limited in capacity and efficiency ($E_{OnRecyc}$) and may not be able to recover large volumes of water due to the decentralized natural of treatment. Efficient modular systems may be moved and reused at various locations to reduce transportation costs and create supplies in production areas.

Centralized facilities may offer increased capacity and efficiency (E_{OffBU}) with centralized operation, larger equipment, and chemical availability. Centralized facilities are also capable generating higher water quality products (V_{SW} and V_{GW}) for beneficial use outside of the industry.

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Appendix – Water Assessment Examples

Scenario 1 – Alternative Water Sourcing

To reduce water requirements from traditional sources non-traditional brackish groundwater supplies were explored for use as fracturing fluid in the Bakken formation in North Dakota by the University of North Dakota's Energy Environment Research Center (EERC) (Kurz, 2010). The following values are defined as part of this case study:

Estimated number of wells developed annually in a basin, $Wells_{Total}$
Based on U.S. Energy Information Administration projections, we assumed that the 2010 increase in well development of around 750 wells per year will stay constant in the Bakken formation. For this scenario, we assumed that the alternative supply evaluated will be used for a well field, adding 10 newly developed wells annually.

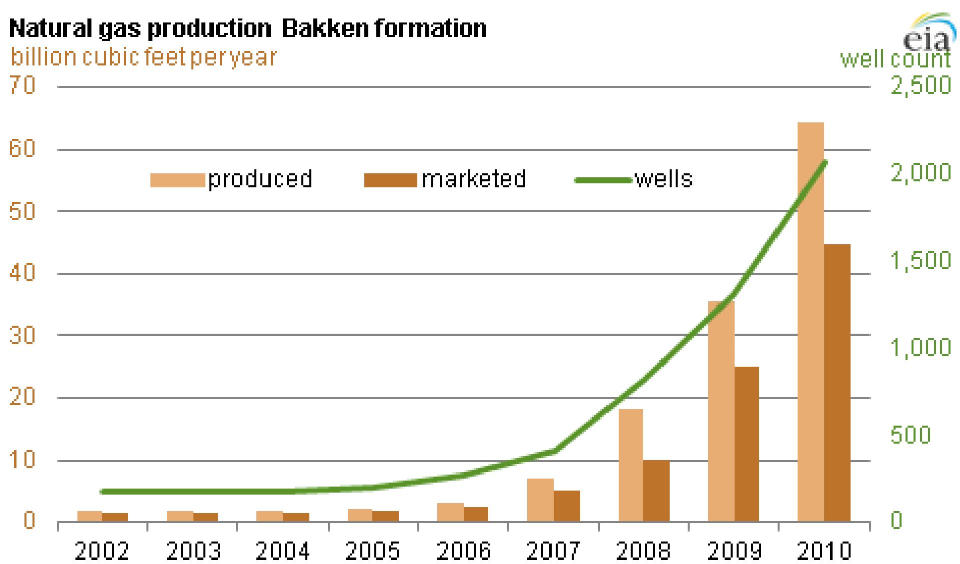

Figure A1. EIA natural gas production well count in the Bakken Formation (Source: Kurz, 2010).

Fracturing frequency, HF_f
Number of fracturing events per well development was not provided, so for the purpose of this scenario it is assumed that ten events occurs per well.

Hydraulic fracturing water volumes, HF_V
The volume of water required per well fracturing ranges from approximately 0.5 to 3 million gallons. For this scenario, 2 million gallons will be used for HF_V.

Traditional supplies, V_{TS}

Transportation costs represent a significant percentage of the total water handling costs, so a non-traditional alternative supply closer to production was explored. For this scenario, we assumed that water supplies would be only from non-traditional supplies and water recycling through treatment, therefore $V_{TS} = 0$.

Recycled water from the industry, V_{RS}

Water recycled from production is assumed to be zero, because the study states that flowback water recovery ranges from 15 to 50 percent and salinity levels may return as high as 220,000 milligrams per liter (mg/L) of TDS making reuse uneconomical. Therefore, $V_{RS} = 0$.

Non-traditional supplies, V_{NTS}

An existing brackish groundwater production well exists in the area near Tioga, North Dakota. This well has a TDS of 9,000 to 11,000 mg/L. The equations will designate the volume of water this well needs to produce, V_{NTS}.

Using Equation 1 and Equation 2, the volume of water use at the site was estimated in acre-feet per year (AFY):

$$V_{Use} = Wells_{Total} x\ HF_f\ x\ HF_V$$

where: $Wells_{Total}$ = total annual well development = 10 wells/year
HF_f = number of fracturing events per well = 10 events/well
HF_v = 2.0 MG/event

$$V_{Use} = 10\frac{wells}{yr}\ x\ 10\frac{event}{well}\ x\ 2.0\frac{MG}{event}$$

$$\boldsymbol{V_{Use} = 200\frac{MG}{yr} = 614\ AFY}$$

$$V_{Use} = V_{TS} + V_{NTS} + V_{RS}$$

where: V_{TS} = volume of traditional supplies = 0 MG/year
V_{RS} = volume of recycled water from the industry = 0 MG/year

therefore:

$$V_{Use} = V_{NTS}$$

$$\boldsymbol{V_{Use} = V_{NTS} = 200\frac{MG}{yr} = 614\ AFY}$$

The volume of non-traditional supply is estimated at 614 AFY. Therefore, the brackish water production well needs to operate continuously at 380 gallons per minute (gpm) to provide sufficient supply for well development in the area.

Scenario 2 – On-site Water Reuse and Recycling

Water reuse technologies are designed as mobile units to accommodate on-site treatment and recycling. As an example, the CleanWave™ Water Treatment Service employed by Halliburton is a mobile service for treating produced and flowback water on-site. The CleanWave™ electrocoagulation and electrofloatation technology treats flowback and produced water with TDS levels ranging from 100 to 300,000 mg/L. Using Scenario 1 parameters for water volumes, fracturing formation, and percentage recovery, the estimated on-site water reuse is defined as follows:

Flowback percent, $HFF_{\%}$
Based on Scenario 1, flowback percentages ranged from 15 to 50 percent in the Bakken. For this scenario, $HHF_{\%}$ is assumed to be 25 percent.

Percentage of flowback water transported directly off-site, $T_{Off\ HFF}$
Units are designed to treat up to 1,000 gpm. Assuming a single unit sits on-site and operates continuously all year, the process can treat up to 5.26 billion gallons (BG) year. This annual volume is more than the water volume expected to return from the formation based on Scenario 1 and the flowback percentage. For Scenario 2, it is assumed that direct off-site transport percentage ($T_{Off\ HFF}$) is zero.

On-site water recycling efficiency, $E_{OnRecyc}$
Literature was unavailable on the efficiency of this treatment unit, but a water recovery efficiency of 50 percent was used for this hypothetical scenario. Therefore, 50 percent of the water treated in these units will be transported off-site for disposal.

The volume of water reused at the site is estimated using Equation 3, and the water rejected by the system and subsequent volume transported off-site is estimated using Equation 4:

$$V_{RSOn} = [(V_{Use} x\ HFF_{\%}) - (V_{Use} x\ HFF_{\%})\ x\ T_{Off\ HFF}]\ x\ E_{OnRecyc}$$

where: V_{Total} = total annual volume of water used for oil and gas development = 200 MG/year
$HFF_{\%}$ = percentage of water returned from the formation = 25 %
T_{OffHFF} = percentage of water transported directly off-site = 0 %
$E_{OnRecyc}$ = water recycling process efficiency = 50 %
$V_{RS\ On}$ = total annual volume of water recycled on-site, MG/year

$$V_{RSOn} = (V_{Total} x\ HFF_{\%})\ x\ E_{OnRecyc} = \left(200\frac{MG}{yr}\ x\ 25\%\right)\ x\ 50\%$$

$$\boldsymbol{V_{RSOn} = 25\ \frac{MG}{yr} = 77\ AFY}$$

and

$$V_{OffTotal} = (V_{Use}\ x\ HFF_{\%}) - V_{RSOn}$$

where: V_{Total} = total annual volume of water used for oil and gas development = 200 MG/year
$HFF_{\%}$ = percentage of water returned from the formation = 25%
$V_{RS\ On}$ = total annual volume of water recycled on-site = 25 MG/year
$V_{OffTotal}$ = annual volume of flowback transported off-site, MG/year

$$V_{OffTotal} = (V_{Total}\ x\ HFF_{\%}) - V_{RSOn}$$

$$V_{OffTotal} = \left(200\frac{MG}{yr}\ x\ 25\%\right) - 25\frac{MG}{yr}$$

$$\boldsymbol{V_{OffTotal} = 25\ \frac{MG}{yr} = 77\ AFY}$$

If on-site water reuse were employed in the previous scenario, the volume of non-traditional supply required would decrease from 614 AFY to 537 AFY. This would reduce the brackish water production well requirements to 330 gpm to support well development in the area.

Scenario 3 – Off-site Beneficial Use of Flowback or Produced Water

Centralized water treatment facilities are designed as permanent facilities to accommodate off-site treatment of flowback and produced water for recycling or beneficial use. High Sierra Energy, LP operates the Pinedale Anticline centralized treatment facility in Pinedale, Wyoming. This centralized facility treats water from hydraulic fracturing in the Hillard-Braxter-Mancos shale and produced water from the Greater Green River Basin. The facility treats water to two tiers of quality: recycled water for fracturing and surface water for discharge into tributaries of the Green River. The facility is connected to 19 miles of pipeline for recycled water delivery, has 147 MG of water storage capacity, and operates one deep injection well for concentrate disposal. Using the Pinedale facility as an example of centralized treatment, the beneficial use of water is calculated for previous scenario values with Equation 5 and Equation 6.

Total off-site transportation, $V_{OffTotal}$
The total volume of water transported off-site in Scenario 2 was estimated at 25 MG/year.

Volume of produced water transported to off-site, $V_{PWTotal}$
Additionally, we assumed that 10 times more produced water is generated within these wells than flowback. With that assumption, off-site transportation of produced water is estimated to be 250 MG/year.

Off-site water recycling for beneficial use efficiency, $E_{Off\ BU}$
Literature was unavailable on the efficiency of the Pinedale facility, but for this scenario, we estimated a water recovery efficiency of 75 percent.

Percentage of off-site transport to disposal wells or impoundments, T_{OffDis}
For this scenario, we assumed that the centralized facility will be sized to the production demand. Therefore, the percentage of water sent directly to disposal will be zero.

Discharge to surface systems as additional supply, V_{SW}
The Pinedale facility is permitted to discharge up to 25 percent of the total facility capacity as surface water.

Aquifer recharge as additional supply, V_{GW}
This facility does not inject water for subsurface storage, so the volume contributed to groundwater resources is assumed to be zero.

Water recycled for industry use, V_{RSOff}
The Pinedale facility estimates up to 75 percent of the total facility capacity is used for industry recycling.

Using Equation 5 and Equation 6, the volume of water treated for beneficial use is estimated for the off-site centralized facility:

$$V_{BU} = [(V_{OffTotal} + V_{PWTotal}) - (V_{OffTotal} + V_{PWTotal})\ x\ T_{OffDis}]\ x\ E_{OffBU}$$

where: $V_{OffTotal}$ = annual volume of flowback transported off-site = 25 MG/year
$V_{PWTotal}$ = annual volume of produced water transported off-site = 250 MG/year
T_{OffDis} = water transported directly for disposal = 0 %
E_{OffBU} = water recycling process efficiency = 75%
V_{BU} = total annual volume of water recycled off-site, MG/year

$$V_{BU} = (V_{OffTotal} + V_{PWTotal})\ x\ E_{OffBU} = \left(25\frac{MG}{yr} + 250\frac{MG}{yr}\right) x\ 75\%$$

$$\boldsymbol{V_{BU} = 206\ \frac{MG}{yr} = 632\ AFY}$$

and

$$V_{BU} = V_{SW} + V_{GW} + V_{RSOff}$$

where: V_{SW} = volume of water used beneficially used for surface water applications = 25% of V_{BU} MG/year
V_{GW} = volume of water used for groundwater applications = 0 MG/year
V_{RSOff} = volume of water recycled off-site for industry = 75% of V_{BU} MG/year
V_{BU} = total annual volume of water recycled off-site, MG/year

$$V_{SW} = V_{BU}\ x\ 25\% \qquad V_{RSOff} = V_{BU}\ x\ 75\%$$

$$\boldsymbol{V_{SW} = V_{BU}\ x\ 25\% = 52\ \frac{MG}{yr} = 160\ AFY}$$

$$\boldsymbol{V_{RSOff} = V_{BU}\ x\ 75\% = 155\ \frac{MG}{yr} = 476\ AFY}$$

If off-site water reuse is employed in the previous scenarios, the volume of non-traditional supply required would decrease from 614 AFY to 61 AFY by using recycled water. This reduction to 10 percent of the original requirements would reduce the brackish water production well requirements to 38 gpm to support well development in the area. Furthermore, if the surface water discharge was recycled as well the non-traditional supply would be unnecessary, and a surplus of 95 AFY of fresh water would be produced from the system. This scenario is a hypothetical projection for ten wells. If these scenarios were applied to the full 750 wells estimated to be developed in the Bakken formation, North Dakota, then a potential water production of 7,125 AFY could occur from the basin annually.