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Summary of the Technical Workshop on Water Acquisition Modeling: Assessing Impacts Through Modeling and Other Means

June 4, 2013

Disclaimer

This report was prepared by EPA with assistance from Eastern Research Group, Inc., an EPA contractor, as a general record of discussions during the June 4, 2013, technical workshop on wastewater treatment and related modeling. The workshop was held to inform EPA's *Study of the Potential Impacts of Hydraulic Fracturing on Drinking Water Resources*. The report summarizes the presentations and facilitated discussions on the workshop topics and is not intended to reflect a complete record of all discussions. All statements and opinions expressed represent individual views of the invited participants; there was no attempt to reach consensus on any of the technical issues being discussed. Except as noted, none of the statements in the report represent analyses or positions of EPA.

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Meeting Agenda

Technical Workshop on Water Acquisition Modeling: Assessing Impacts Through Modeling and Other Means
June 4, 2013

US EPA Conference Center at One Potomac Yards
Arlington, VA

8:00 am **Registration/Check-in**

8:30 am **Welcome and Introductions**.. *Ramona Trovato, US EPA*

8:40 am **Opening Remarks** ....*Glenn Paulson, Science Advisor, US EPA*

8:45 am **Purpose of Workshop** ....*Workshop Co-Chairs:*
Jennifer Orme-Zavaleta, US EPA
James Richenderfer, Susquehanna River Basin Commission

Session 1: Data on Water Acquisition and Water Recycling/Reuse

8:55 am ***Panel Presentations:***

- **EPA Data Review Projects** .... *Andrew Gillespie, US EPA*
- **Sources of Data to Understand Hydraulic Fracturing Water Use in Texas**..................... J-P Nicot, *University of Texas at Austin*
- **Water Acquisition for Unconventional Natural Gas Development Within the Susquehanna River Basin**.. *James Richenderfer, Susquehanna River Basin Commission*
- **Recycling and Reuse of Produced Water to Reduce Freshwater Use in Hydraulic Fracturing Operations**...*Matthew Mantell, Chesapeake Energy Corporation*

Questions of Clarification

Break (10 minutes)

Facilitated discussion among workshop participants focusing on key questions:

- What existing sources of data could be used to better understand the effects of hydraulic fracturing water acquisition on water system availability?
- What are key attributes of a scientifically robust approach to measuring and monitoring hydraulic fracturing water use and disposition?
- What is the current state of industry practice with respect to recycling/reusing water for hydraulic fracturing operations?
- What are the long-term lifecycle implications and regional trends of recycling/reusing water in hydraulic fracturing operations?

11:45 am **Summary of Session 1** .... *Workshop Co-Chairs*

12:00 pm **Lunch and Poster Session**

Session 2: Hydraulic Fracturing Water Acquisition and Water Availability Modeling Approaches

1:30 pm ***Panel Presentations:***

- **Evaluating Scenarios of Potential Impact of Water Acquisition** .... *Stephen Kraemer, US EPA*
- **Mapping Water Availability and Cost in the Western United States** ....*Vincent Tidwell, Sandia National Laboratory*
- **Integrated, Collaborative Water Research in Western Canada**.......*Ben Kerr, Foundry Spatial Ltd.*
- **Water Need and Availability for Hydraulic Fracturing in the Bakken Formation, Eastern Montana** ....*Mitchell Plummer, Idaho National Laboratory*

Questions of Clarification

Break (10 minutes)

Facilitated discussion among workshop participants focusing on key questions:

- What would a more generalized, conceptual model look like for assessing hydraulic fracturing impacts in different areas of the US and at different scales?
- What factors should be included in a generalized model?

3:45 pm **Summary of Session 2** .... *Workshop Co-Chairs*

3:55 pm **Closing Remarks** ....*Ramona Trovato, US EPA*

4:00 pm **Adjourn**

Poster Session

A Simulation Framework for Integrated Water and Energy Resource Planning
Robert Jeffers, Idaho National Laboratory

Utilizing Produced Water and Hydraulic Fracturing Flowback as a New Water Resource
David Stewart, Energy Water Solutions, LLC

List of Meeting Participants

Bruce Baizel
Earthworks

Michael G. Baker
Ohio Environmental Protection Agency

Lily Baldwin
Chevron Energy Technology Company

Laura Belanger
Western Resource Advocates

Lisa Biddle
US EPA Office of Water

Jeanne Briskin
US EPA Office of Research and Development

Thomas Chambers
Southwestern Energy Company

Corrie Clark
Argonne National Laboratory

Bruce Curtis
Kleinfelder, Inc.

R. Jeffrey Davis
Cardno ENTRIX

Michael Dunkel
Pioneer Natural Resources

H. Thomas Fridirici
Pennsylvania Department of Environmental Protection

Andrew Gillespie*
US EPA ORD/National Exposure Research Laboratory

Rowlan Greaves
Southwestern Energy Company

Christopher Harto
Argonne National Laboratory

David Hollas
Halliburton Energy Services, Inc.

Robert Jeffers
Idaho National Laboratory

Stephen Jester
ConocoPhillips

Mary Kang
Princeton University

Ben Kerr*
Foundry Spatial Ltd.

Stephen Kraemer*
US EPA ORD/National Exposure Research Laboratory

Dan Luecke
Consultant

Matthew Mantell*
Chesapeake Energy Corporation

Mike Mathis
Chesapeake Energy Corporation

Lisa Matthews
US EPA Office of Research and Development

Jan Matuszko
US EPA Office of Water

* Presenter

Adam McDonough
American Water Works Service Company, Inc.

Kenneth Nichols
CH2M HILL

Jean-Philippe Nicot*
University of Texas at Austin

Jennifer Orme-Zavaleta (co-chair)
US EPA ORD/National Exposure Research Laboratory

Glenn Paulson
US EPA, Science Advisor

Mitchell Plummer*
Idaho National Laboratory

James Richenderfer* (co-chair)
Susquehanna River Basin Commission

Andrew Ross
Colorado Department of Public Health and Environment

Chantal Savaria
Savaria Experts-Conseils Inc.

Kelly Smith
US EPA ORD/National Risk Management Research Laboratory

Daniel Soeder
US Department of Energy

David Stewart
Energy Water Solutions, LLC

Kate Sullivan
US EPA ORD/National Exposure Research Laboratory

Patrick Sullivan
Aquilogic, Inc.

Brenan Tarrier
New York State Department of Environmental Conservation

Joel Thompson
Stantec, Inc.

Amy Tidwell
ExxonMobil Upstream Research Company

Vincent Tidwell*
Sandia National Laboratories

D. Steven Tipton
Newfield Exploration Company

Ramona Trovato
US EPA Office of Research and Development

Denise Tuck
Halliburton Energy Services, Inc.

Jim Weaver
US EPA ORD/National Risk Management Research Laboratory

W. Joshua Weiss
Hazen and Sawyer, P.C.

Lloyd Wilson
New York State Department of Health

* Presenter

Introduction

At the request of Congress, the U.S. Environmental Protection Agency (EPA) is conducting a study to better understand the potential impacts of hydraulic fracturing on drinking water resources. The scope of the research includes the full cycle of water associated with hydraulic fracturing activities. In the study, each stage of the water cycle is associated with a primary research question:

- **Water acquisition:** What are the possible impacts of large volume water withdrawals from ground and surface waters on drinking water resources?
- **Chemical mixing:** What are the possible impacts of hydraulic fracturing fluid surface spills on or near well pads on drinking water resources?
- **Well injection:** What are the possible impacts of the injection and fracturing process on drinking water resources?
- **Flowback and produced water:** What are the possible impacts of surface spills on or near well pads of flowback and produced water on drinking water resources?
- **Wastewater treatment and waste disposal:** What are the possible impacts of inadequate treatment of hydraulic fracturing wastewaters on drinking water resources?

In 2013, EPA hosted a series of technical workshops related to its *Study of the Potential Impacts of Hydraulic Fracturing on Drinking Water Resources*. The workshops included Analytical Chemical Methods (February 25, 2013), Well Construction/Operation and Subsurface Modeling (April 16–17, 2013), Wastewater Treatment and Related Modeling (April 18, 2013), Water Acquisition Modeling (June 4, 2013) and Hydraulic Fracturing Case Studies (July 30, 2013). The workshops were intended to inform EPA on subjects integral to enhancing the overall hydraulic fracturing study, increasing collaborative opportunities and identifying additional possible future research areas. Each workshop addressed subject matter directly related to the primary research questions.

For each workshop, EPA invited experts with significant relevant and current technical experience. Each workshop consisted of invited presentations followed by facilitated discussion among all invited experts. Participants were chosen with the goal of maintaining balanced viewpoints from a diverse set of stakeholder groups including industry; nongovernmental organizations; other federal, state and local governments; tribes; and the academic community.

The fourth workshop, Water Acquisition Modeling: Assessing Impacts Through Modeling and Other Means, was co-chaired by Dr. Jennifer Orme-Zavaleta (EPA) and Dr. James Richenderfer (Susquehanna River Basin Commission [SRBC]). A morning session addressed *Data on Water Acquisition and Water Recycling/Reuse* while the afternoon session focused on *Hydraulic Fracturing Water Acquisition and Water Availability Modeling Approaches.* In addition, several experts shared technical knowledge during a poster session (see Appendix C of this report).

Summary of Presentations for Session 1:
Data on Water Acquisition and Water Recycling/Reuse

Susan Hazen, Hazen Consulting and Support Services, opened the workshop. She noted that EPA was looking for individual participants' frank input and opinion and was not trying to reach consensus on the topics; the workshop was not being held under the rules of the Federal Advisory Committee Act (FACA). **Ramona Trovato,** Associate Assistant Administrator of EPA's Office of Research and Development, and **Dr. Glenn Paulson,** Science Advisor to the EPA Administrator, welcomed the participants and thanked them for contributing their knowledge and experience to help answer the water acquisition research questions in EPA's drinking water study. Workshop Co-Chairs **Dr. Jennifer Orme-Zavaleta,** Director of EPA's National Exposure Research Laboratory, and **Dr. James Richenderfer,** Director of Technical Programs for the Susquehanna River Basin Commission, also welcomed the participants. They explained that the purpose of the workshop was to hear different stakeholders' perspectives and to better understand industry practices and how they are changing.

Dr. Andrew Gillespie, EPA National Exposure Research Laboratory, provided an overview of EPA's drinking water study approach to studying the water acquisition stage of the water cycle, and described EPA's analysis of existing data about water acquisition for hydraulic fracturing operations. He noted that the primary research question associated with the water acquisition stage of the hydraulic fracturing water cycle is "What are the possible impacts of large volume water withdrawals on drinking water resources?" The secondary research questions related to water acquisition are:

- How much water is used in hydraulic fracturing operations, and what are the sources of this water?
- How might water withdrawals affect short- and long-term water availability in an area with hydraulic fracturing activity?
- What are the possible impacts of water withdrawals for hydraulic fracturing operations on local water quality?

Dr. Gillespie noted that hydraulic fracturing accounts for a very small fraction of the nation's annual water use (less than 0.1 percent). However, the impacts of withdrawal may not be visible at a national scale or state scales. The potential for greater impacts may exist at the local level, depending on such factors as the catchment area and distribution of hydraulic fracturing operations in a given area, the local geology and hydrology, competing local water needs, and climate and seasonal variations. Dr. Gillespie discussed some anecdotal evidence of increased recycling/reuse of produced and flowback water, noting that participants in the April 4, 2013, technical workshop on wastewater had discussed the importance of local conditions for recycling and reuse, the potential for cost savings, and possible reduction in freshwater utilization. He then described the existing data that EPA is analyzing to answer the research questions: scientific literature, FracFocus data, information from nine service companies that hydraulically fractured 24,925 wells in 2009–2010, and well files from 331 oil and gas wells across the United States.

Dr. Jean-Philippe Nicot, Bureau of Economic Geology, University of Texas at Austin, discussed sources of data for understanding hydraulic fracturing water use in Texas. Data on hydraulic fracturing water use in Texas are readily available from operators themselves or from the regulating agency, the Railroad Commission of Texas (RRC). In Texas, hydraulic fracturing occurs in oil and gas plays, shales, and tight formations. In 2011, there was an increase in completion water use in oil/liquid plays because of the decrease in gas prices. Dr. Nicot noted that operators have to report completion water use to the RRC; several private vendors make these data available in a useful form. He described the process he uses to determine the accuracy of RRC data by checking water intensity and proppant loading. He stated that little is known about ground water versus surface water use, the amount of reuse and recycling, or brackish water use, because these data are not captured in the state database. This information must be obtained from operators and the approximately 100 Groundwater Conservation Districts (GCDs) in the state. He stated that hydraulic fracturing water use (the amount of water needed to perform hydraulic fracturing stimulation) and water consumption (the amount of water lost to the system) are both small at the state level. However, there has been a large increase in water use in sparsely populated counties, because of the low baseline (i.e., the amount of water used by the local population is small). Work is underway to compare hydraulic fracturing water use and water consumption to the amount of water available. It is important, he noted, to account for the fact that water used in a county may not come from that county.

Dr. James Richenderfer, SRBC, discussed water acquisition for unconventional natural gas development in the Susquehanna River Basin. The SRBC regulates surface water and ground water withdrawals, consumptive use and diversions (not water quality). Because the SRBC knew so little about the unconventional oil and gas industry, it set all regulatory thresholds for the industry at "gallon one." Major changes have been made to SRBC regulations to stay ahead of industry. For example, if a company gets approval for withdrawal and wants to share water with other companies, this is encouraged because the impact on ecosystems will be smaller. The basin has water quality issues due to legacy acid mine drainage, and SRBC encourages the use of lesser-quality waters for hydraulic fracturing. Another change was a significant investment in information technology to allow online application and reporting. Dr. Richenderfer described challenges for the SRBC, including the extent of operation in headwaters, where the most pristine, sensitive ecosystems are found; the nomadic and short-term nature of projects; increased volume of applications; withdrawals that are distant from the consumptive use; the rapid evolution of the industry in contrast to the pace of bureaucracy involved in environmental protection; and the high level of public scrutiny. He noted that the basin water use profile for the Marcellus for 2008–2012 shows an average of 4.4 million gallons used per well for hydraulic fracturing (86 percent freshwater and 14 percent flowback reused). He described characteristics of SBRC reviews: science-based decision-making, consideration of cumulative impacts, recognition that the location of withdrawals is more important than withdrawal amounts, and use of interruptible courses ("pass-bys") to minimize impacts on aquatic systems during low flow periods.

Matthew Mantell, Chesapeake Energy Corporation, discussed recycling and reuse of produced water to reduce freshwater use in hydraulic fracturing operations. He presented current numbers for water use and water use efficiency for the major plays in which Chesapeake operates. He noted that water use is the most efficient in the Marcellus, at 0.76 gallons per million Btu (MMBtu) of energy. He stated that despite the perceived large volume of water used in drilling and hydraulic fracturing, water efficiency of unconventional oil and gas is in line with conventional energy (1 to 3 gallons of water per MMBtu for conventional [vertical] natural gas vs. 0.76 to 2.97 gallons per MMBtu for Chesapeake deep shale natural gas) because horizontal completions produce comparatively more energy. He presented treatment specifics and applications for produced water treatment, including sedimentation and filtration, chemical precipitation, dissolved air floatation, evaporation, thermal distillation, electrocoagulation, crystallization and direct reuse (no treatment). In Chesapeake's experience, produced water from the Marcellus shale is suitable for treatment by sedimentation and filtration, and almost all produced water is reused. New friction reducers have allowed Chesapeake to substantially increase the use of high total dissolved solids brine for hydraulic fracturing, e.g., in Mississippi Lime wells. Mr. Mantell noted that environmental and economic benefits must be considered when evaluating reuse versus disposal; saltwater disposal wells in close proximity to operations are a low-cost, low-energy alternative to advanced treatment for reuse. He noted that state water use policies are based on a unique understanding of local needs and resources, and all water users must comply with state water programs. Finally, he stated that the chemical process of burning natural gas (methane) for energy results in the production of new water molecules, which over the well production lifecycle will partly or fully offset water lost through subsurface injection.

Summary of Discussions Following Session 1: Data on Water Acquisition and Water Recycling/Reuse

Following questions of clarification, participants were asked to consider the following questions during the discussion:

- What existing sources of data could be used to better understand the effects of hydraulic fracturing water acquisition on water system availability?
- What are key attributes of a scientifically robust approach to measuring and monitoring hydraulic fracturing water use and disposition?
- What is the current state of industry practice with respect to recycling/reusing water for hydraulic fracturing operations?
- What are the long-term lifecycle implications and regional trends of recycling/reusing water in hydraulic fracturing operations?

Key themes from Session 1 discussion:

Existing sources of data. Individual participants made the following comments about data that could help EPA understand the effects of hydraulic fracturing water acquisition on water availability:

- A participant encouraged the use of Dr. Nicot's data on recycling and brackish water use.
- A participant stated that EPA faces challenges in getting data about how much water companies are obtaining from public water systems (PWSs). He stated that where ground water is limited, PWSs are being approached for water for hydraulic fracturing. He noted that some of the water availability problems are self-imposed (e.g., selling beyond capacity).
- A participant said that it was important not to "double-count" when a company purchases water from a municipal water supply that has already been "counted" as withdrawn.
- Several participants stated that the data analysis should consider regulatory/legal policies and requirements (state and local regulations, court decrees, interstate agreements) that affect where and when water may be withdrawn. It was stated that the uncertainty about where and when water will be withdrawn is much greater than the uncertainty about how an aquifer will respond.
- A participant stated that projections of future drilling activity by industry will be the best predictor of future water use.
- A participant recommended that EPA define what it means by "drinking water" in the current study (e.g., does it include irrigation waters, or water meeting drinking water standards?).

Key attributes of a scientifically robust approach. Individual participants made the following comments about the attributes of a scientifically robust approach to measuring and monitoring hydraulic fracturing water use and disposition:

- A participant said that the model should function at multiple scales to understand how water acquisition affects local communities, and it should include water use for agriculture.
- A participant stated that it is important for the modeling effort to include areas experiencing more aggressive hydraulic fracturing activity.
- A participant suggested that the modeling effort prioritize areas that are heavily populated, such as the Denver basin, where there is intense competition for water supplies.
- A participant recommended that, in addition to looking at impacts on drinking water resources, EPA take a broader approach and consider economic and other impacts, such as the relative carbon intensity of unconventional resources versus coal.

Current industry practices. Individual participants made the following statements regarding current industry practices with respect to recycling and reusing water for hydraulic fracturing operations:

- A participant stated that industry is continually looking for water supplies and ways to store water to accommodate sudden changes in demand.
- A participant stated that many companies use injection wells for disposal, but because of conflicts over surface water use (e.g., in the Colorado/Utah region), reuse technologies should be considered.
- A participant suggested that refracturing may not be an important factor in understanding water use: because refracturing gas wells provides a marginal return on investment, industry is likely to drill new wells rather than refracture existing ones.

Long-term lifecycle implications and regional trends. Individual participants made the following comments regarding long-term lifecycle implication and future trends:

- A participant said that the lifecycle of the play matters with respect to water use; in the early stages of development, drilling occurs in many areas of the play and water use is less efficient, but companies are committed to putting an infrastructure in place over time that leads to greater water efficiency (e.g., pipelines for water distribution).
- A participant noted that the uncertainty in the play lifecycle is important to consider; the estimated ultimate recovery and estimates of the number of wells that need to be developed can vary widely.
- A participant stated that water use by oil and gas companies can result in additional funding for municipalities and landowners to improve water infrastructure, which could lead to a net reduction in water use in the long term.

- It was stated that future trends in water use will depend, in part, on economic and policy factors such as how gas prices compare with the price of other fuels, how electricity generation evolves, and whether there is increased use of natural gas in cars.

Summary of Presentations for Session 2: Hydraulic Fracturing Water Acquisition and Water Availability Modeling Approaches

Dr. Stephen Kraemer, EPA National Exposure Research Laboratory, gave a presentation on evaluating scenarios of potential impact of water acquisition. This aspect of the EPA study focuses on the secondary research question "How might water withdrawals affect short- and long-term water availability in an area with hydraulic fracturing activity?" Dr. Kraemer described an activity–stressor/pathway–impact framework for understanding how consumptive use of source water affects drinking water quality (including drinking water quantity). EPA is conducting water availability modeling to evaluate possible impacts of large-volume consumptive water withdrawals supporting hydraulic fracturing compared to water availability in representative basins under hypothetical, yet possible, future scenarios. He described the approach used in this modeling, which involves selecting representative watersheds, establishing baseline hydrological conditions, modifying baselines to include recent water withdrawals (including for hydraulic fracturing), designing future scenarios, running simulations, and investigating the impacts. The two watersheds selected for initial modeling, the Susquehanna River Basin and the Upper Colorado River Basin, allow EPA to explore and identify potential differences in water acquisition due to differences in geology and geography. EPA developed a spatial structure/segmentation informing watershed models for each study area, and is building on two previously calibrated and verified watershed models. Future scenarios are bounded with three possibilities: business as usual, increased well density (energy plus) and increased recycling rates (recycling plus). Dr. Kraemer noted that in the May 2013 Science Advisory Board consultation, several panelists suggested that looking at the large basin/watershed scale might not capture the signal of impact, and they recommended refining the scale of the assessments (both spatially and temporally).

Dr. Vincent Tidwell, Sandia National Laboratory, discussed mapping water availability and cost in the western United States. He described a project funded by the U.S. Department of Energy's Office of Electricity to investigate potential impacts of limited water availability in long-term transmission planning (e.g., where to site the next power plant so that it has water available to it). He noted that new thermoelectric development is a small part of consumptive use, but like hydraulic fracturing, it is a new use. He described mapping of water availability, cost and future projected demand for the 17 conterminous states in the western United States. Water availability was mapped according to five sources: unappropriated surface water, unappropriated ground water, appropriated surface/ground water, municipal/industrial wastewater, and shallow brackish water. State and federal water experts were brought together to develop water availability and cost metrics that reflect the underlying complexity of the system. Dr. Tidwell presented maps of water availability for the five sources of water, future demand for water, relative cost of water and environmental risk. Dr. Tidwell described an interactive decision support system, the Water Use Data Exchange (WaDE), developed to allow better sharing of water use, allocation and planning data among the western states and the federal government. He also described efforts to extend the mapping effort to the eastern United States, and work to assess carbon dioxide saline formation sinks, a potential source of water for thermoelectric plants as well as hydraulic fracturing.

Ben Kerr, Foundry Spatial Ltd., described integrative collaborative water research in western Canada. He described the surface characteristics and water requirements of the major western Canadian shale plays (Horn River, Montney and Duvernay) and collaborative research projects undertaken since 2008. The Horn River Basin Aquifer Project led to the development of a treatment plant for saline water, the first of its kind in Canada. The Northeast British Columbia Hydrology Modeling project was undertaken to represent the spatial and temporal variability of long-term average surface runoff, to be used in issuing water authorizations. The project resulted in the development of an interactive query tool for decision support via the Web. An integrated multi-year assessment of water resources for unconventional oil and gas plays in West-Central Alberta involves compiling existing data, interpreting key factors controlling water availability, and integrating the results from surface to deep subsurface zones. A Web-based mapping framework gives all partners access to the hydrometric data. Mr. Kerr emphasized the advantages of an integrated water resources approach that provides detailed information on all water sourcing options, brings together all stakeholders, presents project results in a unified framework to allow for direct comparison of each option, and communicates information to all interested parties.

Dr. Mitchell Plummer, Energy Resource Recovery and Sustainability Department, Idaho National Laboratory, discussed water needs and availability for hydraulic fracturing in the Bakken formation of eastern Montana. He stated that the U.S. Geological Survey (USGS) has declared the Bakken the largest continuous oil accumulation it has ever assessed. While most development in the Bakken thus far has occurred in western North Dakota, it may expand to eastern Montana. The Montana Bureau of Mines and Geology is undertaking strategic preparation for increasing tight oil development in the state. This effort includes evaluating projected water needs for hydraulic fracturing, characterizing the Fox Hills/Hell Creek aquifer, developing an approach for optimizing water usage with respect to aquifer sustainability and evaluating potential aquifer contamination impacts. Dr. Plummer described competing water management goals (e.g., availability for ranching, agriculture, drinking water and energy development) and issues with water sources in the state. He noted that transportation costs constitute about 80 percent of total costs for water acquisition and disposal. He presented preliminary results of aquifer modeling to examine the sensitivity of the Fox Hills/Hell Creek aquifer to ground water extraction.

Summary of Discussions Following Session 2: Hydraulic Fracturing Water Acquisition and Water Availability Modeling Approaches

Following questions of clarification, participants were asked to consider the following questions during the discussion:

- What would a more generalized, conceptual model look like for assessing hydraulic fracturing impacts in different areas of the United States and at different scales?
- What comments do participants have on the model for the two selected basins?
- What factors should be included in a generalized model?
- What kinds of data are necessary and available?

Key themes from Session 2 discussion:

Individual participants offered the following comments and recommendations about a generalized conceptual model, including factors that should be included:

- Several participants stated their agreement with EPA's focus on the basin level for initial modeling.
- A participant stated that changes in percentages of the water budget are very small, and it is important to incorporate uncertainty and sensitivity analyses.
- A participant stated that it is important to coordinate with USGS, which has conducted some of the premier water resources studies in the nation. The participant stated that it would be important to determine how to extrapolate the data in these studies to other regions in a meaningful way, given geologic variability.
- A participant stated that cost data and economic considerations (e.g., regarding acquisition, transport and disposal) are a critical component of any model, but weren't included in EPA's presentation. An EPA participant stated that the focus has not been on economics, but on intrinsic water availability; however, EPA will use U.S. Energy Information Administration (EIA) data on production in different plays. EIA's modeling system does include economic predictions, so economic considerations are indirectly included.
- A participant raised the issue of considering the water efficiency of thermoelectric energy compared to that of other energy sources. An EPA participant noted that EPA first needs to understand how changes in a water system impact a basin, and then more elaborate drivers for those changes can be built into an econometric framework. A participant stated that a model should account for future energy projections and for other industries that will compete for water use.

- A participant suggested factoring in the regulatory regime as part of the increased well density ("energy plus") scenario, especially for years of low flow; otherwise the model outcomes would be unrealistic. An EPA participant noted that the models of the future are not predictions, but possibilities, and that EPA is exploring ways to represent low flow criteria based on drinking water or environmental standards.

- A participant stated that ground water impacts take place over a longer time period than surface water impacts, and that seasonal time steps could be used for ground water.

- It was suggested that a model account for the fact that industry is flexible and will shift to ground water or alternative sources of water when needed.

- A participant recommended that modeling consider hydrologic interaction between surface water and ground water. The use of the USGS model GSFLOW (a model coupling ground water and surface water flow) was suggested.

- A participant suggested that EPA include in the modeling effort an area dominated by ground water sources.

- A participant raised the question of how water quality is considered in modeling (e.g., from stream flow depletion or lowering of the water table). An EPA participant requested that participants share any published information they have related to water quality.

- A participant noted that total daily maximum load (TMDL) reports and some USGS gauges have water quality information.

- A participant recommended looking at potential consequences of changing the water aquifer gradient when the pattern of water extraction changes (e.g., whether contaminated ground water could contaminate additional wells).

- A participant stated that it is difficult to get data and simulate with any confidence how long it takes saltwater to make its way up to a well. He mentioned work presented at the biannual Saltwater Intrusion Modeling Conference using SEAWAT with MT3D and MODFLOW models to simulate the movement of saltwater.

- A participant suggested that EPA define what it means by "long term," and suggested consideration of cumulative impacts and potential impacts after operations cease. The participant recommended extending the temporal scale to 2050 or 2100 to include impacts of climate change in the modeling effort.

Participants made the following comments regarding the modeling presented for the two selected basins:

- Regarding the time scale of data, a participant stated that the sophistication and accuracy of the model should be commensurate with the precision and accuracy of the data. The participant thought that using hourly input data might mislead the public about how accurate the model actually is, and a monthly time scale might be better. An EPA participant noted that some hourly meteorology data are available, but that EPA is conducting validation/verification calibration on a stepwise basis, and will first see how well the models perform on annual and monthly water budgets.

- A participant stated that the public will see the results of EPA's modeling in only two locations, and that it would be important to conduct abbreviated of qualitative analyses of other study areas.

- For the Colorado River basin, a participant recommended using the state's decision support system model rather than USGS stream gauge data, stating that the river flow is affected by artificial features, such as dams and reservoirs, and salinity is a significant issue.

- A participant asked about documentation for how the model was selected and constructed. An EPA participant noted that the study progress report (available at http://www2.epa.gov/hfstudy/potential-impacts-hydraulic-fracturing-drinking-water-resources-progress-report-december) describes factors taken into account for model selection, including that the model be open source, publicly available and vetted for the appropriate types of analyses.

Concluding Remarks

Ramona Trovato and **Dr. Glenn Paulson** thanked the participants on behalf of EPA for contributing their time and expertise, and for the high-level, constructive comments they brought to the workshop. They encouraged the participants to submit data and scientific literature to inform the current drinking water resources study, noting that stakeholder input will help ensure that EPA's drinking water study is based on sound science and reflects the most up-to-date practices and data from this rapidly changing industry.

Appendix A.

Extended Abstracts from Session 1: Data on Water Acquisition and Water Recycling/Reuse

Water Acquisition: Analysis of Existing Data[1]

Andrew Gillespie
U.S. Environmental Protection Agency, Office of Research and Development

Information presented in this abstract is part of the EPA's ongoing study. EPA intends to use this, combined with other information, to inform its assessment of the potential impacts to drinking water resources from hydraulic fracturing. Mention of trade names or commercial products does not constitute endorsement or recommendation for use.

Introduction

In 2011, the EPA began research to assess the potential impacts, if any, of hydraulic fracturing on drinking water resources, and to identify the driving factors that may affect the severity and frequency of such impacts. Scientists are focusing primarily on hydraulic fracturing of shale formations to extract natural gas, with some study of other oil-and gas-producing formations, including tight sands, and coalbeds.

The EPA has designed the scope of the research around five stages of the hydraulic fracturing water cycle. Each stage of the cycle is associated with a primary research question:

- **Water acquisition**: What are the possible impacts of large volume water withdrawals from ground and surface waters on drinking water resources?
- **Chemical mixing**: What are the possible impacts of hydraulic fracturing fluid surface spills on or near well pads on drinking water resources?
- **Well injection**: What are the possible impacts of the injection and fracturing process on drinking water resources?
- **Flowback and produced water**: What are the possible impacts of flowback and produced water (collectively referred to as "hydraulic fracturing wastewater") surface spills on or near well pads on drinking water resources?
- **Wastewater treatment and waste disposal**: What are the possible impacts of inadequate treatment of hydraulic fracturing wastewater on drinking water resources?

This presentation focuses on the **water acquisition** stage of the water cycle. The EPA is working to better characterize the amounts and sources of water currently being used for hydraulic fracturing operations, including recycled water, and how these withdrawals may impact local drinking water quality and availability. To that end, secondary research questions related to water acquisition have been developed as follow:

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[1] Material in this abstract is drawn primarily from "Study of the Potential Impacts of Hydraulic Fracturing on Drinking Water Resources: PROGRESS REPORT, US EPA, December 2012, EPA/601/R-12/011

- How much water is used in hydraulic fracturing operations, and what are the sources of this water?

- How might water withdrawals affect short-and long-term water availability in an area with hydraulic fracturing activity?

- What are the possible impacts of water withdrawals for hydraulic fracturing operations on local water quality?

The EPA is using a transdisciplinary research approach to investigate the potential relationship between hydraulic fracturing and drinking water resources. This approach includes compiling and analyzing data from existing sources, evaluating scenarios using computer models, carrying out laboratory studies, assessing the toxicity associated with hydraulic fracturing-related chemicals, and conducting case studies.

For specific questions related to water availability, EPA is undertaking two different kinds of research activities to address these research questions. One set of activities involves scenario evaluation in different water basins using spatially-explicit models and different assumptions regarding future water usage. This line of work is the subject of another presentation, and is not discussed further here. The set of research activities, and the topic of this presentation, involves analysis of data from existing sources.

Water Usage in Hydraulic Fracturing

Hydraulic fracturing fluids are usually water-based, with approximately 90% of the injected fluid composed of water (GWPC and ALL Consulting, 2009). Estimates of water needs per well have been reported to range from 65,000 gallons for coalbed methane (CBM) production up to 13 million gallons for shale gas production, depending on the characteristics of the formation being fractured and the design of the production well and fracturing operation (GWPC and ALL Consulting, 2009; Nicot et al., 2011). Assuming an average use of 100 gallons per person per day, five million gallons of water are equivalent to the water used by approximately 50,000 people for one day. The source of the water may vary, but is typically ground water, surface water, or treated wastewater, as illustrated in Figure 1. Industry trends suggest a recent shift to using treated and recycled produced water (or other treated wastewaters) as base fluids in hydraulic fracturing operations.

According to the latest (2005) published estimates of water usage by the USGS (Kenny et al., 2009), the US uses approximately 1.5×10^{14} gallons of water per year, of which 1.5×10^{12} (or ~ 1%) is used for mining, oil and gas. The US EPA estimates that hydraulic fracturing use in 2009-10 ranged from 7 to 14×10^{9} gallons, equivalent to less than 0.1% of the total US usage in 2005 (US Environmental Protection Agency, 2011). At the national level, it appears that hydraulic fracturing accounts for a very small fraction of the Nation's water use.

However, water use for hydraulic fracturing may vary significantly over space and time, with potential impacts depending on the scale and distribution of hydraulic fracturing operations in a given area, the local geology and hydrology, competing local water needs, and with climate and seasonality. Thus a complete analysis of potential impacts on drinking water associated with hydraulic fracturing needs to consider multiple scales.

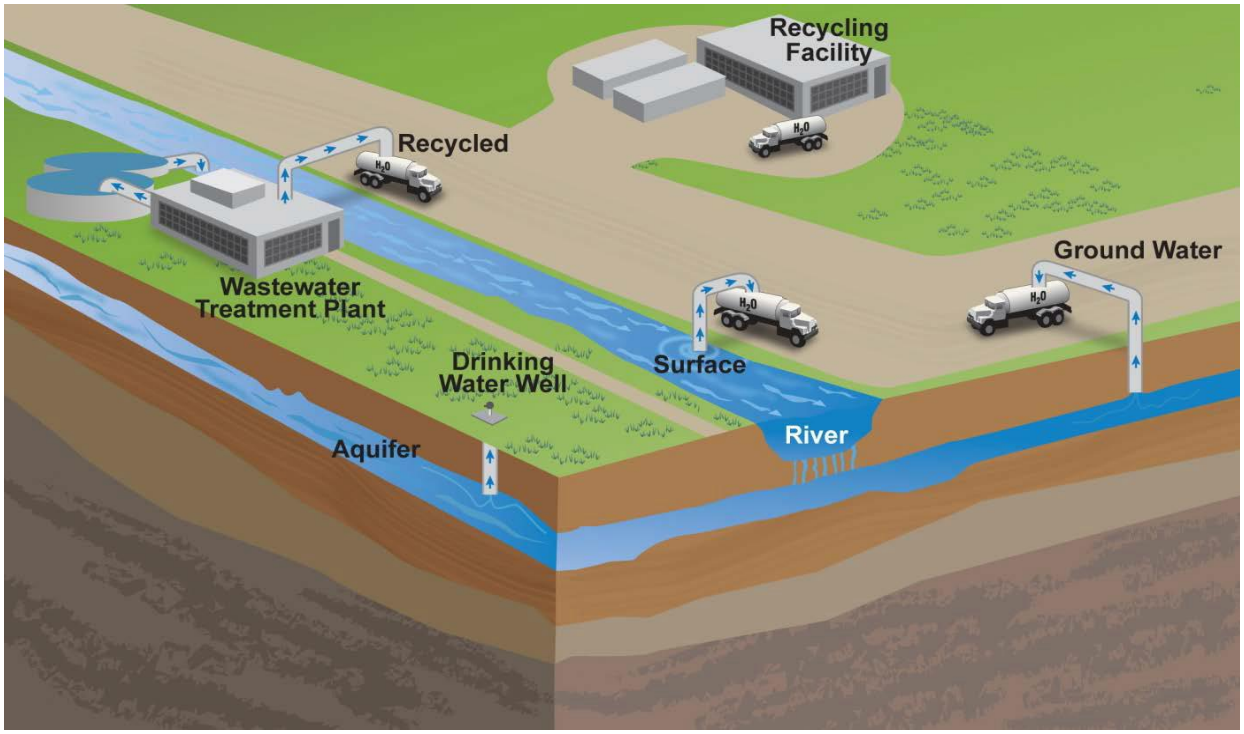

Figure 1. Water acquisition. Water for hydraulic fracturing can be drawn from a variety of sources including surface water, ground water, treated wastewater generated during previous hydraulic fracturing operations, and other types of wastewater.

Analysis of Existing Data on Water Availability

Data from multiple sources have been obtained for review and analysis. First, the EPA is reviewing scientific literature relevant to the research questions posed in this study. A *Federal Register* notice was published on November 9, 2012, requesting relevant, peer-reviewed data and published reports, including information on advances in industry practices and technologies.

Second, additional data come directly from the oil and gas industry with high levels of oil and gas activity.

- Information on practices used in hydraulic fracturing (including water acquisition) has been collected from nine companies that hydraulically fractured a total of 24,925 wells between September 2009 and October 2010.

- Well construction and hydraulic fracturing records provided by well operators are being reviewed for 331 oil and gas wells across the United States; data within these records are being scrutinized for, among other things, information regarding the volume and sources of water used during hydraulic fracturing.

- Additional data on water use for hydraulic fracturing are being pulled from over 12,000 well-specific chemical disclosures in FracFocus, a national hydraulic fracturing chemical registry operated by the Ground Water Protection Council and the Interstate Oil and Gas Compact Commission.

The EPA plans to synthesize results from these different projects, including a critical literature review, in a report of results that will answer as completely as possible the study's research questions.

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Sources of Data for Quantifying Hydraulic-Fracturing Water Use in Texas

Jean-Philippe Nicot
Bureau of Economic Geology, The University of Texas at Austin, Austin, TX

Introduction

In 2011, ~82,000 acre-feet (AF; 1 AF =325,851 gallons) of water was used for hydraulic fracturing (HF) completions in Texas (Nicot et al., 2012; **Error! Reference source not found.**). This amount represents a small fraction of total state water use as reported by the Texas Water Development Board (TWDB). Water use has averaged 15 million AF/yr in the past 10 years, with interannual variations related to population growth and irrigation needs. The focus on Texas is justified by (1) the size of the state with multiple plays undergoing HF, either so-called shale plays (for example, Barnett, Eagle Ford, Haynesville, and Wolfcamp shales), which are actually source rocks for hydrocarbons, or tight formations (for example, Cotton Valley, Cleveland, or Spraberry Formations), which are reservoirs with very low permeability; both types produce either oil or gas or both (Figure 2); and (2) hydrocarbon production from unconventionals relative to production in the entire U.S. Gas production from shales in 2011 was ~3 Tcf (3×10^{12} standard cubic feet), 35% of the entire U.S. shale-gas production (EIA, 2013a; RRC, 2013a). Oil production in 2012 was 730 million barrels (MMbbl), 31% of the entire U.S. oil production (EIA, 2013b; RRC, 2013a) and a significant fraction of which is produced through HF. Information about formations that have HF-enhanced production is available on the Railroad Commission of Texas (RRC) website (RRC, 2013b). Eagle Ford Shale produced 175 MMbbl of oil and condensate, and the Barnett Shale produced 1.77 Tcf, both in 2012 (RRC, 2013b). In the following sections, we examine the sources or potential sources informing water use by the oil and gas industry and, more generally, water use by all stakeholders.

Hydraulic Fracturing Water Use

In Texas, operators are required to report completion information to the regulating agency (RRC). Before drilling a well, including recompletion of an existing well, operators must apply to the RRC for a drilling permit (form W-1). Once the well is completed, operators submit a W-2 form (for oil-producing wells) or G-1 form (for gas-producing wells). The W-2 and G-1 forms contain self-reporting information about well stimulation, including HF (RRC, 2013c). The completed forms can be consulted at RRC facilities, downloaded as scanned files from the RRC website (RRC, 2013d), and are available for purchase in a relatively cumbersome format with information captured from the forms (RRC, 2013e). However, the RRC makes the sharing of this information in the public domain easy with frequent updates; several large and small vendors collect the information, update it as it becomes available from the RRC, and provide it in a form that can be queried for a fee. The data must nevertheless be edited for typos and other errors that would bias the results if not attended to. Water-use intensity (water volume used per unit length of lateral) and proppant loading (amount of proppant per unit volume of water) are examples of ratios that are used to test for errors (see Nicot et al., 2011, and Nicot and Scanlon, 2012, for details). Wells with limited or clearly erroneous data are given water-use values derived from the field average or median water use. Once water use for individual wells is known, it can be summed for any arbitrary geographic area (usually county). Similar information is now available from the website FracFocus (http://fracfocus.org/welcome), but, as of May 2013, not in a format that can be queried, although several groups have started to arrange raw data to allow them to be queried. Since February 2012, State of Texas regulations have required operators to submit water-use information to the FracFocus website.

Water use, however, is different from water consumption, and definitions across professional fields vary slightly. *Water use* is generally defined as the amount of water needed to perform HF stimulation, whatever the source of the water. In the context of a power plant, water use would be equivalent to water withdrawal and represents the amount of water needed for the plant to operate normally. *Water consumption* is defined as the amount of water lost to the system, with actual numbers hinging on the definition of the system and of its boundaries. For a power plant, the system is defined as the plant, and consumption is the amount lost to evaporation, the rest being returned to the (surface) water body. In the HF context, however, water consumption is equivalent to the amount of water originating from surface-water bodies or groundwater aquifers, which in this case compose the system. Additional water used for HF is derived from reuse and recycling of used-water streams. For example, flowback and produced water from nearby and earlier HF operations can be reused. *Flowback* is generally defined as fluids with the same geochemical identity as those of the HF fluid, whereas *produced water* is generally understood as coming from the brine or saline fluid residing in the formation. However, in most cases, the transition period between the two end members is long and complex. Wastewater streams from industrial or municipal treatment plants are another potential source. Unfortunately, such information about the actual source(s) of HF water (surface water, groundwater, other, or a mix thereof) is not captured by the various RRC databases and must be accessed in indirect ways that can be categorized as information obtained from (1) water users (the industry) or (2) water providers. Because oil and gas operations are fragmented among thousands of different operators across the state, even so-called majors and large independents do not control a large percentage of most plays. Therefore, interaction with operators to learn about their operations must be complemented by an independent approach. Only a multipronged approach with independent results consistent with one another can reduce uncertainty.

Water rights follow two very different regimes in Texas: surface water belongs to the State, whereas the Texas Supreme Court recently (TSC, 2012) confirmed that groundwater belongs to the landowner. The prior appropriation doctrine "first in time, first in rights" for surface-water rights is followed by the State of Texas, which grants permits to users in order of seniority. The system managed by the Texas Commission on Environmental Quality (TCEQ) is complex, the basic information about which is accessible in a public database (TCEQ, 2013b). Many water rights are held by quasi-governmental entities, such as the Trinity River Authority of Texas (TRA) or the Brazos River Authority (BRA) in the Barnett Shale area. Information on water sales to oil and gas operators can therefore be accessed, in particular volumes. The information, however, unavailable from the internet, is typically aggregated over a large area and may be mixed with other similar usage, such as water use for quarrying operations. Local water districts (such as the Tarrant Regional Water District) and municipalities (for example, the City of Arlington) have provided water to oil and gas operators for the same Barnett Shale play. The information is also in the public domain but is not compiled across organizations and is accessible only in aggregated form and, in a time-consuming step, by contacting individual entities. Water-source determination is simpler in areas of the state having little surface water (to the west and south), where most, if not all, HF water is from groundwater.

In Texas, groundwater withdrawals follow the rule of capture that is sometimes moderated by rules of Groundwater Conservation Districts (GCD's). Approximately 100 GCD's cover a significant fraction of the state (TWDB, 2013a). Their number recently increased in parallel with HF activities, although some areas within plays that have HF operations are not part of a GCD—for example Webb County in the Eagle Ford Shale next to the border with Mexico or some counties in the Permian Basin. In such cases, groundwater withdrawals for HF may remain uncertain but might be estimated as a complement to surface-water use. Depending on the GCD, groundwater use directed to HF may or may not be available. Some GCD's require registering and reporting of water but do not put limits on pumpage, whereas others meter groundwater pumpage and put a cap on the amount that can be extracted. Each GCD has to be contacted individually because no central database exists. TWDB and Regional Water Planning Groups (TWDB, 2013b) collect and present abundant information on pumping, but obtaining specific HF-related information can be a challenge.

Nicot et al. (2012) relied mostly on information from operators to report the split between surface-water and groundwater sourcing in Texas (Figure 3). Toward the west and south, groundwater use increases mostly because of more limited surface-water resources and follows precipitation distribution across the state, reaching ~80% in the Anadarko Basin, 90% in the Eagle Ford Shale, and close to 100% in the Permian Basin. Surprisingly, the amount of groundwater use toward the east also increases, according to interview results, with ~70% of HF water use sourced from groundwater in East Texas (Haynesville and other tight formations). These data are in contrast to observations in the Louisiana section of the Haynesville Shale, where operators, after relying heavily on groundwater, now rely mostly on surface water (Hanson, 2009). In addition to possible sample bias because surface water is generally plentiful in East Texas, this behavior may be occurring because groundwater is regulated by the Louisiana Department of Natural Resources, whereas in the Haynesville Shale, Texas section, rule of capture applies because no GCD exists to potentially limit groundwater use.

The amount of non-fresh water used for HF also varies across plays (Figure 4) and across operators. The amount of recycled water used in HF (which is different from amount of recycling) is generally low across the state, at a few percent in the Barnett, Haynesville, and Eagle Ford shales. It is also low in the Permian Basin. More recycling occurs in the Anadarko Basin because flowback/produced water is less saline than elsewhere. Note that the amount of recycled water is used for new HF operations is contingent to the amount available for recycling. The amount is generally low for producing shales—for example, ~15% and ~20% of HF water in the Haynesville and Eagle Ford Shales and somewhat higher, ~60%, in the Barnett Shale after 1 year (Figure 5). Tight formations, such as the Cotton Valley in East Texas (~60%) or in the Permian Basin (75–80% on average) or Anadarko Basin (100% on average), generally produce more water than do shales. Producing more water means that more water is available for recycling. In Texas, most flowback/produced water is injected into deep injection wells—information that has recently become specifically available from the RRC (RRC, 2013f). In the past, injection from HF operations was combined with conventional salt water disposal and collected through the H-10 form (RRC, 2013c).

In conclusion, if data on HF water use are relatively easy to access, water consumption and water sourcing are more difficult to evaluate. Information on water quality and brackish-water use is also lacking. So that the lack of neatly compiled information can be compensated for, all information sources must be considered and their consistency ensured. In addition, HF water use and consumption must be understood within the context of water use and consumption of all other sectors.

Comparison with Other Water Uses

Several papers and reports have documented that HF water use is a small fraction of the total water use in the state (for example, Nicot et al., 2012, for Texas; Murray, 2013, for Oklahoma; Colorado state agencies for Colorado, 2013). However, HF demands are irregularly distributed throughout the state and, in Texas; HF water use fraction of total water use can be much higher at the county level (Nicot, 2013). TWDB has commonly reported results from annual mandatory and voluntary water use surveys (TWDB, 2013c), but information in terms of true water consumption is less available. Clearly, in order for HF water use and consumption to be better compared with total water use and consumption for a given geographic area, water use and water consumption must be characterized and differentiated. State-level water use is generally reported at ~15 million AF distributed among irrigation, municipal, and manufacturing, along with other minor water uses (Figure 6). Irrigation is the largest sector, and 85% of irrigation water use has been estimated to have been actually consumed (Solley et al., 1998; Scanlon et al., 2010). Municipal water use is the second-largest sector, and consumptive use could amount to ~30% of water use at the state level (Hermitte and Mace, 2012); the remainder is treated and disposed of into surface-water bodies to be reused downstream (for example, the Dallas-Fort Worth metroplex and Houston through the Trinity River).

If comparing state HF and total water use turned out to be straightforward, comparison at the county level could be more challenging because of the discrepancy between point of withdrawal and point of use. For example, Fort Worth and adjoining communities receive most of their water through the Tarrant County Regional Water District, which imports water from sometimes distant counties. In other words, large water users in Tarrant County do not rely on local resources. Therefore, locally sourced HF water may seem artificially to be a small fraction of total water use but, in a true comparison, it should be compared with other locally sourced water usage, such as groundwater used in some suburbs. Differentiating between local and other water sources is especially difficult for large urban counties, some of which overlie shale plays and other tight formations. In addition to Tarrant County in the Barnett Shale play, San Antonio and Bexar and surrounding counties in or near the Eagle Ford play offer the same challenges. Water use in rural counties is locally sourced, but significant amounts of water may be transferred to distant cities. Municipal water of some midsize cities can also be sourced away from the county in which they are located. Such complex interactions can be partly exposed through (1) the TCEQ WUD database, which provides information on the source of the municipal water but not its amount (TCEQ, 2013b), and (2) abundant documentation from Regional Water Planning Groups (TWDB, 2013b).

Conclusions

Data to quantify HF water use in Texas are plentiful and originate either from the operators themselves or from water providers or permitting authorities. Data sources fall into two broad categories: (1) centralized databases with easy access and (2) data dispersed through several agencies and other entities. However, the political climate and the high-level interest in these data have driven several of these agencies to collect HF data, most likely improving future data collection. Groundwater use is typically less regulated and sometimes unregulated, and accurate records are more difficult to collect. In addition, although significant numbers of data are potentially available about ground- and/or surface-water HF use, collecting these data from many entities with various legal statuses and goals represents a large effort. Ultimately, HF water-use data may be patchy, but they are crucial to our ability to crosscheck data from different sources and assess their consistency. Also, when aquifer heads or water tables are being considered, all usage must be documented accurately, in addition to areas where HF is taking place. For example, droughts typically increase groundwater withdrawals for all uses, and access to such data is important to an understanding of the impact of HF water use.

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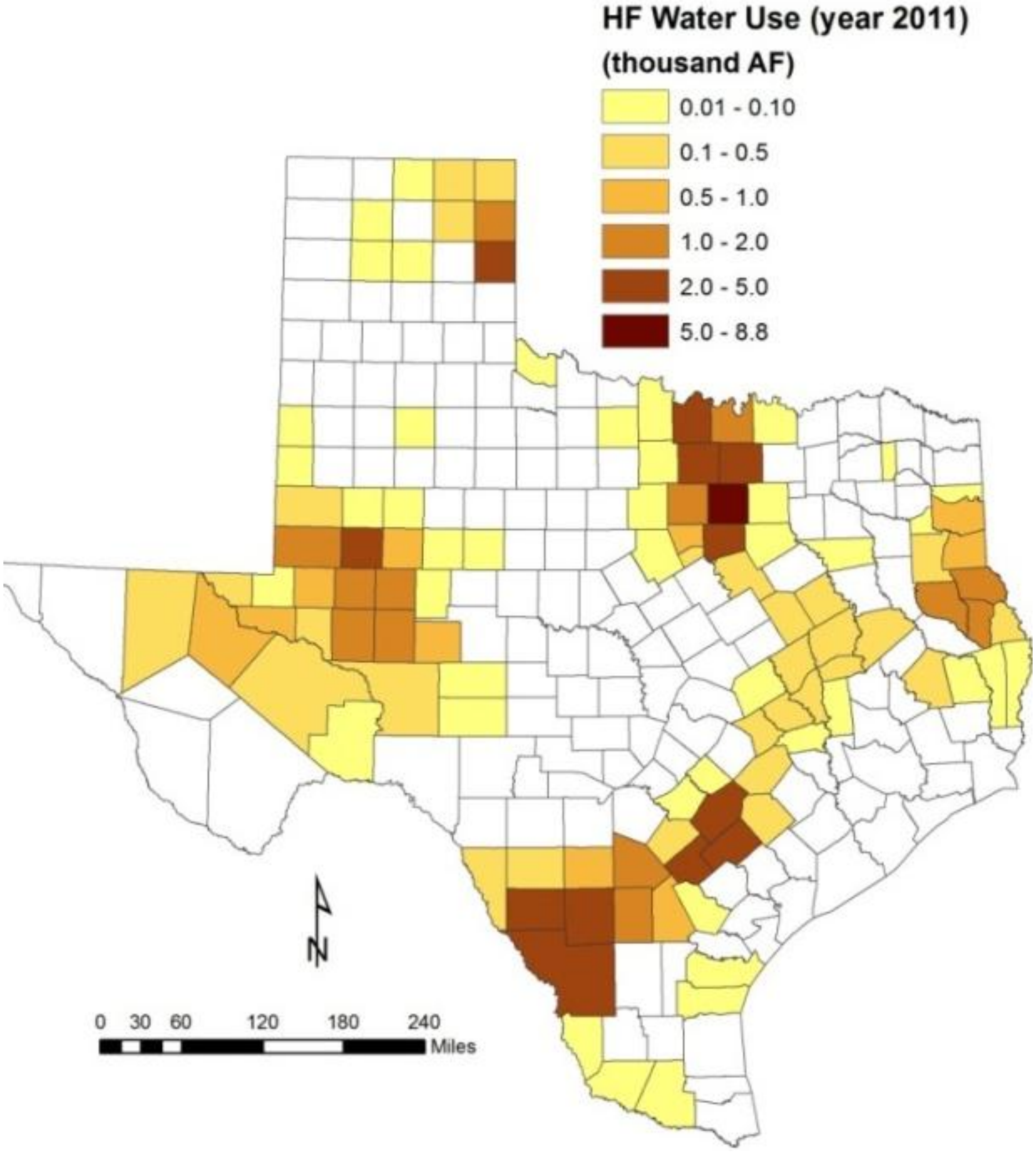

Figure 1. HF water use in Texas.

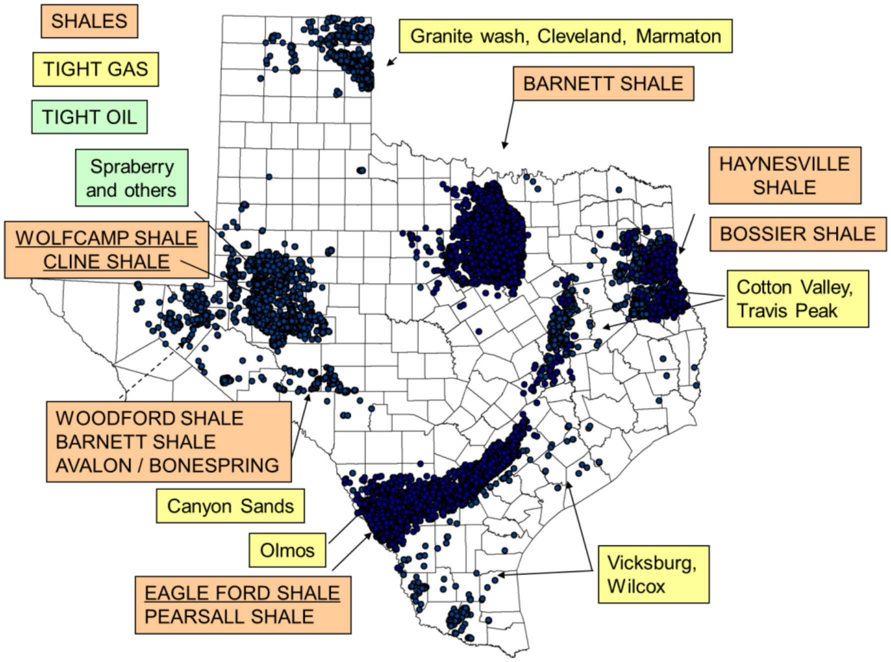

Figure 2. Some HF plays in Texas.

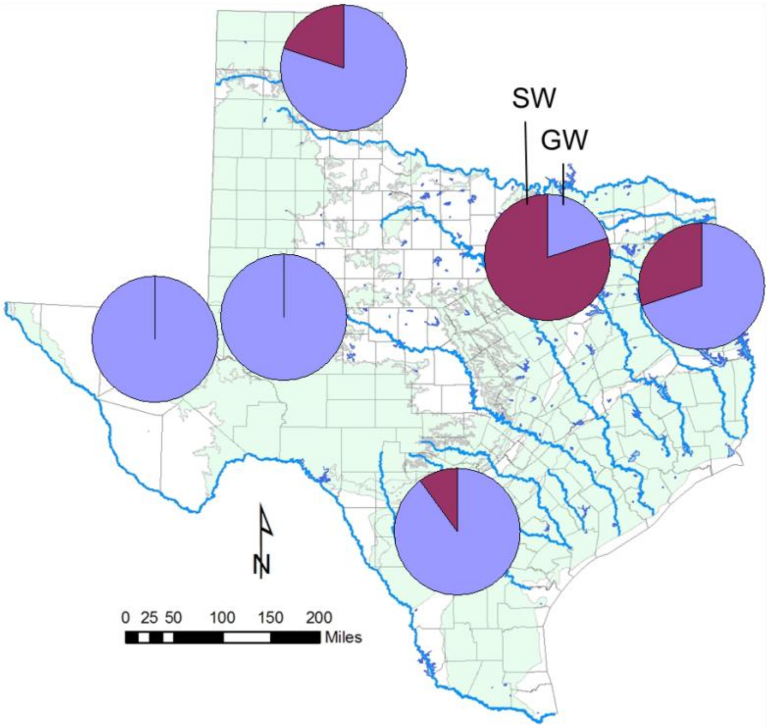

Figure 3. Estimate of groundwater/surface water split for selected plays. Background shows outline of major aquifers, as well as main rivers. Figure based on operator information equivalent to ~30% of statewide HF water use. From Nicot (2013).

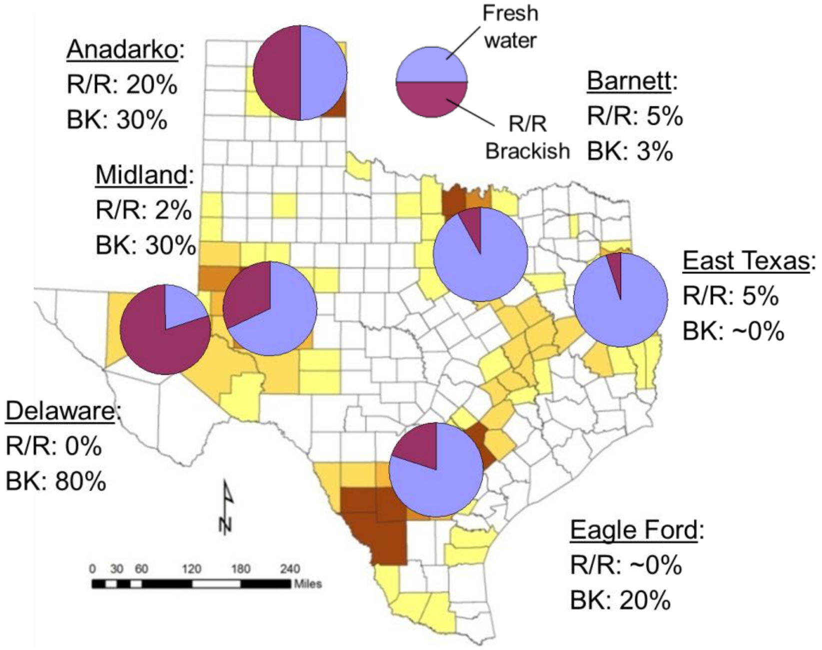

Figure 4. Fraction of HF water sourced from brackish water and from recycling in selected plays. Background shows 2011 HF water use. Figure based on operator information equivalent to ~30% of statewide HF water use. From Nicot (2013).

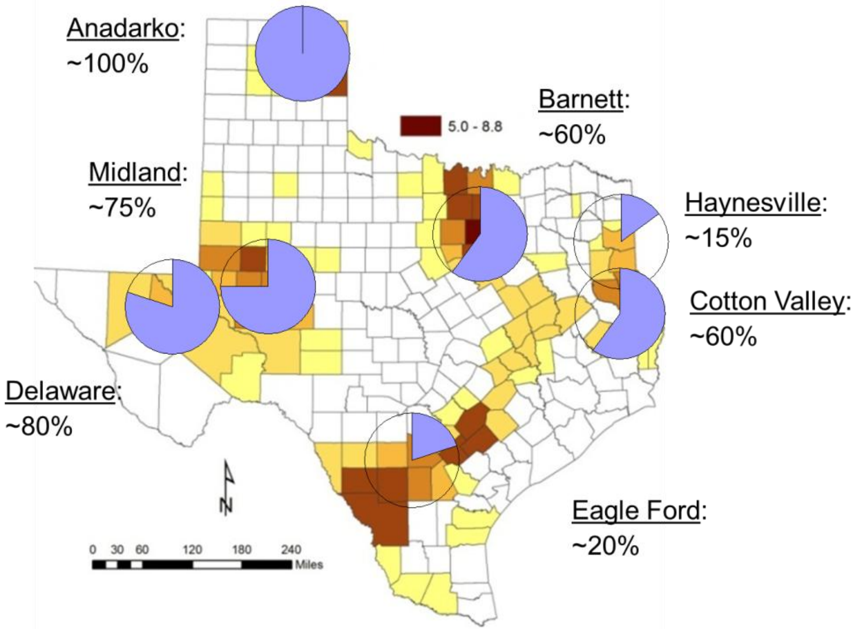

Figure 5. Amount of flowback/produced water relative to amount injected after 1 year of production in selected plays. Background shows 2011 HF water use. Figure based on operator information equivalent to ~30% of statewide HF water use. From Nicot (2013).

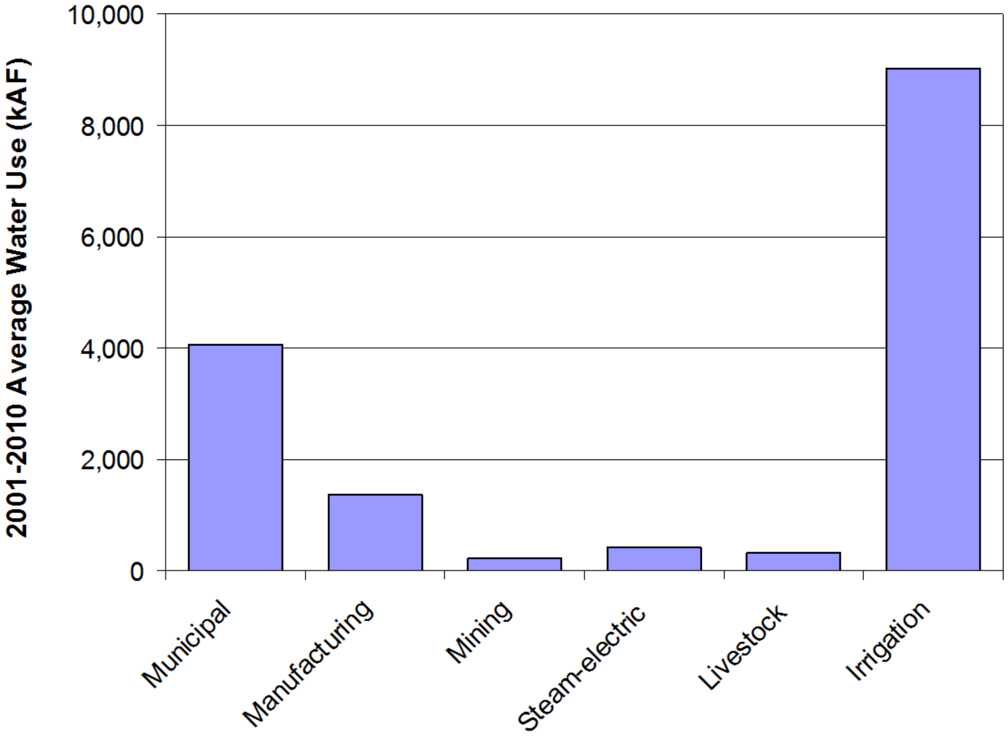

Figure 6. Average statewide water use for the 2001–2010 period in Texas. Total water use ~15 million AF.

Water Acquisition for Unconventional Natural Gas Development Within the Susquehanna River Basin

Jim Richenderfer
Director, Technical Programs
Susquehanna River Basin Commission

The statements made during the workshop do not represent the views or opinions of EPA. The claims made by participants have not been verified or endorsed by EPA.

Introduction and Background

The Susquehanna River Basin Commission (SRBC) is a federal compact formed by an act of Congress between New York, Pennsylvania, Maryland, and the federal government. The federal government is represented by the U.S. Army Corps of Engineers.

The Susquehanna River Basin (Basin) is approximately 27,510 square miles in size. It is home to approximately 4.3 million people, comprises 43 percent of the watershed area of the Chesapeake Bay, and sends on average approximately 18 million gallons per minute (or 26 billion gallons per day) to the Chesapeake Bay. Approximately 84 percent of the Basin is underlain by natural gas containing geologic formations, including the well-known Marcellus Shale and Utica Shale Formations.

The development of oil and gas resources within the Susquehanna River Basin is not new to the Basin. Development of these energy resources using conventional vertical wells has been ongoing for decades. However, what is new to the Basin is the use of unconventional horizontal drilling techniques in concert with high volume, high pressure hydraulic fracturing techniques. These techniques enable the gas industry to successfully access the Marcellus Shale located 5,000 to 7,000 feet below grade and facilitate the movement of the natural gas from the surrounding shale formation into the newly drilled wells. To complete the hydraulic fracturing process, approximately four and a half million gallons of water are needed per horizontal well.

The majority of the Marcellus Shale play has occurred and will continue to occur within the northern tier counties of the Pennsylvania portion of the Basin, primarily within the Appalachian Plateau. The Plateau is generally characterized by relatively small watersheds occupied by pristine, low order headwater streams. In these headwater areas, the typical streamflow rates are relatively low, are hydrologically flashy in nature, lack any significant baseflow component, have limited recharge areas, and commonly support cold water aquatic ecosystems. These cold water ecosystems can be more sensitive to environmental changes, including flow alteration, than the warm water ecosystems located farther down-basin.

In the spring of 2008, when the Marcellus Shale play first began within the Basin, very little was known regarding the quantities of water needed and the patterns of water use associated with the unconventional gas industry. For those reasons, the SRBC made the decision to regulate all surface water and groundwater withdrawals and all consumptive use of water for unconventional gas development beginning at "gallon one." This extremely low threshold differs from the normal 100,000 gallon per day threshold for all other withdrawals and 20,000 gallons per day threshold for all other consumptive uses. In addition, approvals have been written for a term of 4 years as opposed to the more common 15-year period. This conservative approach has been effective and remains in place today.

Water Acquisition: Withdrawal and Consumptive Use Approval Process

In general, the gas industry relies on water taken from surface water withdrawals, groundwater withdrawals, public water systems, wastewater treatments plants (public or private), and from impaired waters such as mine drainage. To date, the gas industry has focused primarily on surface water withdrawals, with public water systems second in order of preference. Only a few groundwater withdrawals and mine drainage waters have been approved by the commissioners, and to date they have been responsible for only a very small percentage of the total water used by the industry. Given the very dry conditions that frequently occur in the upper basin in late summer and early fall, and the frequency with which the gas industry has had to suspend its water withdrawals due to low flow conditions during these periods, it is believed that the gas industry may refocus some of its future attention on the development of groundwater withdrawals.

To gain approval from the SRBC for either surface water withdrawals, groundwater withdrawals, or consumptive use, the natural gas industry is required to make a formal application. General information required in both withdrawal applications and consumptive use applications include the exact location of the proposed withdrawal or use (latitude/longitude), the maximum instantaneous rate of the requested withdrawal, and the maximum daily amount of the withdrawal or consumptive use. In addition, there are public notices and legal notices that must be filed, adjacent landowner notices that must be given, and other legal requirements regarding ownership or legal access to the proposed point of withdrawal.

Site-specific technical information submitted by the applicant, together with site inspections and information generated by SRBC staff, are critical parts of the technical review process for each withdrawal or consumptive use application. Once all of the regulatory requirements have been met and a project has been approved by the SRBC, daily monitoring data and compliance data are required as conditions of the approval. These data are submitted quarterly online by the unconventional natural gas industry. This information has enabled SRBC staff to clearly define the water use profile for the industry.

Water Withdrawals and Consumptive Use Rates

With respect to regulated surface water withdrawals made during calendar year 2012, the unconventional natural gas industry ranks fourth, with an average withdrawal rate of 8 million gallons per day (MGD), behind electric generation (2,749 MGD), water supply (57 MGD), and manufacturing (25 MGD). The consumptive use monitoring data indicate that the unconventional natural gas industry ranks second (currently at 9.3 MGD) behind electric generation (92.7 MGD), with water supply (8.9 MGD) and manufacturing (8.3 MGD) ranked a close third and fourth, respectively.

As of December 31, 2012, a total of 10,285 MGD of water (10.285 billion gallons) were consumptively used by the unconventional gas industry within the Basin since the Marcellus play began in early 2008. This number represents the total consumptive water use for all of the individual gas companies involved in the play (an industry-wide total).

As previously noted, the water consumptively used by the unconventional gas industry originates primarily from one of two types of approved water sources: surface water withdrawals docketed (approved) by the SRBC, and from bulk water purchased from public water suppliers that were approved but not docketed by the SRBC. The relative amounts of water taken from these two primary types of approved sources have varied over time. During the early stages of the play (calendar year 2008), the majority of water (approximately 75 percent) was taken from public water systems, while approximately 25 percent of the water was taken from docketed surface water withdrawals under the direct control of individual gas companies. No approved groundwater withdrawals occurred for the unconventional gas industry during 2008.

During calendar year 2009, on average, approximately 46 percent of the water was taken from docketed sources and 54 percent was taken from public water systems. During calendar year 2010, the docketed water withdrawals increased to 87 percent of the water taken, and public systems dropped to approximately 13 percent of the water taken. No approved groundwater withdrawals occurred for the unconventional gas industry during calendar years 2009 or 2010. Calendar year 2011 found the industry taking approximately 77 percent of their water from docketed sources and 23 percent from public water systems. Less than 1 MGD of groundwater and mine drainage were withdrawn by the industry during calendar year 2011.

By calendar year 2012, the industry was taking approximately 73 percent of their water from docketed surface water sources and 27 percent from public water systems. Reliance on groundwater withdrawals and mine drainage for calendar year 2012 remained below 1 MGD for the industry. The overall trends in water takings in amounts and source types during the 5-year period (2008 through 2012) were the result of the industry establishing more docketed surface water withdrawal approvals over time and relying less on the more expensive public water systems for their water needs.

Water Use Profile for Hydraulic Fracturing

By December 31, 2012, after the Marcellus play had been in progress for more than 5 years, a total of 1,977 unconventional natural gas wells had been hydraulically fractured within the Basin. On average, each well's hydraulic fracturing effort consumed 4.4 million gallons of water. Eighty-six (86) percent of that average amount of water was comprised of freshwater (3.8 million gallons), and 14 percent (0.6 million gallons) was comprised of reused flowback waters from previous fracturing events. The amount of flowback waters that returned to each wellhead within the first 30 days after fracturing pressures were released ranged from a low of 5 percent (220,000 gallons) to a high of 12 percent (528,000 gallons).

The SRBC places a very high priority on the sustainability of the water resources within the Basin. All projects, whether proposed by individuals, by municipalities, or by industries, are evaluated from a sustainability perspective. Great efforts are made by SRBC staff to thoroughly study and understand the hydrologic attributes of each subbasin in which a water-related project is proposed. Common hydrologic tools used in these efforts include calculations of surface water and groundwater budgets, definition of recharge areas, cumulative impacts, potential impacts on existing water users, and trend analyses to name just a few. In addition, for every surface water project (and some groundwater projects), reference streamflow gages are identified, passby triggers are calculated when needed to protect aquatic ecosystems during low flow periods, and environmental assessments including aquatic resource surveys are routinely performed. All of these steps are part of the ongoing efforts of the SRBC to best manage in a sustainable manner the valuable water resources of the Basin.

Recycling and Reuse of Produced Water to Reduce Freshwater Use in Hydraulic Fracturing Operations

Matthew E. Mantell
Chesapeake Energy Corporation

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Introduction

Water is an essential component of unconventional oil and gas development. Operators use water for drilling, where a mixture of clay and water is used to carry rock cuttings to the surface, as well as to cool and lubricate the drillbit. Drilling a typical Chesapeake unconventional well requires between 85,000 and 600,000 gallons of water. Water is also used in hydraulic fracturing, where a mixture of water and sand is injected into the formation at high pressure to create small cracks in the rock and allows gas to freely flow to the surface. Hydraulically fracturing a typical Chesapeake well requires an average of 3.7 million gallons of water. The water supply requirements of unconventional oil and gas development are isolated in that the water needs for each well are limited to drilling and hydraulic fracturing, and the placement of wells are spread over the entire play. Subsequent fracturing treatments of wells to re-stimulate production are possible, but unlikely, and re-stimulation is dependent upon the particular characteristics of the producing formation and the spacing of wells within the field. A breakdown of approximate water use for drilling and fracturing by play is provided below:

Table 1. Water Use in Select Unconventional Oil and Gas Plays

Unconventional Oil and Gas Play	CHK [1] Average Drilling Water Use per Well (in gallons)	CHK [1] Average Hydraulic Fracturing Water Use per Well (in gallons)	Total Average Water Use Per Well [1]
Gas Shale Plays (primarily dry gas)			
Barnett	250,000	3,100,000	~ 3.4 Million Gallons
Marcellus	85,000	4,400,000	~ 4.5 Million Gallons
Haynesville / Bossier	600,000	4,800,000	~ 5.4 Million Gallons
Liquid Plays (Gas, Oil, Condensate)			
Mississippi Lime	100,000	2,000,000	~ 2.1 Million Gallons
Cleveland / Tonkawa	200,000	2,500,000	~ 2.7 Million Gallons
Niobrara	300,000	3,400,000	~ 3.7 Million Gallons
Utica	100,000	3,700,000	~ 3.8 Million Gallons
Granite Wash	200,000	4,600,000	~ 4.8 Million Gallons
Eagle Ford	125,000	4,800,000	~ 4.9 Million Gallons

[1] *Based on 2012 CHK Operating Data*

Produced Water Management

Produced water plays a key role in the environmental and economic viability of unconventional oil and gas development. Produced water is a byproduct of all oil and natural gas (energy) development. In order to successfully develop these resources, produced water has to be effectively managed.

For the purposes of this discussion, *produced water* is all water that is returned to the surface through a well borehole and is made up of water injected during the fracture stimulation process, as well as natural formation water. Produced water is typically produced for the lifespan of a well, although quantities may vary significantly by play. Produced water quality can also vary tremendously from brackish (not fresh, but less saline than seawater) to saline (similar salinity to seawater) to brine (which can have salinity levels multiple times higher than seawater). Furthermore, the term *flowback* refers to the *process* of excess fluids and sand returning through the borehole to the surface. For this discussion, the water produced during flowback operations is considered produced water.

The feasibility of produced water reuse is dependent on three major factors. First is the quantity of the produced water generated, including the initial volume of produced water generated (typically during the first few weeks after stimulation). The second factor is the duration in time of produced water generation, including the rate at which water is generated and how it declines over time. Wells that produce significant volumes of produced water during the initial time period are preferred for reuse due to the logistics involved in storing and transporting the water for reuse. A continuous volume can keep tanks and trucks moving, increasing the economic efficiency of reusing the produced water from one wellsite to another. The Mississippi Lime and Permian Basin wells produce the highest amount of initial produced water. These plays contain wells that produce over one million gallons of water in the first 10 days after completion. This volume is sufficient to provide nearly 50% of the water needed to fracture a new well in these plays. The Barnett, Eagle Ford, Granite Wash, Cleveland / Tonkawa Sand, Niobrara, Marcellus and Utica Shale all produce a significant volume of initial produced water, enabling the effectiveness of reuse. These plays produce between 300,000 to 1,000,000 gallons of water per well in the first 10 days after completion (a volume sufficient to provide approximately 10% to 40% of the total water needed to fracture a new well (see Table 1 above). The Haynesville Shale produces less water, approximately 250,000 gallons per well in the first 10 days after completion. This is approximately 5% of the total water needed to fracture a new well, and thereby less favorable in terms of reuse (due to logistics as mentioned above) (Chesapeake Energy, 2012).

Long-term produced water production is also important because wells that produce large volumes of produced water for long periods of time will require a disposal or reuse option that is located in close proximity to the wellsite in order to retain the economic viability of the operation. The unit of measurement used for comparison of long term produced water is gallons of water per million cubic feet (MMCF) of gas or hydrocarbon liquid equivalent (MMCFe). This unit of measurement for comparing volumes is exclusive to unconventional plays because there appears to be a direct correlation between hydrocarbon production and long term produced water generation in the major unconventional plays. Mississippi Lime and Permian Basin wells generate the largest volumes of produced water of the unconventional plays at greater than 5,000 gallons per MMCFe. Both of these plays and basins are believed to contain larger volumes of natural formation water present in, and in close proximity to the target oil and gas development zone. The Barnett Shale and Cleveland / Tonkawa Sand also generate relatively large amounts of long term produced water, on the order of greater than 2,000 gallons per MMCFe. The Granite Wash, Niobrara, Eagle Ford, and Haynesville Shale are moderate produced water generating plays at approximately 500 to 2,000 gallons per MMCFe. These shale formations are relatively desiccated and allow less fluid production per MMCFe. The lowest long term produced water volumes come from the Marcellus and Utica Shales. These plays are highly desiccated formations that tend to bind water to the shale through physical / chemical interactions. Water production in both plays is less than 500 gallons per MMCFe with some wells producing virtually no water with long term hydrocarbon production (Chesapeake Energy, 2012).

The third major factor in produced water reuse is the quality of the produced water. Total dissolved solids (TDS), total suspended solids (TSS) (the larger suspended particulates in water), scale causing compounds (calcium, magnesium, sulfate) and bacteria growth all have a major effect on the feasibility of reusing produced water. Also, in the emerging liquids rich plays, hydrocarbon content in the produced water also can have a major impact on the ability to treat, store, and reuse produced water. Historically, TDS has been managed in the reuse process by blending with freshwater to reduce the TDS. Blending was necessary because high TDS can decrease the effectiveness of certain chemicals used for friction reduction which can be problematic in the hydraulic fracturing process. However, new advancements in the development of salt tolerant friction reducers by chemical suppliers have allowed operators to significantly increase the amount of produced water reused in fracturing operations. TSS, on the other hand, can be managed with relatively inexpensive filtration systems. Filtration of TSS is necessary because elevated solids can cause well plugging, decrease biocide effectiveness and interfere with other additives. Scale and bacteria causing compounds (particularly sulfates, calcium, and magnesium) can be managed with chemical treatments or advanced filtration, but each additional treatment step reduces the economic efficiency of the process. Hardness compounds (calcium and magnesium) can be managed with blending, but sulfate content should be kept as low as possible to prevent the formation of barium sulfate scale in the formation (many of the formations contain naturally high amounts of barium). Hydrocarbons can be managed with mechanical and chemical separation processes. It is very important to control hydrocarbon content because it can prevent the activation of certain hydraulic fracturing additives if hydrocarbon containing produced water is blended into a future completion (frac). The ideal produced water for reuse has low hydrocarbon content, low TSS and little to no scale or bacteria causing compounds.

Produced Water Treatment Options: The Chesapeake Experience

While produced water is generated with the production of oil and gas (energy) as stated above, energy also plays a key role in determining the best way to manage produced water. Most produced water is of relatively poor quality and may contain very high levels of natural salts and minerals that have dissociated from the target hydrocarbon reservoir.

Many different technologies are available for treatment and reuse of produced water but most can be categorized into one of eight different treatment types. This paper will discuss the basics of each treatment type, and will offer an operator's perspective and experience with the application of the technology on unconventional oil and gas produced water.

Sedimentation and Filtration: Sedimentation is simply gravity separation in a tank or impoundment. This is the most basic of all water "treatment" processes. No chemicals or energy are added to the water and it involves simply storing fluid for a period of time to allow the suspended solids to "fall" out of solution. In the oilfield, this "treatment" type is only effective for removing or settling suspended solids and if there is any type of entrainment mechanism at work in the fluid, the solids will not properly settle out. Filtration is another simple produced water treatment option that typically involves the use of porous media (either a "sock" or "sand" column filter) to filter solid particles out of solution. Filtration is a great option because it is inexpensive, the media is easy to dispose or back wash, and the systems are very easy to operate. Most oilfield filtration systems operate on a pressure differential where sensors detect a set pressure value (based on a clogged or dirty filter) and trigger a filter replacement or a backwash cycle. Chesapeake Energy has utilized both sedimentation and filtration technologies extensively in the Marcellus Shale for over 3 years. There are numerous providers offering sedimentation and filtration "treatment systems" and the water quality in the Marcellus Shale is suitable for these systems due to the low hydrocarbon content of the water and the low scaling tendency of the dissolved salts that remain in solution. Chesapeake's program in the Marcellus Shale has been tremendously successful by reducing water disposal volumes by over 95% and is also extremely cost effective through the reduction in transportation, water acquisition, and produced water disposal costs. (Chesapeake Energy, 2012)

Chemical Precipitation: Chemical precipitation has a long and successful history in conventional drinking water treatment systems. The technology utilizes chemicals and the processes of coagulation, flocculation and sedimentation to remove contaminants from water. Coagulation and flocculation are processes that increase the tendency of small particles in aqueous suspension to attach to one another and accumulate in size and weight to allow for the process of gravity settling (sedimentation) to remove the contaminants from solution (American Water Works Association, 1999). Due to the history of the technology in municipal wastewater treatment, many chemical precipitation providers are expanding their focus into oil and gas produced water treatment. Typically these systems are more expensive than sedimentation and filtration options as discussed above, but they are less expensive than the more advanced treatment options involving membranes and thermal processes discussed below. Chesapeake Energy is currently utilizing a chemical precipitation system (followed by filtration) to treat produced water and drilling wastewater in the Utica Shale. The system involves chemical precipitation with a coagulant (currently utilizing aluminum chloride) to remove suspended solids, followed by a series of filters and the addition of a small amount of biocide to control bacteria growth in the treatment process. All of the treated water is tested for remaining contaminants (specifically hardness, sulfates, hydrocarbons, and TDS) and then is blended with fresh water for use in subsequent completion operations (Chesapeake Energy, 2013).

Dissolved Air Flotation: Dissolved Air Flotation and its comparable sister technology (Induced Gas Flotation) utilize a chemical polymer with an air or gas stream injected through a column of fluid to promote the "floating" of contaminants to the surface so they can be removed through a skimming mechanism at the top of the column. This treatment technology is particularly effective for produced waters with free or entrained hydrocarbons due to the fact that hydrocarbons naturally "float" on water. This treatment technology is slightly more expensive than most chemical precipitation options, but it is great for hydrocarbon removal and often does not require the use of secondary filtration to remove the remaining suspended solids. As a result, this technology has a promising future for use in the emerging oil and hydrocarbon liquid rich unconventional plays. Chesapeake Energy is currently evaluating this technology for produced water reuse in a number of liquid rich operating areas.

Evaporation: Evaporation is less of a produced water "treatment" technology and more of a "waste reduction" technology. The process is very simple and uses natural processes of evaporation to turn a portion of produced water into water vapor. Evaporation systems in the oilfield are very energy intensive and recover no fluid or water. Due to the energy intensity of the systems, costs can vary depending on the available energy or heat source. Many providers are focused on using "waste heat" to drive their evaporation systems. From late 2009 to 2012 Chesapeake Energy tested and operated an evaporative reduction and solidification system in the Barnett Shale. The utilized system was designed to run off of "waste heat" from a nearby Chesapeake owned compressor station which was intended to reduce or eliminate the need for the system to consume fuel. The project was successful because Chesapeake was able to significantly reduce a large amount of produced water from being disposed of in a nearby permitted underground injection well. However, the technology struggled to maintain the anticipated cost effectiveness and was plagued by technical problems running off of the waste heat from the nearby compressors (Chesapeake Energy, 2012).

Thermal Distillation: Thermal distillation is an advanced water treatment technology that targets the removal of total dissolved solids (or salts) from produced water. The most common type of thermal distillation method utilized in the oilfield is Mechanical Vapor Recompression (MVR). MVR utilizes low pressure to evaporate produced water and mechanically recompresses steam to produce the distilled water effluent. MVR systems require pretreatment with either chemical precipitation or dissolved air flotation (as discussed above) in order to remove suspended solids and hydrocarbons. Due to the addition of the more expensive thermal component, these systems can be significantly higher in cost than the "pretreatment" systems (chemical precipitation and dissolved air floatation) alone. Chesapeake Energy is currently running some long term trials with a MVR unit in the Anadarko Basin in northwest Oklahoma and the Texas panhandle. Chesapeake's purpose in trialing this advanced treatment system is to help manage the risk associated with the transport and storage of high TDS waters over long distances. Specifically, the MVR system being utilized by Chesapeake produces three streams: one sludge waste stream of mainly suspended solids that can be dried and landfilled, one "clean" high TDS brine waste stream that can be transported by truck and utilized as a clay stabilizer or winterizing agent on the next completion, and finally the distilled pure effluent stream which can be transported by pipeline and stored in a similar method to fresh water due to the highly pure nature of the water (Chesapeake Energy, 2013).

Electro-Coagulation: Electro-coagulation is an electrically driven treatment process that utilizes fewer chemicals. In these systems an electric charge is passed through the fluid stream that changes the surface charge on the solid particles and causes them to agglomerate and drop out of solution or be more efficiently filtered from solution. Electro-coagulation systems are increasingly being offered by numerous providers, and the systems are good at removing suspended solids and most heavy metals. The system does not treat total dissolved solids nor does it remove hydrocarbons and it can be relatively energy intensive and does require knowledgeable operators. Chesapeake Energy has not found a suitable application for this technology but continues to evaluate electro-coagulation systems to see if they can compete in terms of economics and performance versus other treatment systems.

Crystallization: Crystallization is the most comprehensive and advanced treatment technology available for produced water on the market today. Crystallizers are utilized to completely remove all dissolved solids (including all salts) from solution and can achieve a zero liquid waste discharge (only solid salt and distilled water outputs). Crystallizers do require pretreatment (via chemical precipitation, dissolved air floatation, or membrane filtration), followed by distillation, before the crystallization step is applied. Due to the advanced and comprehensive nature of the treatment system, and the thermal energy input required to run the system, this is the most expensive treatment option available, but as mentioned, it does eliminate the need for liquid disposal. Chesapeake Energy has been in discussions with a number of vendors about the possibility of utilizing a crystallizer at some point in the future in the Marcellus Shale, but at this time Chesapeake has no current or planned use.

Reverse Osmosis Membranes: Reverse Osmosis (RO) membrane filtration is the preferred treatment technology for seawater desalination and the technology has naturally migrated over for consideration in the oilfield. Due to the nature of the technology, RO systems require a very steady water quality and a comprehensive pretreatment system to ensure suspended solids and hydrocarbons do not impact the membrane as they can immediately foul or ruin most RO membranes. RO systems are also very prone to scaling without comprehensive pretreatment and output efficiency begins to decline sharply for TDS levels above that of seawater. Due to the high salinity and variability in water quality of most unconventional produced water brines, RO has limited potential in most unconventional plays. For reference, most unconventional produced water TDS levels can easily reach 2-5 times the TDS content in typical seawater. Due to these hurdles, Chesapeake Energy has not found a suitable application for the technology, but as new advancements in scale and hydrocarbon resistant coatings and robust membrane materials advance, potential applications could emerge in the future (Chesapeake Energy, 2013).

Despite the numerous classifications and types of treatment technologies described above, all treatment processes have energy, environmental and economic impacts that are directly impacted by produced water quality. Simple conventional water treatment processes (coagulation, flocculation, sedimentation, and filtration) do require energy, but are typically *much less* energy intensive than advanced salt separation treatment processes (reverse osmosis membranes, thermal distillation systems, and crystallization systems). Furthermore, some of the water treatment processes such as coagulation and flocculation, dissolved air floatation, distillation, and crystallization require chemicals (sometimes in large volumes) which also have energy, environmental and economic related impacts.

Advancements in Hydraulic Fracturing Chemistries Reduce Need for Fresh Water

Chesapeake Energy has been very involved with a number of hydraulic fracturing chemical suppliers in getting salt or "brine" tolerant chemicals developed in an effort to increase the use of produced water in fracturing operations. One area of tremendous success has been the industry development of salt tolerant friction reducers. Friction reducers are polymers that are the primary component of "slickwater" fracturing fluid systems. In the past, high TDS produced waters would prevent the fresh water-based friction reducers from working properly. With the advancements in chemistry, these new friction reducers have allowed Chesapeake Energy to substantially increase the percentage of high TDS brine utilized in hydraulic fracturing operations. Specifically, in the Mississippi Lime play in northwest Oklahoma, Chesapeake has completed over three dozen wells using 100% high TDS (over 200,000 ppm TDS) produced water. A recent evaluation of the trial program has shown no detrimental impact to production utilizing the high TDS produced water and the program has yielded some substantial economic benefits (particularly the reduction in produced water sent to disposal). The one water quality criteria that must be managed very carefully in these direct reuse applications is the presence of hydrocarbons in the produced water which can interfere with friction reducer performance. Also, the new salt tolerant chemistries are more expensive than their fresh water counterparts, an important consideration to keep in mind. Chesapeake Energy is continuing to work with chemical suppliers to develop other salt tolerant hydraulic fracturing products including gelling agents and cross linkers (which can be particularly susceptible to some dissolved solids) (Chesapeake Energy, 2013).

Other Considerations

Outside of treatment for reuse, disposal, via permitted, Class II UIC wells, is the long standing and safe, produced water management option. Outside of the Marcellus Shale, salt water disposal wells (SWDs) are by far the most common method of disposing of produced fluids from unconventional oilfield operations. Surface discharge via wastewater treatment plants has historically been a common treatment technique in the northeast United States, but has been phased out due to strict discharge regulations and natural evolution of the industry due to the Marcellus Shale development. As a note, Chesapeake Energy does not currently discharge any produced water either directly, or via wastewater treatment plants in any operating area.

Conclusions

Energy, environmental and economic considerations must be carefully considered when discussing possible reuse and disposal options for produced water. Much discussion and technology development has focused on treatment technologies that can treat produced water so it is suitable for some form of reuse. These options include reuse in oil and gas operations, municipal, agricultural, and/or industrial operations. Lower dissolved solids produced water (< 30,000 ppm TDS) may be feasible for treatment to reuse outside of oil and gas operations. Higher dissolved solid produced waters (> 30,000 ppm TDS) should only be reused where the high salt/salinity content can be kept in solution (to avoid the intense energy input to separate salts). Operators have successfully demonstrated this ability by using conventional treatment processes on high TDS waters and managing the TDS by blending the fluids in hydraulic fracturing operations, or by utilizing new salt tolerant hydraulic fracturing additives. The feasibility of relying on high TDS produced waters for potential municipal or agricultural water supply does not make sense from an energy, economic or environmental perspective due to the availability of alternative low quality water resources that could be treated to acceptable standards with far lower energy inputs. This includes municipal wastewater, brackish groundwater, and even seawater when logistically feasible. Based on this same logic, environmental and economic benefits may directly correlate when evaluating reuse versus disposal. For example, in areas with extensive salt water disposal well infrastructure like the Barnett Shale or Mississippi Lime, salt water disposal wells are in close proximity to operations, and are a low cost, low energy, safe and effective alternative to advanced reuse. The energy requirements needed to treat Barnett Shale or Mississippi Lime produced water (outside of direct filtration and blending) is significant. Since all energy sources result in some form of air emissions, water use, and/or waste generation; reusing produced water in these plays using an advanced treatment technology may have greater negative environmental impacts than salt water disposal. Furthermore, oil and gas operations that keep dissolved solids in solution and use the fluid in completion operations for subsequent wells can effectively reduce the volume of fresh water needed for future operations by significant amounts. The onshore unconventional oil and gas industry has recently been very successful in utilizing conventional, low energy treatment systems to remove suspended solids, metals, and hydrocarbons from produced water and then reusing this water in hydraulic fracturing operations. From an energy efficiency standpoint, this is a much more efficient use of energy and water than treating produced water to drinking water standards.

APPENDIX A: Removal of Water from the Effective Hydrologic Cycle: Concerns Put to Rest

One of the major criticisms to the use of water in the development of oil and natural gas supplies, particularly in the hydraulic fracturing of unconventional oil and gas plays, is the so-called "permanent removal" of water from the surface and near sub-surface hydrologic cycle referred to in this paper as the *effective hydrologic cycle*. While the focus of this paper is recycling and reuse of produced water to reduce fresh water use in hydraulic fracturing operations, it is important to address this "permanent removal" from the effective hydrologic cycle criticism.

Like all energy development, all oil and natural gas development activities use water resources. In unconventional oil and gas development, water is used specifically for drilling and hydraulic fracturing. As discussed earlier, the majority of water is used in the hydraulic fracturing process. Water demands for hydraulic fracturing and the volumes of produced water generated can vary significantly between plays. Highly desiccated, water loving formations like the Marcellus and Utica Shales trap and bind a majority of the water used in the hydraulic fracturing process to the formation. As a result, these wells, over their productive lifetime, will generate only a fraction of the produced water used during the fracturing process. Higher water bearing plays or plays near water bearing formations like the Mississippi Lime and Barnett Shale generate much higher volumes of produced water. These wells over their lifespan will generate many times the original volume used in the fracturing process. However, regardless of how much produced water is generated, the safest and highly preferred disposal method for produced water is underground injection via permitted Class II SWDs. (Chesapeake Energy, 2012)

Regardless of the unconventional play, since the majority of produced water either remains in the formation or is disposed of in another suitable geologic formation (via Class II SWDs), this water is indeed removed from the effective hydrologic cycle. This may lead some to criticize and treat oil and natural gas water use differently than other major water users like power plants who *consume* water during the cooling process. The argument is the power plant type of *consumption* is *evaporation* and the volume of water evaporated is simply released to the atmosphere as water vapor and is still in the effective hydrologic cycle.

These concerns about the permanent loss of water from the effective hydrologic cycle via drilling and hydraulic fracturing can easily be addressed with a simple explanation of natural gas combustion (and a slightly more complicated variation can explain liquid hydrocarbon combustion). When natural gas is combusted with oxygen (air) it forms two by-products, carbon dioxide and water vapor. The balanced combustion reaction is shown below:

$$\mathbf{CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O}$$

It is the generation of water vapor that ultimately offsets the removal of water from the effective hydrologic cycle. Based on some common assumptions about natural gas and natural gas combustion, approximately 10,675 gallons of water vapor are produced with the combustion of one MMCF of natural gas. (These calculations are shown in detail along with all assumptions in Appendix below.) This volume of water vapor generation was applied to determine approximately how much natural gas needs to be generated and combusted to offset the volume of water used in the development of a typical dry gas well in each of the major shale gas plays.

The results are calculated and shown in Table 2 including the average amount of time needed for a typical Chesapeake well to produce the volume of natural gas needed to offset the water used in the well.

Table 2: Water Vapor Combustion and Effective Hydrologic Cycle Volume Recovery by Major Shale Gas Play

Shale Play	Average Water Use Per Well (in gallons)*	CHK Estimated Average Natural Gas Production Over the Life of Well (in cubic feet) **	Cubic Feet of Natural Gas Needed for Combustion to Offset Shale Gas Water Use (Based on 10,675 gal/MMCF Natural Gas Combusted)	Time for an Average CHK Well to Produce Needed Natural Gas to Offset Water Used in Well
Haynesville	5,400,000	6,500,000,000	505,000,000	< 6 Months
Marcellus	4,500,000	5,750,000,000	421,000,000	< 6 Months
Barnett	3,400,000	3,300,000,000	320,000,000	< 6 Months

*Source: *Chesapeake 2012, **Chesapeake 2012a*

As shown above, a well in any of the three major shale gas plays produces enough natural gas in less than six months, that when combusted, offsets the entire volume of water used in the development of that well. Keep in mind these wells are anticipated to produce natural gas for more than 20 years (Chesapeake Energy, 2012).

Water Vapor from the Combustion of Natural Gas Calculations

Assumptions:

- Typical natural gas makeup assumptions:

$$\begin{array}{rl} \text{Methane } (CH_4) & \sim \mathbf{95\%} \end{array}$$

$$\left.\begin{array}{r} \text{Ethane } (C_2H_6) \\ \text{Propane } (C_3H_8) \\ \text{n-Butane } (C_4H_{10}) \\ \text{Carbon Dioxide } (CO_2) \\ \text{Nitrogen } (N) \\ \text{Sulfur } (S) \end{array}\right\} \sim\mathbf{5\%\ combined}$$

- Due to variations in natural gas makeup (above), the conservative approach was to only use methane to calculate water vapor production, although ethane (C_2H_6), propane (C_3H_8) and n-butane (C_4H_{10}) when combusted will also produce water vapor.
- Balanced Equation for Methane Combustion: $\mathbf{CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O}$
- Assume normal temperature and pressure (68^{o}F and 1atm)
- Volume of 1 mole of CH_4 at 68^{o}F is 0.0026 lb mole/ft^3
- Molecular weight of water is 18 lb/lb mole
- Liquid water density at 68^{o}F is 8.33 lbs/gallon

Calculations:

Step One: Determine how much methane is in one million cubic feet (MMCF) of natural gas:

1. 1,000,000 cu-ft of natural gas x 0.95 (methane component) = 950,000 cu-ft of CH_4

Step Two: Determine the number of pound mol of CH_4 using the assumption above for the volume of one mole of CH_4.

2. 950,000 cu-ft of CH_4 x (0.0026 lb mol CH_4 / ft3 of CH_4) = 2,470 lb mol CH_4

Step Three: Using the balanced equation above, determine how many pounds of mols of water vapor are produced in the combustion process.

3. 2,470 lb mol CH_4 x (2 lb mol H_2O / 1 lb mol CH_4) = 4,940 lb mol H_2O

Step Four: Using the molecular weight of water, determine how many pounds of water vapor are produced in the combustion process.

4. 4,940 lb mol H_2O x (18 lb H_2O/1 lb mol H_2O) = 88,920 lb H_2O

Step Five: Using the liquid water density, determine the volume of water vapor produced.

5. 88,920 lb H_2O x (1 gal H_2O/8.33 lb H_2O) = **10,675 gals H_2O (as vapor) per MMCF**

Note: Not all natural gas that is consumed is combusted. According to a 1995 DOE Topical Report on "Economic Evaluation and Market Analysis for Natural Gas Utilization," approximately 3.5% (relatively negligible) of natural gas is used as feedstock for ammonia, methanol, ethylene and hydrogen production.

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Appendix B.

Extended Abstracts from Session 2: Current and Future Trends in Hydraulic Fracturing Wastewater Management

Evaluating Scenarios of Potential Impact of Water Acquisition for Hydraulic Fracturing

Stephen R. Kraemer
U.S. Environmental Protection Agency, Office of Research and Development

Information presented in this abstract is part of the EPA's ongoing study. EPA intends to use this, combined with other information, to inform its assessment of the potential impacts to drinking water resources from hydraulic fracturing. Mention of trade names or commercial products does not constitute endorsement or recommendation for use.

The US EPA Hydraulic Fracturing (HF) study is evaluating the question "How might water withdrawals affect short- and long-term water availability in an area with hydraulic fracturing activity?" The project described here is using computer simulations to evaluate future scenarios of water withdrawals supporting HF and the potential impact on water resources available for drinking water use. The background and progress of this project is contained in *Study of the Potential Impacts of Hydraulic Fracturing on Drinking Water Resources: Progress Report* (US EPA, 2012). The Quality Assurance Project Plan (QAPP) outlines the approach for the basin scale assessment (Cadmus, 2012).

An outline of the project critical path for modeling impact is shown in **Figure 1**.

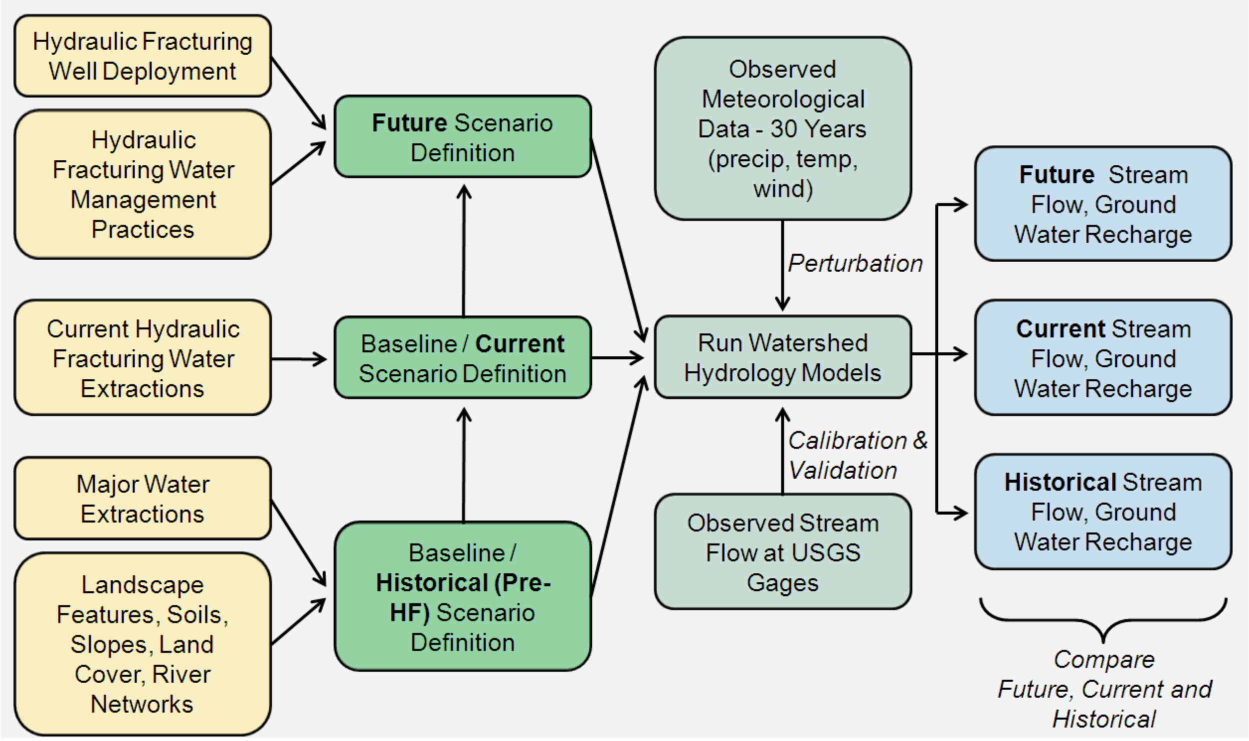

Figure 7. Watershed modeling critical paths, from setup to calibration/validation to scenario runs starting with the foundational baseline/historical, updating to baseline/current, culminating in the evaluation of the futures (business-as-usual, energy plus, and recycling plus).

The EPA recognizes the unique circumstances of the geography and geology of every unconventional oil and gas resource and has chosen two study sites to initially explore and identify the potential differences related to water acquisition. The study areas include: the

Susquehanna River Basin (SRB) located in the eastern United States (humid climate) and overlying the Marcellus Shale gas reservoir; and the Upper Colorado River Basin (UCRB) located in the western United States (semi-arid climate) and overlying the Piceance structural basin and tight gas reservoir (**Figure 2**).

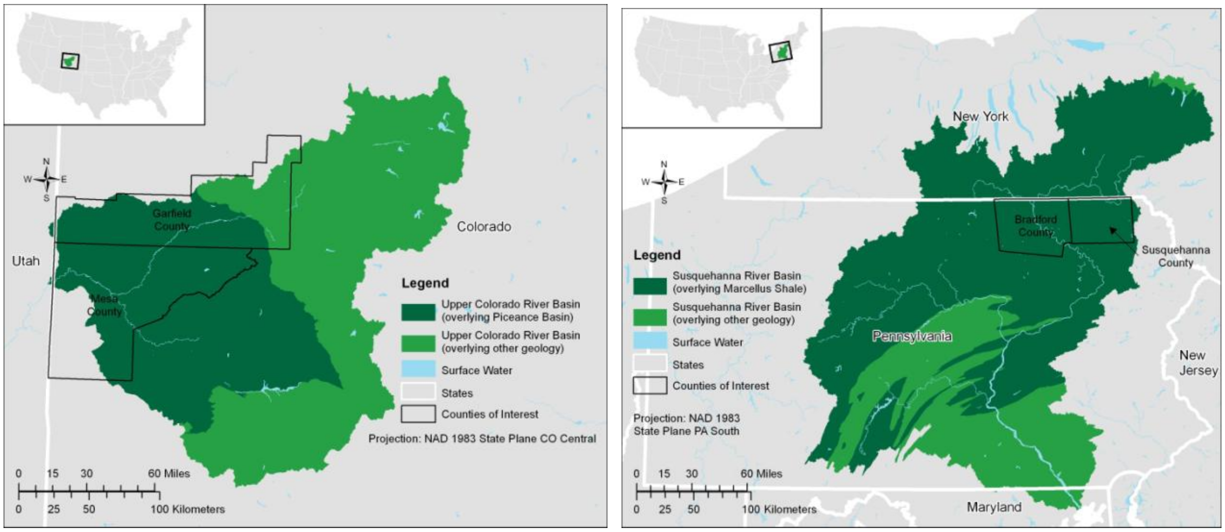

Figure 8. The Upper Colorado River basin and Williams Fork Sandstone (gas) and the Susquehanna River Basin and Marcellus Shale (gas).

In order to assess the impact of hydraulic fracturing water withdrawals on drinking water availability at watershed and county spatial scales as well as annual, seasonal, monthly and daily time scales, the EPA is developing separate hydrologic watershed models for each study area. The models are based in part on the calibrated and verified watershed models (hereafter called the "foundation" models) of the EPA Global Change Research Program (Johnson et al., 2012), namely the Hydrologic Simulation Program FORTRAN (HSPF) and the Soil and Water Assessment Tool (SWAT). Both HSPF and SWAT are physically-based, semi-distributed watershed models that compute changes in water storage and fluxes within drainage areas and water bodies over time. Each model can simulate the effect of water withdrawals or flow regulation on modeled stream or river flows. Key inputs for the models include meteorological data, land use data, and time series data representing water withdrawals. The models give comparable performance at the scale of investigation (Johnson et al., 2012). SWAT is being used in the UCRB given the importance of consumptive water use by agriculture and vegetative land cover, while HSPF is being used in the SRB to allow benchmark comparisons with the mature watershed models of the EPA Chesapeake Bay Program. .

Refined watershed modeling analysis is being planned for additional spatial scales (zero order, 1st order, 2nd order streams and associated catchments) and temporal scales (monthly, daily) in focus areas of Garfield/Mesa County, Colorado, and Bradford/Susquehanna County, Pennsylvania (see **Figure 2**) that have experienced hydraulic fracturing and oil and gas production.

Acknowledgements

This work was supported by EPA Contract EP-C-08-002, Task Order 32 (Stephen Kraemer, EPA WAM) to The Cadmus Group, Inc.(Laura Blake, Project Manager, Jonathan Koplos, Andy Somor, Corey Godfrey) in conjunction with subcontractors AQUA TERRA Consultants (Paul Duda, John Imhoff, Tony Donigian) and Texas A&M University (Debjani Deb, Raghavan Srinivasan). We also acknowledge the contributions in the area of data collection by Shaw Environmental Consultants (Johnathan Shireman) under EPA Contract EP-C-08-034, Work Assignment HF-2-10 (Susan Mravik, EPA WAM). Jim Kitchens is the project Quality Assurance Manager. Refinement modeling work continues with the assistance of Yusuf Mohamoud, Chris Knightes, Mark Gabriel, Lourdes Prieto, and Keewook Kim, John Johnston, Kate Sullivan, and Roy Sidle of the EPA ORD laboratory in Athens, Georgia.

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Mapping Water Availability and Cost in the Western United States

Vincent C. Tidwell,[1] Barbara D. Moreland,[1] Katie M. Zemlick,[1] Barry L. Roberts,[1] Howard Passell[1]
Daniel Jensen,[2] Christopher Forsgren,[2] Gerald Sehlke[3]
Margaret Cook,[4] Carey King,[4] and Sara Larsen[5]
[1]Sandia National Laboratories
[2]Idaho National Laboratory
[3]University of Idaho
[4]University of Texas
[5]Western States Water Council

The statements made during the workshop do not represent the views or opinions of EPA.
The claims made by participants have not been verified or endorsed by EPA.

Introduction

Concern over the availability of water to meet future energy sector demands has been expressed (GAO 2013; DOE 2006). In 2011 the Department of Energy's Office of Electricity initiated a project with the Western Electricity Coordinating Council (WECC) and the Electric Reliability Council of Texas (ERCOT) to investigate potential impacts of limited water availability on long term transmission planning. Technical support for the effort is led by Sandia National Laboratories with the supported of Argonne National Laboratory, Idaho National Laboratory, the National Renewable Energy Laboratory, Pacific Northwest National Laboratory, the University of Texas, and the Electric Power Research Institute.

As a basis for transmission planning, water availability, cost, and projected future demand are mapped for the 17-conterminous states in the western U.S. Specifically, water availability is mapped according to five unique sources including unappropriated surface water, unappropriated groundwater, appropriated surface/groundwater, municipal waste water, and brackish groundwater. Associated costs to acquire, convey and treat the water, as necessary, for each of the five sources are also estimated. To complete the picture, competition for the available water supply is projected over the next 20 years.

Methods

Raw data were acquired from a variety of sources. Where available, data were collected directly from the western states. In collecting the data we worked directly with state water data experts to identify and at times gain access to the data. In most cases the data came from the state's water plan that was generally available from on-line sources. Efforts were made to vet the collected water data with the state experts to verify the fidelity of data collected and any data conversion/translation made to render the data in a consistent and comparable format. Federally reported data were used as necessary to fill in gaps, including information derived from the U.S. Geological Survey, Environmental Protection Agency, Energy Information Administration, U.S. Department of Agriculture and others.

This analysis makes use of multiple data sets from multiple sources reported at differing geographic resolutions (e.g., point, county, watershed, state). For purposes of this analysis, a consistent reference system is required. The 8-digit Hydrologic Unit Code (HUC) watershed classification (e.g., Seaber et al. 1987) is adopted, which resolves the 17 western states into1208 unique hydrologic units. The 8-digit HUC is selected as it provides a physically meaningful unit relative to water supply/use and provides the highest level of detail that can be justified with the data consistently available across all 17 western states. For raw data reported in point-format, translation to the 8-digit HUC is achieved by simple aggregation/averaging. For raw data reported in polygonal-format, translation follows a simple population or areal weighting. In the case of water use data, the 1995 USGS water use reported at the 8-digit level (Solley et al. 1995) provides the needed spatial weighting function.

There are no definitive measures of water availability and cost that entirely span the full 17-state region. Rather, these metrics must be developed from the raw data collected from the states and federal agencies. The challenge is to formulate water availability and cost metrics that appropriately balance the underlying complexity of the system (e.g., physical hydrology, climate, use characteristics, technology and water management institutions) with the data that is consistently available across the entire western U.S. To assist in striking such a balance, water availability/cost metrics are formulated with the help of subject experts. Specifically, representatives from the Western Governors' Association, Western States Water Council, USGS, and individual state water management agencies assisted in defining appropriate and informative water metrics (in total the team included 11 participants plus the author team). These metrics were developed and vetted over a two month period during 6 webinars lasting roughly 90 minutes each. The resulting metrics are described below.

Water Availability Metrics

Unappropriated Surface Water

States exercise full authority in matters pertaining to off-stream water use. In the western states water is managed according to the doctrine of prior appropriation, which defines a system of priority where the first to make beneficial use of water has the first right to it in times of drought. Access to this water requires only a permit or water right issued by the state's water management agency. However, any new water development is allocated the most junior priority in the basin, thus delivery in times of drought may be limited. Whether water is available for new development depends on characteristics of the physical water supply, the water rights structure in relation to supply, and related instate compacts and international treaties. Additionally, navigational or environmental regulation may further limit allocation or timing of deliveries. Particularly in arid regions the states have estimated how much surface water is available for new development. Although the states have different terms for such water, we refer to it as unappropriated surface water.

For purposes of this analysis, state estimated unappropriated surface water values are adopted where available, including Arizona, Colorado, Nevada, New Mexico, Oklahoma, Oregon, Texas, Utah, and Wyoming. Estimates of available unappropriated surface water are based on years with normal stream flow. Although availabilities based on drought flows would yield a more dependable estimate for new development, such estimates were available only for a single state, Texas. For states that have not estimated unappropriated surface water availability, efforts are made to first identify basins closed to new appropriation, in such cases available unappropriated water is set equal to zero. In the remaining open basins, streams tend to lack regulation by interstate compacts and flows tend to be large with respect to water use. Given this lack of stringent control on water use, environmental concerns are the most likely factor to constrain new water development. A widely used environmental standard in the U.S. (Reiser et al. 1989) is based on studies by Tennant (1976) which found streams maintain excellent to good ecosystem function when stream flows are maintained at levels of ≥60-30% of the annual average. For this study we adopt a conservative threshold of 50% to define unappropriated surface water. Thus for basins where estimates are not available directly from the states, unappropriated surface water is calculated as:

where *j* designates the watershed, Q_{avg} is the long term annual average gauged stream flow, C is the total consumptive use of water upstream of the gauging point. Annual average stream flow data are taken from the National Hydrography Dataset (NHDPlus 2005) while consumptive water use data are taken directly from individual state estimates.

Unappropriated Groundwater
States exercise full authority over the allocation of groundwater resources. Determining the availability of groundwater for future development is complicated by numerous factors including the manner with which groundwater is managed (e.g., strict prior appropriation, right of capture); the physical hydrology of the basin; degree of conjunctive management between surface and groundwater resources; allowable depletions, and a variety of other issues. Except in very limited cases, the states have not broadly estimated and published data on the availability of unappropriated groundwater.

Given the aforementioned complexity and relative lack of supporting data, a simple water balance approach is adopted to identify potable groundwater that is potentially available for development. That is, unappropriated groundwater is set equal to the difference between annual average recharge and annual groundwater pumping. Recharge rates are taken from U.S. Geological Survey (2003), which are derived from stream baseflow statistics, while pumping rates are taken from state data where available or from U.S. Geological Survey (Kenny et al. 2009) otherwise.

To account for unique groundwater management and/or aquifer characteristics, further restrictions on unappropriated groundwater availability are introduced. Specifically, availability is set to zero in watersheds located within state defined groundwater protection zones (data acquired directly from each state). Groundwater availability is likewise set to zero in watersheds realizing significant groundwater depletions (historical groundwater declines exceeding 40 ft. as given by Reilly and others [2008]). Finally, groundwater availability is set equal to zero in any watershed that 10% or less of its land area is underlain by a principle aquifer (Reilly et al. 2008).

Appropriated Water
This source attempts to quantify water that could be made available for new development by abandonment and transfer of the water right from its prior use. Such transfers have traditionally involved sales of water rights off irrigated farm land to urban uses. The potential for such transfers is estimated based on the irrigated acreage in a given watershed that is devoted to low

value agricultural production; specifically, irrigated hay and alfalfa. Data (irrigated acreage and water volume applied) are taken from the U.S. Department of Agriculture's Agricultural Census (USDA 2007). There is often resistance to large areas of irrigated agriculture being abandoned. As such, land abandonment is limited to 5% of the total irrigated acreage in the watershed. This limit is based on the state projected average decline in irrigation across the western U.S. For watersheds experiencing significant groundwater depletions (see unappropriated groundwater metric above) the available appropriated water is reduced by 50%. This is to account for the fact that some portion of future water rights abandonment is likely to be used to offset the groundwater depletion (Brown 1999).

Municipal Waste Water
Non-fresh water supplies offer important opportunities for new development. Municipal waste water is rapidly being considered as an alternative source of water for new development, particularly in arid regions. Municipal waste water discharge data is relatively consistently available throughout the U.S. The Environmental Protection Agency publishes a pair of databases (Permit Compliance System [EPA 2011], and Clean Watershed Needs Survey [EPA 2008]) that provide information on the location, discharge, and level of treatment for most waste water treatment plants in the U.S. Additionally, the U.S. Geological Survey (Kenny et al. 2009) publishes municipal waste water discharge values aggregated at the county level. These three sources of information are combined to provide a comprehensive view of current waste water discharge across the West. Lastly, the projected growth in municipal waste water discharge to 2030 is estimated (see future Water Demand section below) and added to the current discharge rates.

However, not all of this discharge is available for future use. A considerable fraction of waste water discharge is currently re-used by industry, agriculture, and thermoelectric generation. Re-use estimates are determined both from the U.S. Geological Survey (Kenny et al. 2009) data as well as the Environmental Protection Agency databases (as they record the point of discharge, e.g., stream, agriculture, power plant and in some cases are designated as discharging to 'reuse'). These re-use estimates are subtracted from the projected discharge values.

In western states the availability of municipal waste water must consider return flow credits. Those municipalities that discharge to perennial streams receive return flow credits for treated waste water. This water is not available for new development as it is already being put to use downstream. Unfortunately, there are no comprehensive data on waste water return flow credits. In efforts to identify plants that are likely credited for their return flows, those plants that directly discharge to a perennial stream are identified (point of discharge is identified in the databases noted above). These plants are excluded as a source of available municipal waste water.

Shallow Brackish Groundwater
For this analysis brackish water availability is limited to resources no deeper than 2500 feet and salinities below 10,000 total dissolved solids (TDS). Deeper, more concentrated resources would generally be very expensive to exploit.

Estimates of brackish groundwater resources across the western U.S. are very spotty. To cover this entire area requires the use of multiple sources of information. The best quality data are state estimated volumes of brackish groundwater that are potentially developable; however, this data is only available for Texas (LBG-Guyton Associates 2003), New Mexico (Huff 2004), and Arizona (McGavock 2009). States limit exploitation of the resource by applying some type of allowable depletion rule. In this case it is assumed that only 25% of the resource can be depleted over a 100 year period of time (annual available water is determined by multiplying estimated total volume of brackish water by 0.0025).

The next best source of data is reported use of brackish groundwater as published by the U.S. Geological Survey (Kenny et al. 2009). This does not provide a direct measure of available water, simply an indication that brackish water of developable quality is present. Conservatively we assume that double the existing use could be developed up to a maximum limit of $8.4X10^{-2}$ acre-feet per year (AF/yr). Also assumed is that the minimum quantity available is $8.4X10^{-3}$ AF/yr.

Finally, if a watershed has no brackish water volume estimate or brackish water use then the presence of brackish groundwater wells is used. The U.S. Geological Survey maintains the National Water Information System (NWIS) database which contains both historical and real-time data of groundwater well depth and quality (USGS 2011). Where at least one well exists brackish water availability is set to $8.4X10^{-3}$AF/yr. To avoid brackish water that is in communication with potable stream flow, availability is set to zero when the average depth to brackish water is less than 50 ft. and the salinity is less than 3000 TDS.

Water Cost Metrics

Each of the five sources of water carry a very different cost associated with utilizing that particular supply. The interest here is to establish a consistent and comparable measure of cost to deliver water of potable quality to the point of use. As with water availability, costs are resolved at the 8-digit HUC level. Considered are both capital and operating and maintenance (O&M) costs. Capital costs capture the purchase of water rights as well as the construction of groundwater wells, conveyance pipelines, and water treatment facilities, as necessary. All capital costs are amortized over a 30-yr horizon and assume a discount rate of 6%. O&M costs include expendables (e.g., chemicals, membranes), labor, waste disposal as well as the energy to lift, move and treat the water. Below, specifics unique to each source are discussed.

Unappropriated Surface Water

No costs are assigned to unappropriated surface water. It is recognized that there are costs associated with constructing intake structures and permitting. Such costs are not considered in part because of the wide range of variability across use types and location. More importantly, similar intake and permitting costs will be realized with all five sources of water, thus estimating these uncertain costs are of little value to this effort.

Unappropriated Groundwater

Estimated costs consider both capital and O&M costs to lift water for use. Capital costs for drilling are estimated along with electricity to lift water following the approach outlined in Watson and others (2003). Depth to groundwater is taken from U.S. Geological Survey well log data (USGS 2011) and averaged at the 8-digit HUC level.

Appropriated Surface Water

Water rights transfer costs are based on historic data collected by the *Water Strategist* and its predecessor the *Water Intelligence Monthly* (Water Strategist 2012). Costs are estimated by state because of the limited availability of data. Only transactions involving permanent transfers from agriculture to urban/industrial use are considered. Recorded transfers are averaged by year and by state and the average of the last 5 years used for purposes of this study. No efforts are made to project how costs may vary in time given the wide range of factors and associated uncertainty that plays into the water transfers market.

Municipal Waste Water

Estimated costs consider expenses to lease the waste water from the municipality, convey the water to the new point of use, and to treat the waste water. Fees charged to lease treated waste water from the municipality were estimated based on the initial work of the Electric Power Research Institute (EPRI 2008). Values reported in the EPRI report were verified and updated as necessary based on a review of fees published on line. As no geospatial or plant related trends were noted in the pricing an average of the reported fees was adopted for this study, which was calculated at $1.21 per thousand gallons.

Conveyance of treated waste water from the treatment plant to the point of use is a potentially important cost. Considered are both capital construction costs for a pipeline and O&M costs principally related to electricity for pumping. Associated costs calculations are consistent with Watson and others (2003). The key factor in this analysis is the distance between the treatment plant and point of use. Distance values are calculated as a function of the land use density around the existing treatment plant. Land use densities were calculated within a 5 mile buffer around all existing treatment plants with conveyance distances simply distributed according to a rank order of land density with low values given a conveyance distance of 1 mile to the highest land use density given a distance of 5 miles.

It is assumed that all waste water must be treated to advanced standards before it can be re-used. This conservative assumption was adopted considering both realized improvements in downstream operations (e.g., increased cycles of use, reduced scaling, improved feed quality) and the current trend of regulation toward requiring advanced treatment (EPRI 2008). Plants operating at primary or secondary treatment levels (EPA 2008; 2011) are assumed to be upgraded to advanced standards. Capital construction costs are based on the analysis of Woods et al. (2012), which scale according to treatment plant throughput and original level of treatment. Associated O&M costs consider expenses for electricity, chemicals and labor.

Shallow Brackish Groundwater

Estimated costs consider both capital and O&M costs to capture and treat the brackish groundwater. Cost calculations follow standards outlined in the Desalting Handbook for Planners (Watson et al. 2003). Capital costs include expenses to drill and complete the necessary groundwater wells and construct a treatment plant utilizing reverse osmosis. Number of wells and treatment plant capital costs are based on the treated volume of water, which is assumed to be $4.2\text{X}10^{-2}$AF/yr. Other key design parameters include the depth of the brackish water and TDS. These data averaged at the 8-digit HUC level, were estimated from the U.S. Geological Survey brackish groundwater well logs (USGS 2011). O&M costs capture expenses for labor, electricity, membranes and brine disposal.

Water Demand

There are a number of water use sectors competing for the available water supplies mapped above. As with water availability we worked closely with state water managers to characterize projected water demand across the western U.S. Acquired data has largely come from the state's individual water plans and online databases (see Table 1). Water demands are distinguished according to current verses projected future demands; withdrawal verses consumptive use; and, the source water (e.g., surface water, groundwater, waste water, saline/brackish water). Demands are also distinguished by use sector; specifically, municipal/industrial, thermoelectric, and agriculture.

Water demand projections vary by state in terms of spatial resolution, target dates, and categories of growth. All projected demands are mapped to an 8-digit HUC level following a strategy similar to that adopted and discussed for water availability. Projections were also uniformly adjusted to the year 2030. This was achieved through simple linear extrapolation between current use estimates and that projected at target dates beyond 2030. Although data were collected for all reported growth scenarios (e.g., high, medium and low), the medium growth projections are reported here.

Results

Water Availability

Water availability is mapped for the five unique sources of water for the 17 conterminous western states at the 8-digit HUC level as shown in Figure 1. Water availability for all five sources is mapped using a consistent but non-linear scale. Watersheds marked in white designate basins with no availability for that source of water (or insufficient information to suggest a reliable supply in the case of brackish groundwater). A quick review of all five maps clearly reveals significant variability across the five sources of water as well as watershed-to-watershed variability within each source of water. The expressed variability is a function of the physical hydrology, water use characteristics, and water management practices unique to each watershed. Another notable feature is the lack of available water for any of the three potable water sources in the state of California. This reflects the fact that California requires new thermoelectric power plants to fully exhaust alternative water sources before considering freshwater (California Water Code, Section 13552).

Availability of unappropriated surface water (Figure 1a), that water that only requires a permit from the state's water management agency to develop, is largely limited to the north. Little to no unappropriated surface water is available in Arizona, New Mexico, Nevada, eastern Colorado and southern California and Texas. Also note that several large watersheds are closed to new water appropriations in Oregon, Wyoming and Montana. However, where unappropriated surface water is available, appropriable volumes tend to be large relative to other sources.

Availability of unappropriated groundwater (Figure 1b) is similar to that of unappropriated surface water. Notable differences are Nevada and northern Arizona. Nevertheless, availability is very limited in the Southwest with pockets of closed groundwater basins in the Northwest. Where available, unappropriated groundwater volumes tend to be relatively large.

Availability of appropriated water, both surface and groundwater that must be transferred from another use, is consistently distributed throughout the west (Figure 1c). Quantities likely to be transferred are relatively small, generally less than 2500 AF/yr. The greatest availability corresponds to regions with heavy irrigated agriculture including, southern Arizona, central California, eastern Colorado, panhandle of Texas, central Washington, and the Snake River basin in Idaho.

Availability of municipal waste water is sporadically distributed across the west (Figure 1d). Availability is most uniform in the far eastern portion of the study area where the density of communities is the greatest. The highest availabilities are associated with large metropolitan areas such as along the southern coast of California and near Tucson and Phoenix in Arizona.

Brackish groundwater is available throughout much of the west except in the far Northwest (Figure 1e). The highest availabilities are noted in Arizona, New Mexico and Texas, where detailed brackish groundwater studies have been conducted. Thus mapped availability is more an indication of what we know and currently use than an indication of the actual resource in the ground.

Future Water Demand

Projected future demands for water (consumptive use) are mapped in Figure 1f. Mapped are new demands projected between 2010 and 2030. Excluded from these projected demands is water for new thermoelectric development as that component will be developed through interaction with the WECC and ERCOT planning process. Demands are mapped at the same scale as water availability (Figures 1a-e) but with the color scale reversed to distinguish high demands with hot colors. A noteworthy aspect of the map is the large regions with zero to negative projected future demands (white areas on map). These are regions where the state projects some level of abandonment of irrigation combined with limited rural population growth. While the states project little growth (or declines) in irrigated agriculture, healthy increases in the municipal and industrial sectors are expected. It follows that the largest growth is clustered around metropolitan areas; particularly, along the West Coast (north and south), Tucson/Phoenix, Dallas/Fort Worth, Houston, Denver, Salt Lake City, Las Vegas and Albuquerque.

Water Budget

Comparison of water availability with projected future demand provides an indication where future consumption will challenge available supplies unless measures are taken. To explore this issue available water sources (Figure 1a-e) are aggregated and the projected future demand (Figure 1e) subtracted to yield a simple water budget at the 8-digit HUC level across the conterminous western U.S. Two budgets are constructed, one that only considers unappropriated surface/groundwater sources (Figure 2a) and a second that considers all five sources of available water (Figure 2b). The unappropriated water budget is constructed as this is generally the first supplies of water that are considered because they have the lowest utilization costs (see below).

As expected, unappropriated surface and groundwater supplies are unlikely to be sufficient to meet future demands throughout much of the Southwest. This is indicated by the broad areas with negative water budget values, where projected future demand exceeds the available supply (areas mapped as white). The few exceptions are the far East and the intermountain region in Colorado and Utah. There are also a few pockets of negative water budgets in the Northwest, generally in areas of heavy irrigation. In total 399 watersheds have 2030 water demands that exceed the available unappropriated surface and groundwater. These watersheds are home to nearly 50 million people or 54% of the western states population.

The picture improves considerably when all five water sources are considered (Figure 2b). Fortunately, appropriated, brackish, and municipal waste water tend to be available in watersheds with limited or no unappropriated water supply. In fact, only 69 watersheds have insufficient supplies to meet 2030 demand when all five sources of water are considered. However, these watersheds tend to be associated with areas experiencing strong urban growth; specifically, over 30 million people or 38% of the western states population.

It is recognized that in many cases, plans are in place aimed at addressing the identified short fall. Unfortunately, there is a lack of uniform and comparable data on planned projects across the West. Additionally, project planning runs the full spectrum from conceptualization to initial construction. As such, no attempt has been made to quantify "new" sources of water, as there is no means of quantifying such efforts in a consistent and comparable manner.

Water Cost

Water costs associated with all sources of water except unappropriated surface water are mapped in Figure 3. In order to map all four costs comparably, a non-linear color scale was necessitated to capture the broad range in values. Note that costs were not calculated for watersheds where a particular supply of water was unavailable (watersheds mapped white).

Each water supply shows some degree of watershed-to-watershed variability. This variability is masked to some extent for the brackish and wastewater maps by the large bin sizes necessitated for the scale. Variability in cost for unappropriated groundwater largely corresponds with the average depth to groundwater. Appropriated water transfers are seen to be more costly in the Southwest where water supplies are most limited. Municipal waste water costs tend to increase as the size of the waste water treatment plant decreases and the level of treatment increases. Brackish water costs tend to increase as depth and TDS increases.

The most important feature of these maps is the significant variability across sources, particularly between fresh and non-fresh. Average costs for unappropriated groundwater run $107/AF while appropriated water is estimated at $21/AF. Alternatively non-fresh supplies are considerably more expensive with municipal waste water running $400/AF and brackish water $704/AF. Historically, development has largely relied on inexpensive unappropriated water or transfers of appropriated water. The cost of water is likely to play a much more important role in planning and design of future development.

Decision Support System

To help visualize and analyze the breadth of water and energy data collected through the project a web-served, interactive decision support system (DSS) has been developed. The DSS is created in ArcView Geographic Information System. Data are imported as unique data layers in point or polygonal format. Broad data types include individual power plant attributes (e.g., type, capacity, water source, water use), water demand (current/future, source, withdrawal/consumption, sector), water supply (gauged flows, groundwater recharge, reservoir storage), institutional controls (e.g., unappropriated water, closed basins, compact deliveries), and planning metrics (water availability, cost, environmental). All data are rendered in consistent units for the 17 conterminous western United States. Data can be viewed over a range of different reference systems including 8-digit HUC, county, state, and interconnection. Data can be viewed, overlaid, and displayed in bar and pie charts.

The DSS is implemented within the framework of the Water Use Data Exchange, which is a collaborative effort between the WSWC, the Western States Federal Agency Support Team (WestFAST), the WGA, and the Department of Energy Labs. The purpose of the Water Use Data Exchange is to better enable the western states to share water use, water allocation, and water planning data with one another and with the Federal Government. It also seeks to improve the sharing of Federal data that supports state water planning efforts.

The exchange relies upon a web-services-based approach allowing each of the states to maintain their current data systems as they currently exist, with their data mapped to a standard format. Using automated processes, these data are published over the web using eXtensible Markup Language (XML) and are discoverable via a common catalog that is maintained at the WSWC.

Acknowledgements

Key to this effort was a team of volunteer water management experts who helped construct the water availability and cost metrics reported in this paper. In particular, the authors would like to recognize Bret Bruce (U.S. Geological Survey), Dan Hardin (Texas Water Development Board), Sara Larsen (Western States Water Council), Dave Mitamura (Texas Water Development Board), Andy Moore (Colorado Water Conservation Board), Ken Stahr (Oregon Water Resources Department), Todd Stonely (Utah Division of Water Resources), Steve Wolff (Wyoming State Engineer's Office), and Dwane Young (Environmental Protection Agency). The work described in this article was funded by the U.S. Department of Energy's Office of Electricity Delivery and Energy Reliability through the American Recovery and Reinvestment Act of 2009 under Contract No. M610000581. Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

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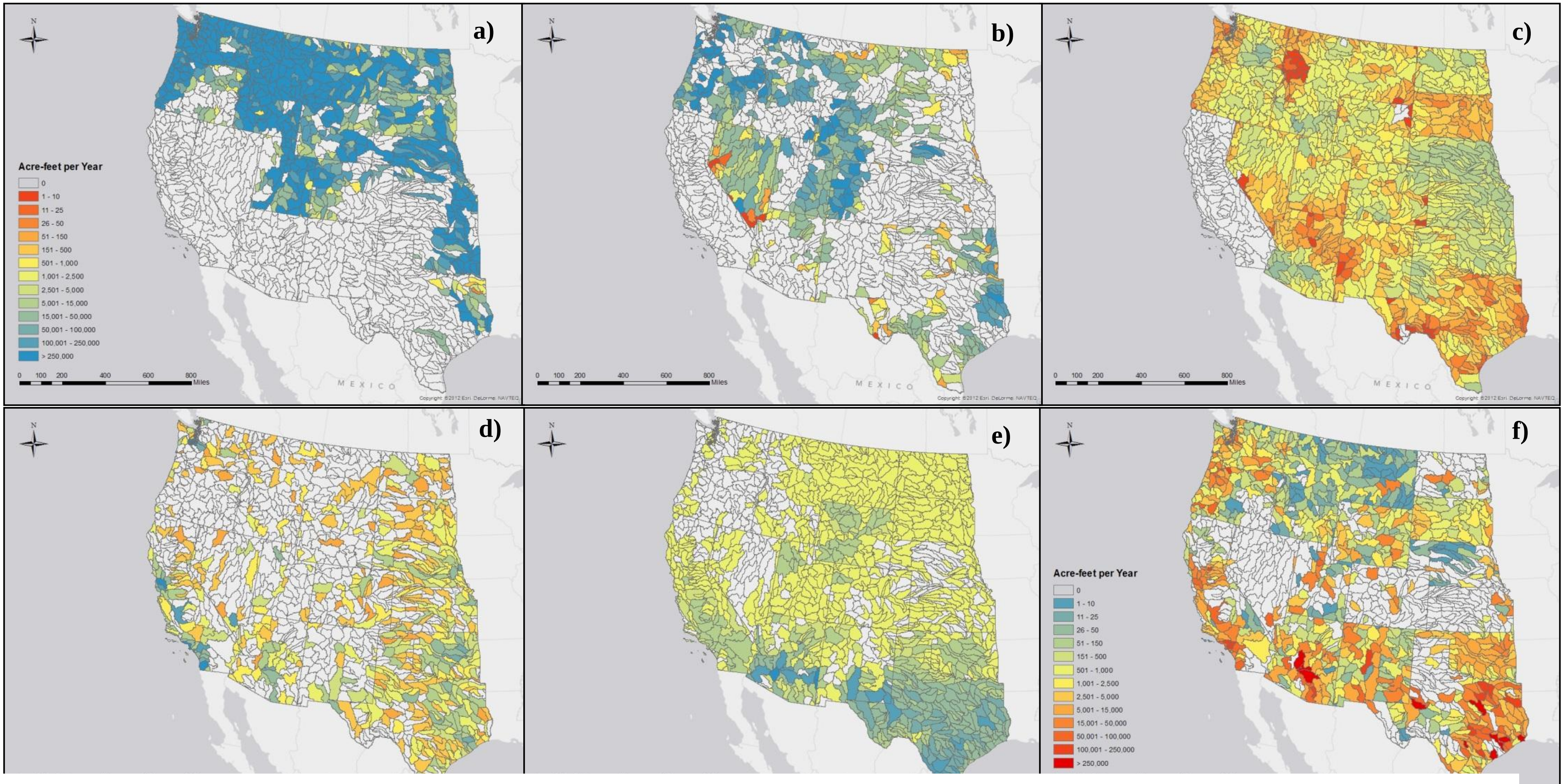


Figure 1. Water availability and future demand. Mapped are water availability metrics for a) unappropriated surface water, b) unappropriated groundwater, c) appropriated water, d) municipal waste water, e) brackish groundwater, and f) projected increase in consumptive water use between 2010 and 2030. All metrics are mapped at the 8-digit HUC level. All are mapped to a consistent non-linear color scale; however the color scheme is reversed between availability and demand (e.g., hot colors indicate limited availability and high demand).

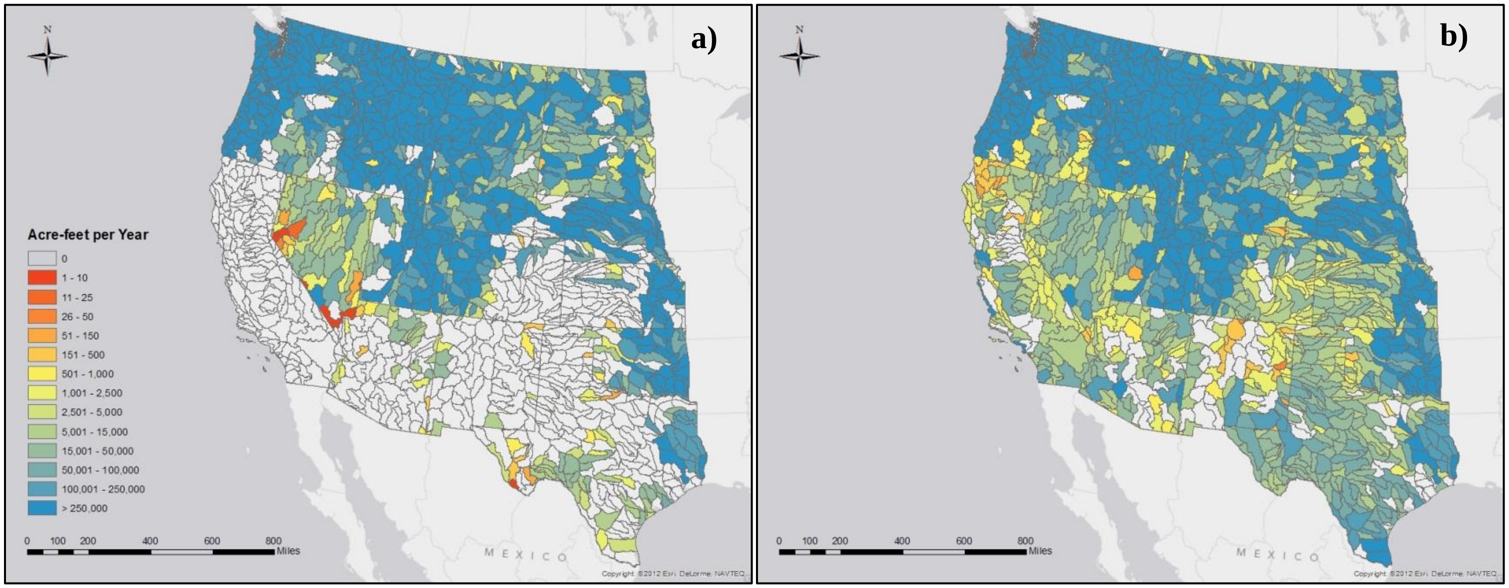


Figure 2. Water budgets constructed by aggregating available water and subtracting projected future demand. Budgets were constructed a) considering only unappropriated water sources, and b) all water sources. Areas in white suggest there is insufficient supply to meet projected demands in that basin.

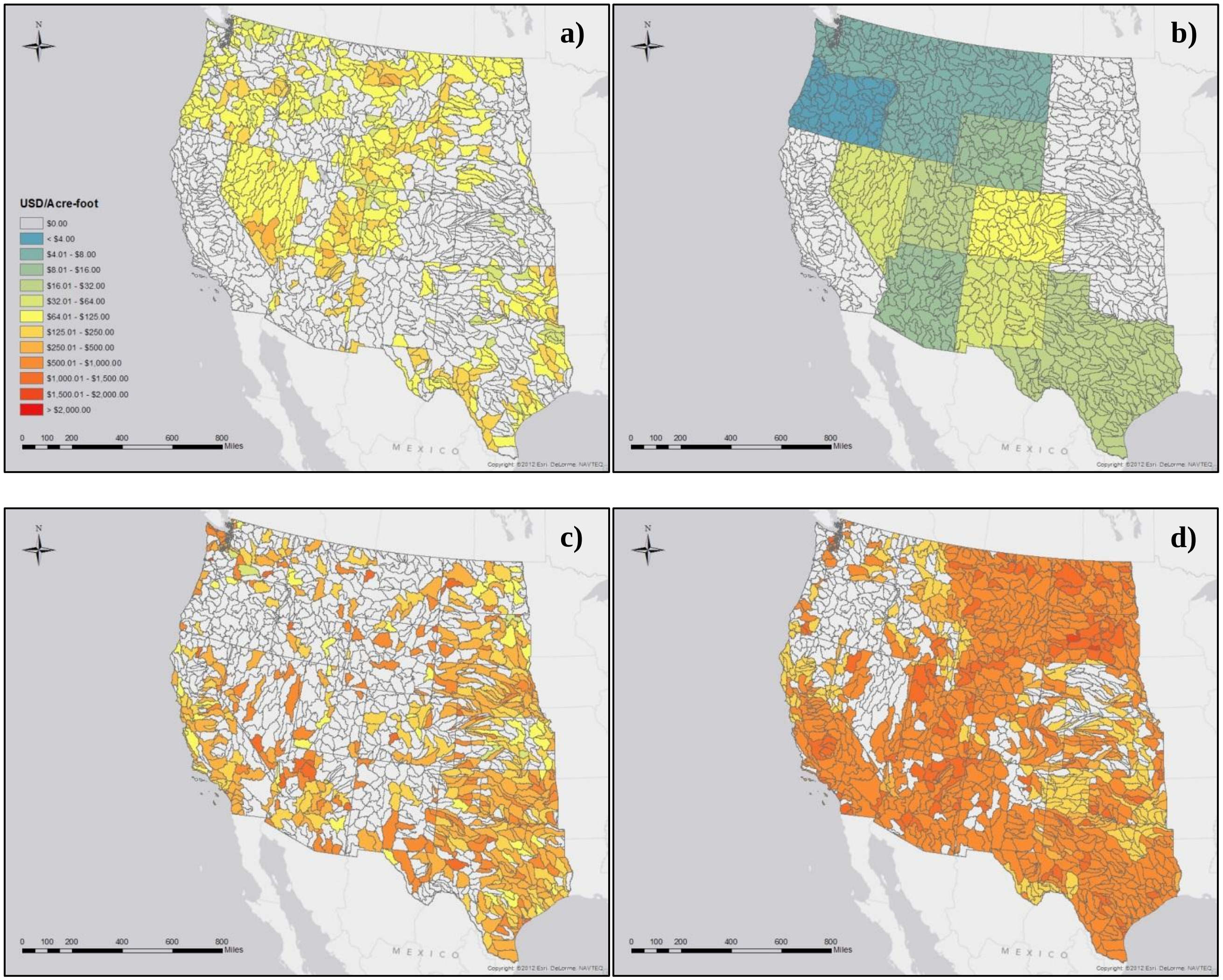


Figure 3. Water cost. Mapped are water cost metrics for a) unappropriated groundwater, b) appropriated water, c) municipal waste water, and d) brackish groundwater. All metrics are mapped at the 8-digit HUC level. All are mapped to a consistent non-linear color scale.

Integrated, Collaborative Water Research in Western Canada

Ben Kerr
Integrated Water Resources / Foundry Spatial Ltd.

Introduction

Water is a key requirement for the production of oil and gas from many shale and tight sand reservoirs. The volume of water required for hydraulic fracturing depends on the unique characteristics of each geologic formation, but is typically 2-18 million gallons per well. Multiple source options exist to supply water requirements, including surface water, shallow fresh groundwater, deep saline groundwater, recycled flow-back and produced water from existing producing wells, and treated wastewater from other sources. The viability of each of these sources varies geographically depending on numerous factors.

Beginning in 2008, several collaborative projects have been undertaken and continue to be executed across Western Canada to regionally characterize the suitability of water sourcing options for emerging shale gas and oil developments. Based on the results of these studies, oil and gas companies operating in Western Canada have developed innovative projects to access water. Companies have also been able to make transparent water sourcing decisions based on a solid foundation of publicly available geoscience data and tools describing water availability from surface water, shallow groundwater and deep saline aquifers.

Integrated Water Resources (IWR) is a team made up of three Canadian companies: Foundry Spatial Ltd., Petrel Robertson Consulting Ltd., and Strategic West Energy Ltd. These firms have broad experience in water-related projects associated with unconventional oil and natural gas plays. Over the past 5 years, several large projects have been completed by IWR in plays across Western Canada, and in the process several key factors to project success have been identified.

Western Canadian Shale Plays

Significant deposits of shale occur across the Western Canadian Sedimentary Basin. The Devonian Horn River and Triassic Montney in British Columbia have been initial targets of significant investments starting in the middle and latter part of the last decade (Figure 1). Current investment continues in the Montney in Alberta along with the Duvernay and Muskwa shales, with recent estimates of over 3,000 tcf of gas, 58.6 billion bbl of natural gas liquids, and 423 billion bbl of oil (Rokosh 2012). Early stage exploration is also underway in the Central Mackenzie Valley in the Northwest Territories, and in several areas of the Yukon Territory.

Initial geologic work in the Horn River identified very thick, organic-rich shales and drilling results proved that significant initial production rates and reserves were possible (Crum 2008). Water requirements for individual wells in the Horn River are typically between 6 and 18 million gallons (Paulson 2012). The sparsely populated, surface terrain of the Horn River Basin is predominantly muskeg and spruce forest, with little pre-existing development or hydrometric and climatic data, which provides challenges for water sourcing.

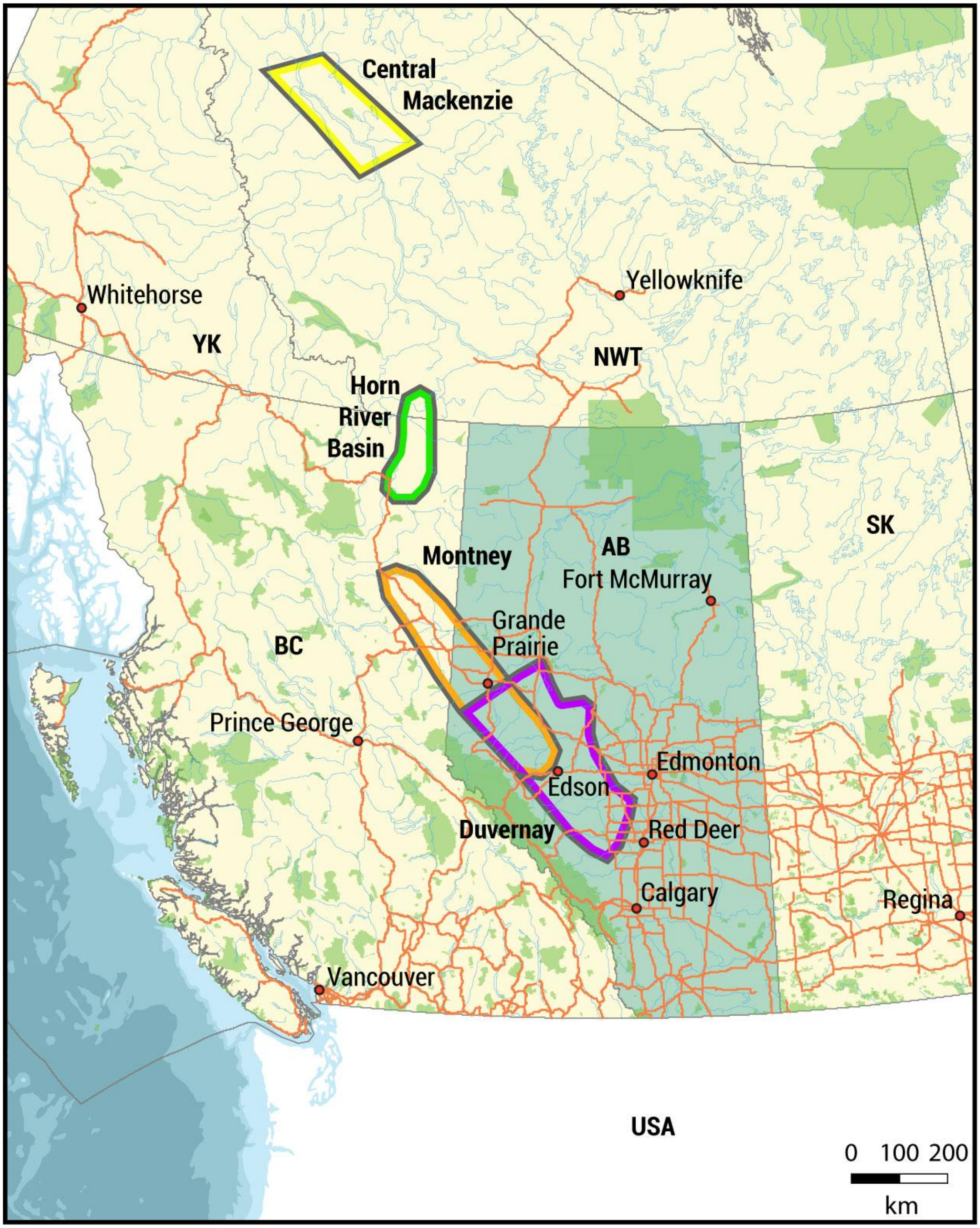


Figure 1. Major shale plays in Western Canada

Development in the Montney play in British Columbia continues, with higher natural gas liquids and closer proximity to market and existing transportation infrastructure than the Horn River Basin. Significant exploration activity is currently underway in Alberta focusing also on oil-prone and liquids-rich plays. The Montney and Duvernay fairways in Alberta extend southeastward from the BC / Alberta border, and parallel the Rocky Mountains.

Water requirements for completions in these plays range from 2.5-15 million gallons per well (Paulson 2012, Heffernan 2013). Surface terrain in these regions ranges from coniferous forests in the foothills through deciduous forests to grass and rangelands moving into the prairies. Several major tributary rivers of the Mackenzie River flow through these plays. Groundwater provides an important source for rural communities and agricultural use in many areas.

Further north, in the Northwest Territories and Yukon, several major oil and gas companies have acquired the rights to explore for oil and gas, but are at the early stages of appraisal. These areas are north of 60 degrees latitude and are typically sparsely populated portions of the boreal forest, and have limited hydrometric and climatic data.

Water Research

The Horn River Basin Producers Group (HRBPG) formed in 2007 and has more than 10 member companies active in the region. In late 2008, the HRBPG in partnership with Geoscience BC identified the need for regional study of potential deep saline aquifers to support water sourcing and also spent fluid disposal. From this partnership the Horn River Basin Aquifer Project was initiated and Petrel Robertson Consulting was appointed as project manager. The project produced a stratigraphic framework, and undertook a systematic hydrogeological investigation into the reservoir capacity and productivity / injectivity potential (PRCL 2010). This work identified significant potential in the Debolt formation, a deep, non-potable carbonate aquifer (Figure 2). The identification of this water source led to the development of Encana and Apache's Debolt Water Treatment Plant, the first of its kind in Canada, and the Pressurized Fracturing on Demand system by Nexen. Subsequent work continued in 2011 to undertake research on surface water and shallow, fresh groundwater.

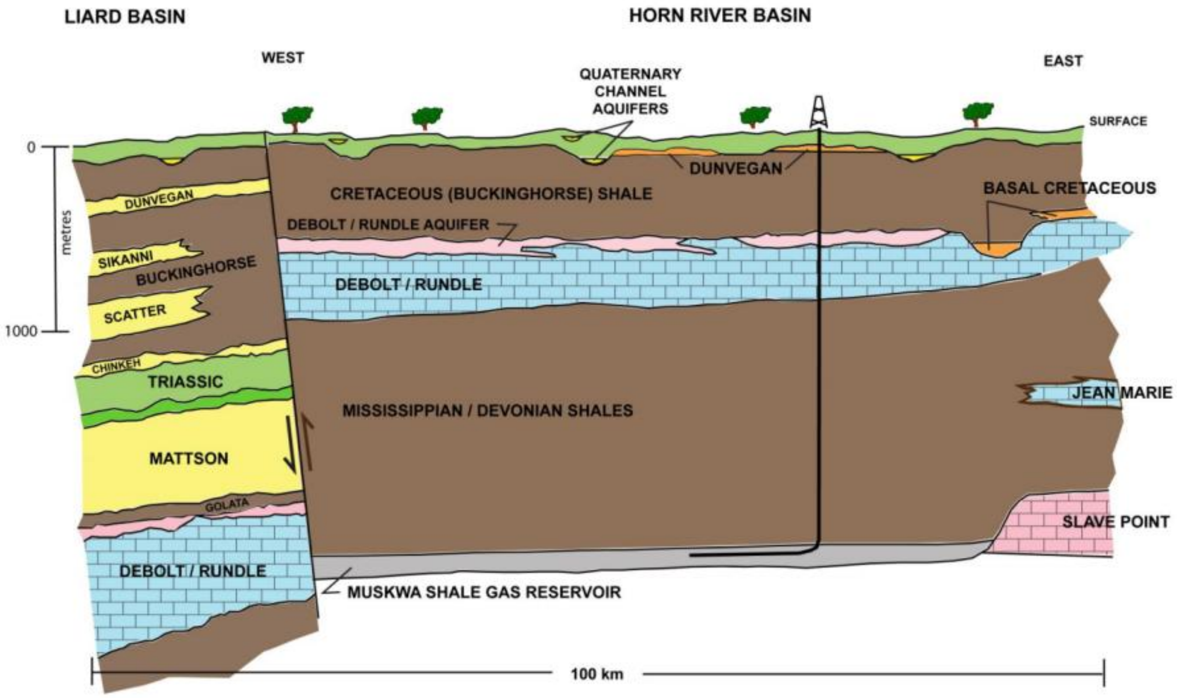
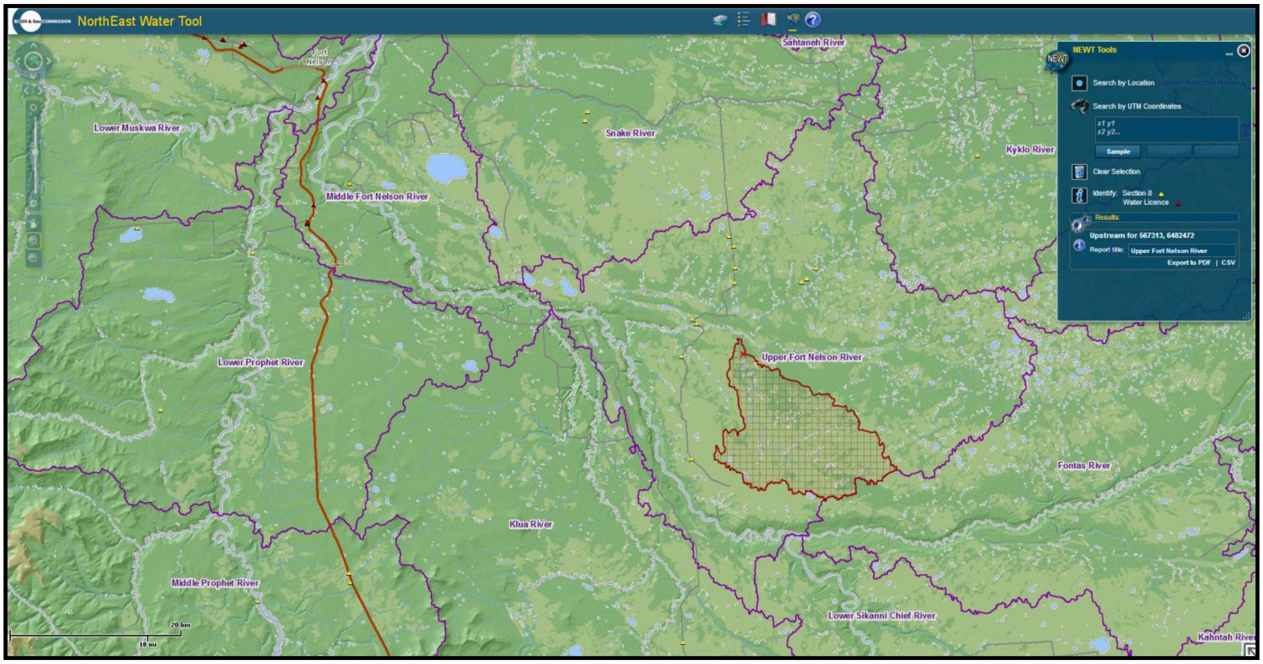


Figure 2. Horn River Basin stratigraphy (PRCL 2010).

In the Montney play in BC, a similar collaborative project was begun in early 2010. Led by Geoscience BC, several oil and gas operators with land holdings in the area were brought together with government agencies, academia, and local communities to undertake regional studies of the surface water, shallow groundwater, and deep saline aquifer resources. Contrasting with the staged work completed further north in the Horn River Basin, from the outset each water source was considered in the Montney Water Project (MWP). Foundry Spatial was the lead contractor on the surface water components, with Petrel Robertson Consulting completing deep saline aquifer work and Strategic West Energy providing overall technical project management. This project provided partner companies and other stakeholders in the region with information on the viability of each water source option across the play (Brown 2011). Two organizations involved in the MWP, Shell Canada and the City of Dawson Creek, have since collaborated on the Dawson Creek Reclaimed Water Project. The facility constructed treats municipal wastewater for use by Shell in hydraulic fracturing in their nearby operations, and also provides the City of Dawson Creek with additional water for municipal use or sale to other industrial clients.

Another project stimulated by the MWP was the Northeast Water Tool (NEWT, Figure 3). Foundry Spatial worked closely with hydrologists at the BC Oil and Gas Commission and Ministry of Forests, Lands and Natural Resource Operations to undertake hydrological modeling across much of Northeast BC (Chapman 2011, Wilford 2012).

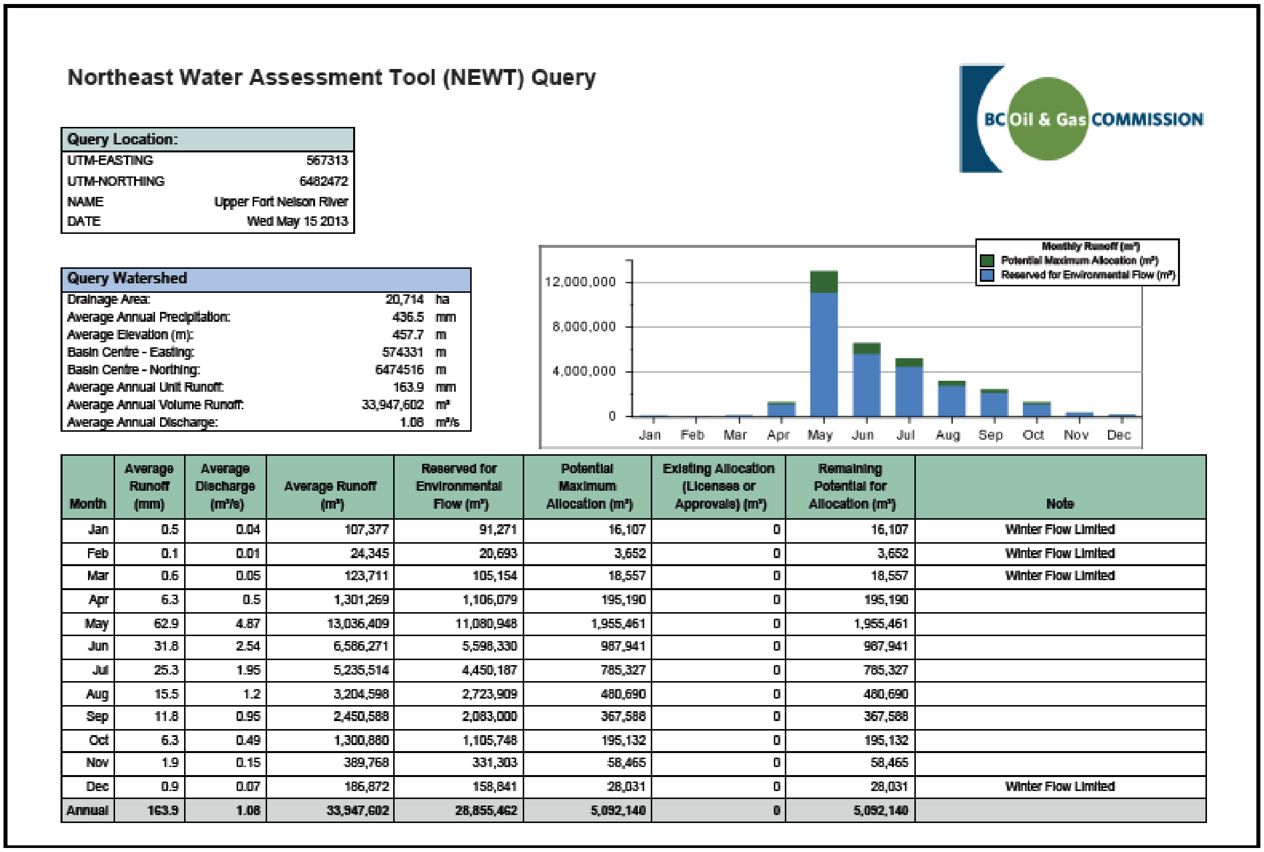


Upstream for 567313, 6482472

Report title: Upper Fort Nelson River

Figure 3. NEWT decision support map interface.

The modeling objective was to represent the spatial and temporal variability of long-term average surface runoff, to be used by licensing authorities in issuing water authorizations. The model was a custom, fully distributed, physically based equation model calibrated using detailed climate, vegetation and topography and validated using existing hydrometric data from BC, Alberta and the Northwest Territories. Model results were integrated with the BC Freshwater Atlas, which allowed for up and downstream query capabilities. Query functionality was built into a web-based decision support system, which is currently publicly available (http://www.bcogc.ca/public-zone/northeast-water-tool-newt) and provides on-demand information on modeled water availability, environmental flow requirements, and existing licensed allocations in the watershed context, at any scale and for any location across Northeast BC (Figure 4).



Northeast Water Assessment Tool (NEWT) Query

BC Oil & Gas COMMISSION

Query Location:	
UTM-EASTING	567313
UTM-NORTHING	6482472
NAME	Upper Fort Nelson River
DATE	Wed May 15 2013

Query Watershed		
Drainage Area:	20,714	ha
Average Annual Precipitation:	436.5	mm
Average Elevation (m):	457.7	m
Basin Centre - Easting:	574331	m
Basin Centre - Northing:	6474516	m
Average Annual Unit Runoff:	163.9	mm
Average Annual Volume Runoff:	33,947,602	m³
Average Annual Discharge:	1.08	m³/s

Month	Average Runoff (mm)	Average Discharge (m³/s)	Average Runoff (m³)	Reserved for Environmental Flow (m³)	Potential Maximum Allocation (m³)	Existing Allocation (Licenses or Approvals) (m³)	Remaining Potential for Allocation (m³)	Note
Jan	0.5	0.04	107,377	91,271	16,107	0	16,107	Winter Flow Limited
Feb	0.1	0.01	24,345	20,693	3,652	0	3,652	Winter Flow Limited
Mar	0.6	0.05	123,711	105,154	18,557	0	18,557	Winter Flow Limited
Apr	6.3	0.5	1,301,269	1,106,079	195,190	0	195,190	
May	62.9	4.87	13,036,409	11,080,948	1,955,461	0	1,955,461	
Jun	31.8	2.54	6,586,271	5,598,330	987,941	0	987,941	
Jul	25.3	1.95	5,235,514	4,450,187	785,327	0	785,327	
Aug	15.5	1.2	3,204,598	2,723,909	480,690	0	480,690	
Sep	11.8	0.95	2,450,588	2,083,000	367,588	0	367,588	
Oct	6.3	0.49	1,300,880	1,105,748	195,132	0	195,132	
Nov	1.9	0.15	389,768	331,303	58,465	0	58,465	
Dec	0.9	0.07	186,872	158,841	28,031	0	28,031	Winter Flow Limited
Annual	163.9	1.08	33,947,602	28,855,462	5,092,140	0	5,092,140	

Figure 4. Example report output from NEWT.

The Integrated Water Resources (IWR) team is currently delivering the largest integrated, collaborative water project to date across a significant portion of Alberta, including the fairways of the Montney and Duvernay plays (Figure 5). The Integrated Assessment of Water Resources for Unconventional Oil and Gas Plays in West-Central Alberta Project is a multi-year project, nearing the completion of the initial year. First year activities have focused on compiling existing data and research results, interpreting key factors controlling water availability, and integrating the results from surface to deep subsurface zones. The project is supported by the Petroleum Technology Alliance of Canada, the Canadian Association of Petroleum Producers, and eight mid to large size producers with land holdings in the region. The project is well aligned with emerging regulatory developments in Alberta targeting the unconventional gas industry (ERCB 2012) and will assist project participants with numerous aspects related to water acquisition and management.

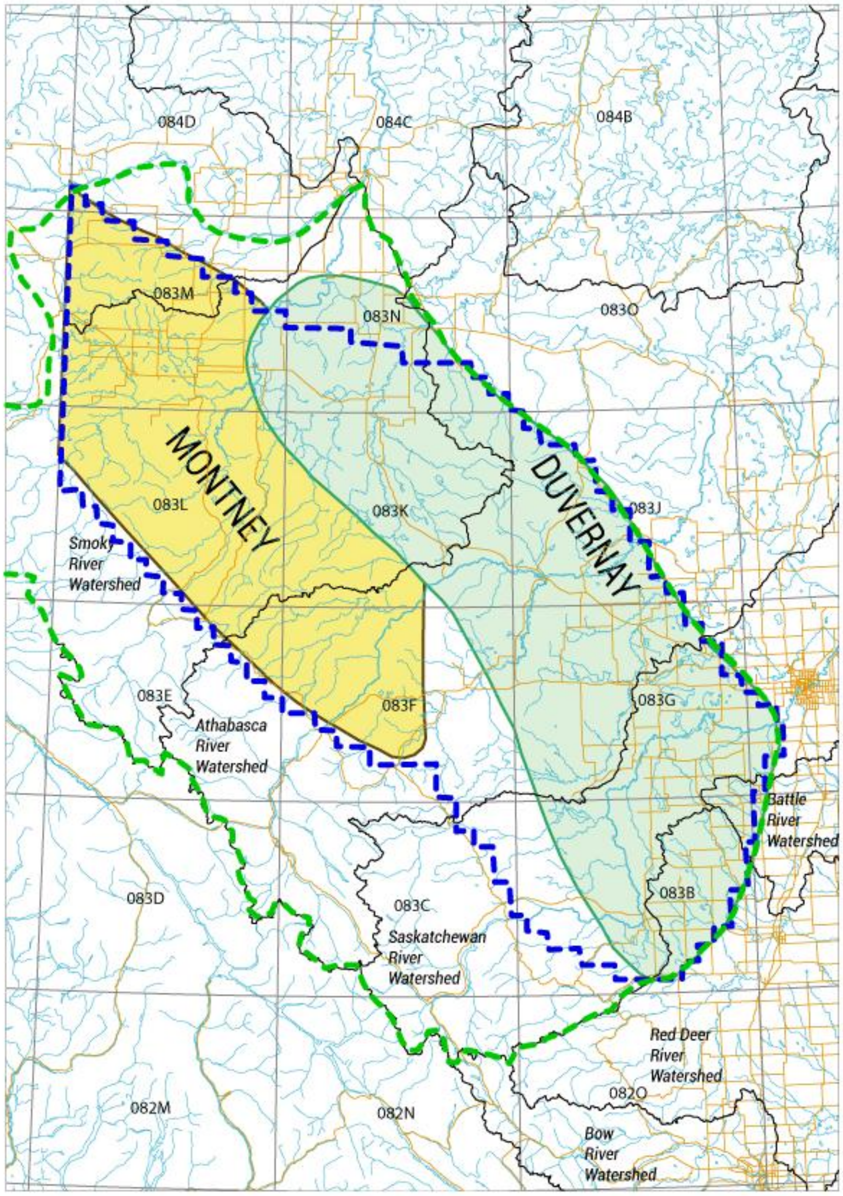


Figure 5. Integrated Assessment of Water Resources for Unconventional Oil and Gas Plays, West-Central Alberta, surface (green, 142,000 km^2) and subsurface (blue, 91,000 km^2) study areas.

Key Findings

Initial geoscience research activities in Western Canada that addressed water sourcing needs for the unconventional oil and gas industry were targeted at identifying fresh water alternative water sources for use in hydraulic fracturing. This remains a key motivating factor for continued work, and is mandated in industry operating practices (CAPP 2012). The IWR team has developed a unique approach that provides information on saline water sources alongside freshwater resources. Freshwater is currently the dominant source of water used for hydraulic fracturing, and will continue to play an important component of water sourcing strategies where saline, recycled, or treated industrial wastewater cannot meet needs. Understanding the geographic availability of freshwater alternatives will be a critical factor in the development of transparent water sourcing and management strategies.

Collaboration has proven to be critical to project success. By bringing together multiple oil and gas producers with government agencies, community groups and others, a significantly expanded geographic scope for projects has been made possible. Having a diverse set of perspectives involved has ensured the delivery of well rounded projects and allowed all stakeholders to work from a level playing field. By having access to third party research on all available options for water sourcing, each concerned party can engage in discussions on the advantages and disadvantages of each potential source, and transparent, defendable decisions can be made, as ultimately all project results are made publicly available.

Each IWR project is based on a robust spatial database. This ensures that data collected for every component comes together in a compatible format and at an appropriate scale for comparison. Continual communication amongst the research team working on various components identifies common ground and potential areas of collaboration in representing and understanding processes that overlap between the surface water, shallow groundwater, and deep saline aquifer components.

Project partners have access to the spatial database compiled during the projects, and receive all of the compiled data for integration into their corporate systems after project completion. Foundry Spatial has developed a web-mapping framework, NOLA, that acts as a key hub for partners to interact with the data. NOLA allows users to investigate the characteristics of various layers of information across the study area visually, and also to interact with spatial analysis results quantifying unique characteristics of sub-basins within the study, typically including:

- monthly and annual precipitation and temperature
- annual runoff, flood and drought flows
- current and historical weather data
- current and historical hydrometric monitoring - quality and quantity
- vegetation / landuse characteristics
- surficial materials, infiltration and recharge
- shallow fresh aquifer potential
- existing water well development and groundwater chemistry
- deep saline aquifer potential

By integrating information on each water source, industry partners and concerned stakeholders can compare the potential from each in a consistent manner. The guiding principle is to provide easy access to transparent analysis on documented data sets, thereby improving understanding of the relevant information and supporting better water sourcing decisions.

Summary

Shale gas and oil resources are significantly changing the global energy landscape. Developing these resources presents several challenges. These include drilling and producing wells in regions with little previous oil and gas activity, and the requirement for sourcing and handling much larger volumes of water than associated with conventional oil and gas activities. Water is a critical resource for the environment, economy, and society, and its management requires balancing sometimes conflicting priorities. Past project experience has shown that bringing together diverse groups of stakeholders, including industry, government, and local communities in integrated, collaborative water research projects, results in improved and informed water management decision-making.

Acknowledgements

The author would like to thank collaborators in past and current projects, including Strategic West Energy Ltd., Petrel Robertson Consulting Ltd., Dendrite Geoscience, Geoscience BC, BC Oil and Gas Commission, BC Ministry of Forests, Lands and Natural Resource Operations, BC Ministry of Energy and Mines, Alberta Ministry of Environment and Sustainable Resource Development, Alberta Energy Resources Conservation Board, Cequence Energy, Chevron, Canadian Natural Resources Ltd., EnCana Corporation, Husky Energy, Talisman Energy, ConocoPhillips, Shell, ARC Resources Ltd., Devon Energy and Progress Energy.

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Appendix C.

Poster Abstracts

A Simulation Framework for Integrated Water and Energy Resource Planning

Robert Jeffers
Idaho National Laboratory

The statements made during the workshop do not represent the views or opinions of EPA.
The claims made by participants have not been verified or endorsed by EPA.

Introduction

Affordable electricity and accessible, clean water are fundamental to economic production and human livelihood. They are so much so in fact that wars are now fought over energy resources and access to water commonly separates the poor from the desperate and oppressed poor (The World Bank, 2010). While these problems are world-reaching, even the richest nations struggle to equitably and economically plan for the acquisition, use, and distribution of energy and water resources. In the United States for example, groundwater aquifers are being drained for agricultural production, electricity generation suffers unplanned shutdowns during extreme droughts, and questions surrounding hydraulic fracturing of natural gas are causing many to doubt the future of their water supplies (Tidwell et al., 2009). Improved water and energy planning can help avoid these negative outcomes.

The primary purpose of this work is to improve the holistic value of energy development strategies by integrating water resources management criteria into the energy system planning process. Many energy planners fail to adequately incorporate the long-term public interest, instead targeting least-cost development. To assess performance given the long-term goals of the public alongside the goals of private energy development, this work integrates multiple decision criteria for water and energy stakeholders into a simulation framework for integrated resource planning. The simulation framework presented – titled the Water and Energy Simulation Toolset (WEST) – combines salient aspects of many disparate models into one system for the purpose of exposing decision makers and stakeholders to a coupled representation of water and energy systems subject to multiple scenarios.

A Western Energy-Water Collision

The details of both the water and energy planning processes create difficulty for even the richest societies. For instance, water quality and water availability are closely coupled with economic development and the productivity of managed and natural ecosystems. Merely assessing water availability can be a daunting task, highly dependent on spatial and temporal scales. Finally, to appropriately plan one must understand the potential for changes in all of these aspects through time. This is not to mention the effort of navigating a thick political atmosphere, bureaucratic red tape, and the host of private interests all trying to manipulate the planning process for personal gain.

The United States suffers from a fragmented approach to water resource planning and management. Over 20 different federal agencies have various responsibilities for national water policy, and in most cases water resource planning is performed at a state level by an additional host of agencies (US DOE, 2006; Jackson et al., 2001). In an assessment on water resource planning research, the National Research Council found that government organizations overseeing management of water lack top-down vision because authority is spread among these agencies at both federal and state levels (Committee on Assessment of Water Resources Research, 2004). For example, many states decouple the management of water quality and quantity, with separate agencies commonly attempting to coordinate via interpersonal communication and offline agreement. Instead, a comprehensive water resource plan should include policy to manage water availability and quality from a holistic viewpoint. The plan should be comprehensive not only in its technical breadth, but also in the people it involves in the process and the viewpoints it incorporates, in order to truly understand how to best increase benefit to the public.

Effective planning for the sustainable use of water resources requires understanding of how the intricacies of law set the rules for the use of water. In the West, laws governing water use have evolved in a commonly water-limited environment. As the West was settled rapidly in the mid 1800's, early state and territory governments (most notably in Colorado and California) found that traditional riparian water law limited the productive and equitable use of land, particularly for the agricultural and mining interests that dominated early settlements (Reisner, 1993). These pioneers developed the water governing system of prior appropriation, which is commonly summarized as "first in time, first in right." Ownership of the water is assigned to the state, but the right to divert and apply that water to a beneficial use may be held by an individual. That individual is said to have a water right, which confers an associated date of appropriation, a location of use, and an amount of water ideally commensurate with the stated beneficial use. It is the state's role to ensure that all senior water rights holders are given priority over those junior, if in fact the seniors continue to put their water to beneficial use and that use is within the laws that govern waste and abandonment.

In Idaho, one of the most famous instances of conflict over water availability is also a prime example of a problem for integrated energy-water management. In the early 1950's, the Idaho Power Company (IPCo) and the US Army Corps of Engineers were each planning hydropower projects on the Hells Canyon of the Snake River. The competing projects were the main act in a national battle between public and private power ideologies (Brooks, 2006). To gain the support of the Idaho State Government, IPCo agreed to subordinate its water right at Hells Canyon to future upstream development. This means that they would have a right to use any water that passed through the facility, but this right would always be junior to upstream users. Partially due to the state's support for the project, IPCo won the hydropower permit from the Federal Power Commission and by 1967 the Hells Canyon Complex was complete. To date, it is IPCo's largest power producer and an important revenue source (Idaho Power, 2011). With the new hydropower complex, IPCo was flush with inexpensive generation so they lowered rates for agricultural users, partially to encourage investment in electric groundwater pumps which were undergoing rapid technological advancement (Galbraith, 2010). Groundwater pumpers spread across the Snake River Basin, to the point that irrigated land in Southeast Idaho is nearly half-sourced by groundwater resources today. At the same time, surface water users were becoming more diversion efficient, increasingly using sprinkler technology instead of flood irrigation practices. This combination of increased pumping from new groundwater users and decreased recharge from existing surface water users has caused levels in the Eastern Snake Plain Aquifer (ESPA) to decline rapidly over the past three decades. Springflows from the ESPA have similarly declined, and IPCo relies on these springflows for a large fraction of their hydropower generation. With a dose of irony, IPCo is in direct conflict for water with the groundwater pumpers that they helped thrive.

In 1978, a group of ratepayers noticed the decreasing springflows and sued IPCo claiming that the electric utility was not doing everything in its power to protect its water rights at its older dams, which themselves are upstream of the Hells Canyon Complex. In response, IPCo initiated Idaho Power Co. v. State (104 Idaho 575) seeking a determination of validity for water rights at all of its dams and contesting the state water plan at the time. The resulting settlement is called the Swan Falls Agreement, which confirmed IPco's senior rights, and required IDWR to enforce a minimum flow downstream of the major agricultural producers. Historically, IDWR has been able to meet the Swan Falls right primarily with springflows from the ESPA in summer, but because of the declining groundwater levels this is impossible in years of consecutive drought. IDWR's plan to recover the aquifer levels is called the Comprehensive Aquifer Management Plan (CAMP), which has a goal to increase the water budget to the aquifer by 500 kAF/yr and is funded largely by taxpayer dollars.

The Swan Falls Agreement, subsequent adjudication, and CAMP highlight the need for integrated planning from a water law perspective in Idaho. Instead of waiting for senior users to make water calls and often settling water disputes in court, it would be more cost effective to plan in advance for changes in water demand. These changes can be driven by electricity development, such as those experienced in the 1970's after the construction of the Hells Canyon Complex. At the time very little was known about the connectivity between the ESPA and the Snake River. If this knowledge were available, however, increasing the integration between planning for energy generation and water allocation would have avoided much of the cost and conflict being experienced today.

Modeling and Simulation for Integrated Energy-Water Planning

As indicated in the preceding description, many problems that involve energy and water feedback require tightly coupled understanding of these systems' co-dependencies. To combine the strengths of models with high realism (Hamlet et al. 2009, Elsner et al. 2009) with models which are highly usable for integrated analysis (Ford, 1996; Tidwell et al., 2004), the Water and Energy Simulation Toolset (WEST) manages complexity using an object-oriented system dynamics approach (Li et al., 2010). Object-oriented system dynamics combines the object-oriented programming philosophy to create abstraction of categorical complexity (Meyer, 2000), along with the system dynamics philosophy that describes dynamic behavior with a series of stocks (accumulators), flows (derivatives), and feedback loops (Forrester, 1969; Forrester, 1971).

WEST is currently primarily a hydrology modeling tool. However, it is structured so that the collection of objects may evolve depending on the problem at hand. It simulates multiple criteria relevant to water resource managers and electricity development planners, but it uses hydrologic variables such as streamflow, snowpack, and agricultural diversions to determine these criteria. It simulates natural hydrology as well as human behavior relevant to electricity and water supply and demand. The four WEST components are the natural water balance, irrigated agriculture, managed reservoir, and groundwater aquifer components. The detailed rationale, design, and defense of each component are performed by Jeffers (2013). A high-level view of the inputs and outputs for each component is shown in Figure 1. Every component-level input in figure 1 that is not precipitation or temperature is calculated using other components, giving rise to endogenous behavior. In contrast to the low number of inputs, WEST models can have thousands of outputs, because a large number of physically representative behaviors are simulated by each component. A summary of the most relevant physical variables for each component is included in Table 1.

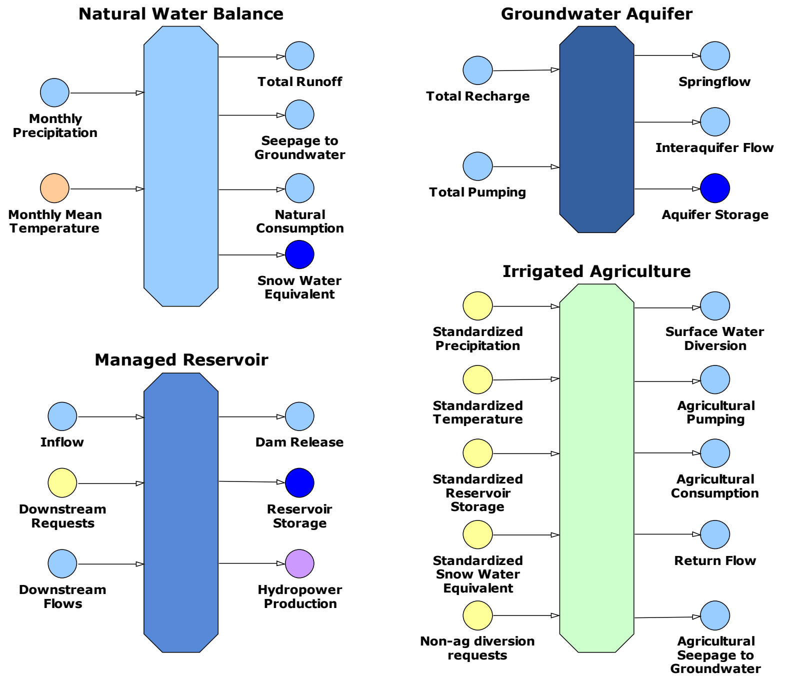


Figure 1. An "input-output" depiction of the four WEST components. Octagons are the modeling components, while circles are variables that pass in and out of the components.

Table 1. A list of selected physical variables within each WEST component

Component Name	Stocks	Flows
Natural water balance	snow water equivalent, upper Soil Moisture, lower Soil Moisture	snowfall, rainfall, incident moisture, direct runoff, surface runoff, baseflow, evapotranspiration, soil seepage, groundwater seepage
Irrigated agriculture	N/A	surface agriculture diversions, surface managed recharge diversions, groundwater pumping, groundwater pumping losses, canal losses, water applied to fields, field evapotranspiration, lateral returns, groundwater seepage
Groundwater aquifer	groundwater storage	total recharge, total pumping, interaquifer flow, springflow
Managed reservoir	reservoir storage	reservoir inflow, reservoir outflow

Modeling the Snake River Basin using WEST

WEST was utilized to simulate the major criteria that water and energy planners use in the Snake River Basin. These criteria are summarized in table 2. The resulting proof-of-concept WEST model is called the *Cutthroat River Model,* in which the names of geographic features have been changed for learning purposes. Figure 2 depicts the collection of watersheds, reservoirs, and groundwater bodies that were assessed over the Snake River Basin. The study area in figure 2 spans over 190,000 square kilometers (73,000 square miles). The Snake River stretches from its clean, clear headwaters in western Wyoming and eastern Idaho south to Idaho's "fertile crescent," and turns north again at the Idaho-Oregon border, passing through Hells Canyon on its way to join the Columbia River in Washington. In 2005, Idaho withdrew 21.9 million acre-feet (AF) from its rivers and aquifers, third in the nation behind California and Texas (Kenny et al., 1995). The use of groundwater in Idaho is significant, consisting of about 20% of annual withdrawal. Almost all water withdrawal in Idaho – 98% – is performed by irrigated agriculture and aquiculture. The great majority of this agricultural withdrawal is from the Snake River and its connected aquifers. Because of fast drainage by the SRB's sandy-loam soils, application of water by irrigated agriculture is among the most intense in the nation, exceeding 5 acre-feet of water per acre per year.

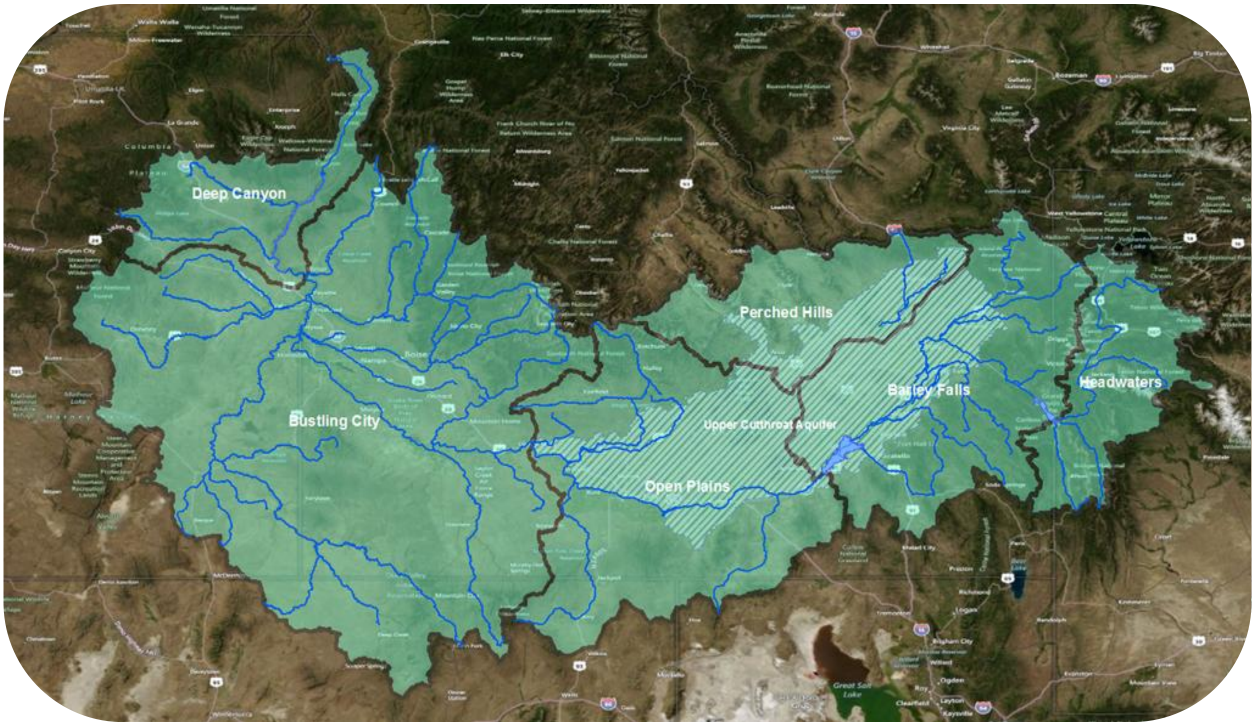


Figure 2. Geography of the WEST proof-of-concept study area and the Cutthroat River Model's fictionally-named watersheds. The area of the underlying Cutthroat Aquifer (ESPA) is shown with blue hashing. The river flows from east to west.

Detailed connection diagrams describing the Cutthroat River Model are available in (Jeffers, 2013) to aid in understanding the description of model development. The only time series inputs for WEST models are watershed-scale monthly precipitation and temperature. Watershed polygons for Geographic Information System (GIS) applications were obtained from the USGS Watershed Boundary Dataset (US Geological Survey, 2013), from which smaller 8-digit Hydrologic Unit Code watersheds were joined to create six macro watersheds and compute their area. The Parameter-elevation Regressions on Independent Slopes Model (PRISM) was used for precipitation and temperature input, whose results are available for download (PRISM Climate Group, 2011). PRISM data was aggregated to a single value for each watershed in each month. The amount of land irrigated using surface water and groundwater was obtained from Hoekema (2011).

Table 2. Water Management Goals in the Cutthroat River Model

Water Management Goal	Metric of Performance	Units
Electricity generation	Average energy generated per year	aMW
Flood control	Average yearly volume above flood stage	AF/yr
Agricultural delivery	Percentage of agricultural requests denied	%
Environmental protection	Average volume of deficit versus targets	AF/yr
Groundwater maintenance	Mean flow from King and Barley Springs	ft^3/s

Simulating the Dynamic Problem

Figure 3 illustrates the results of calibrating the Cutthroat River Model to historic Snake River behavior. The model exhibits a good fit to historic data (detailed analysis in Jeffers, 2013). To project the potential behavior of the Snake River assuming that no changes in management, climate, or behavior modes occur into the future, climate inputs of 1970-1999 were looped three times and named the past, present, and future eras, respectively. There is also a three year input buffer before 1970 to give the model a warm-up period. Thus, the simulation begins with hypothetical inputs in 1967, runs through the observed climate and behavior for the past era, and projects using the looped climate inputs for the present and future eras. This is called the long-term planning mode of the Cutthroat River Model.

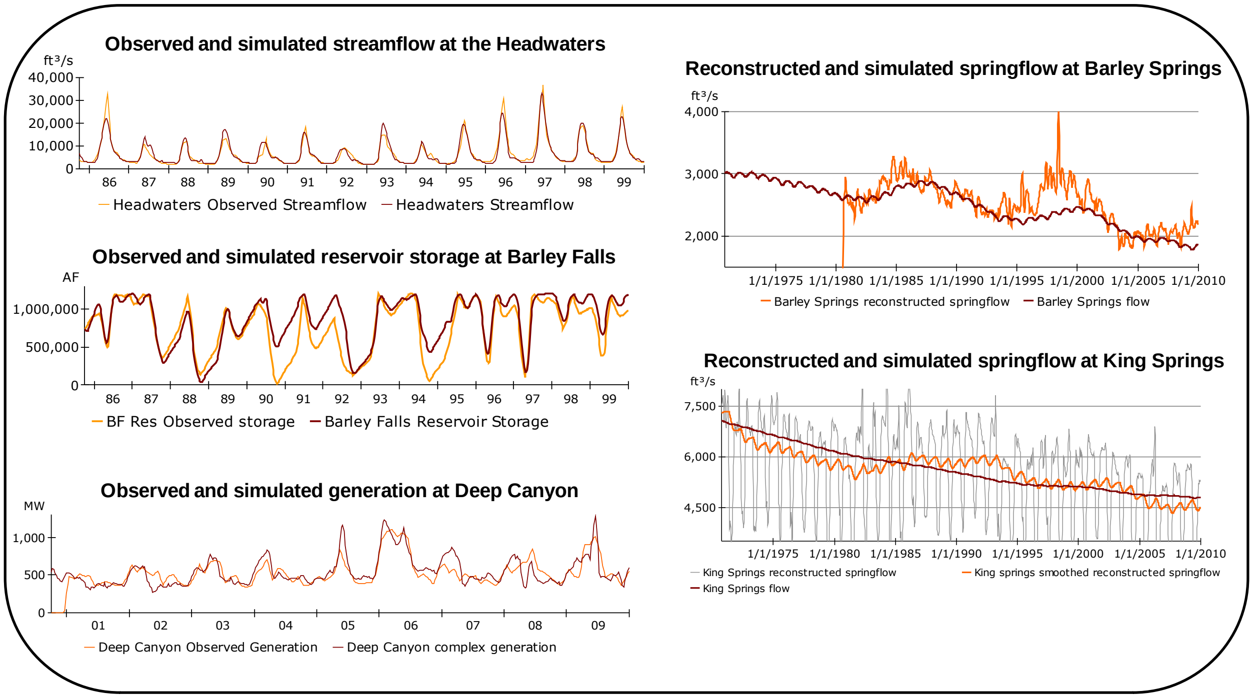


Figure 3. Declining springflows were reconstructed from spring gauge data and are represented for Barley Springs and King Springs. The simulated Barley Springs flow matches the reconstructed data well, while the simulated King Springs flow more closely matches a three-year average of the reconstructed data.

Figure 4 illustrates the problems apparent if no changes in management practices occur into the future era that represents years 2030-2059. Hydropower at the Deep Canyon Complex decreases by 36 aMW (6%) between past and future eras. The monthly average hydropower profiles suggest this decrease happens nearly equally in every month. A greater number of agricultural delivery requests are denied in Open Plains, and in the future more requests are denied in Open Plains than in Barley Falls. This suggests that it may be harder to follow priority of water rights in the future because Open Plains agricultural users will rely more heavily on storage higher in the system. Environmental flow deficits are increasing at Deep Canyon but stay stable in Barley Falls, and flooding declines on average. As suggested, Open Plains releases an increasing amount of water to meet IPC's instream right.

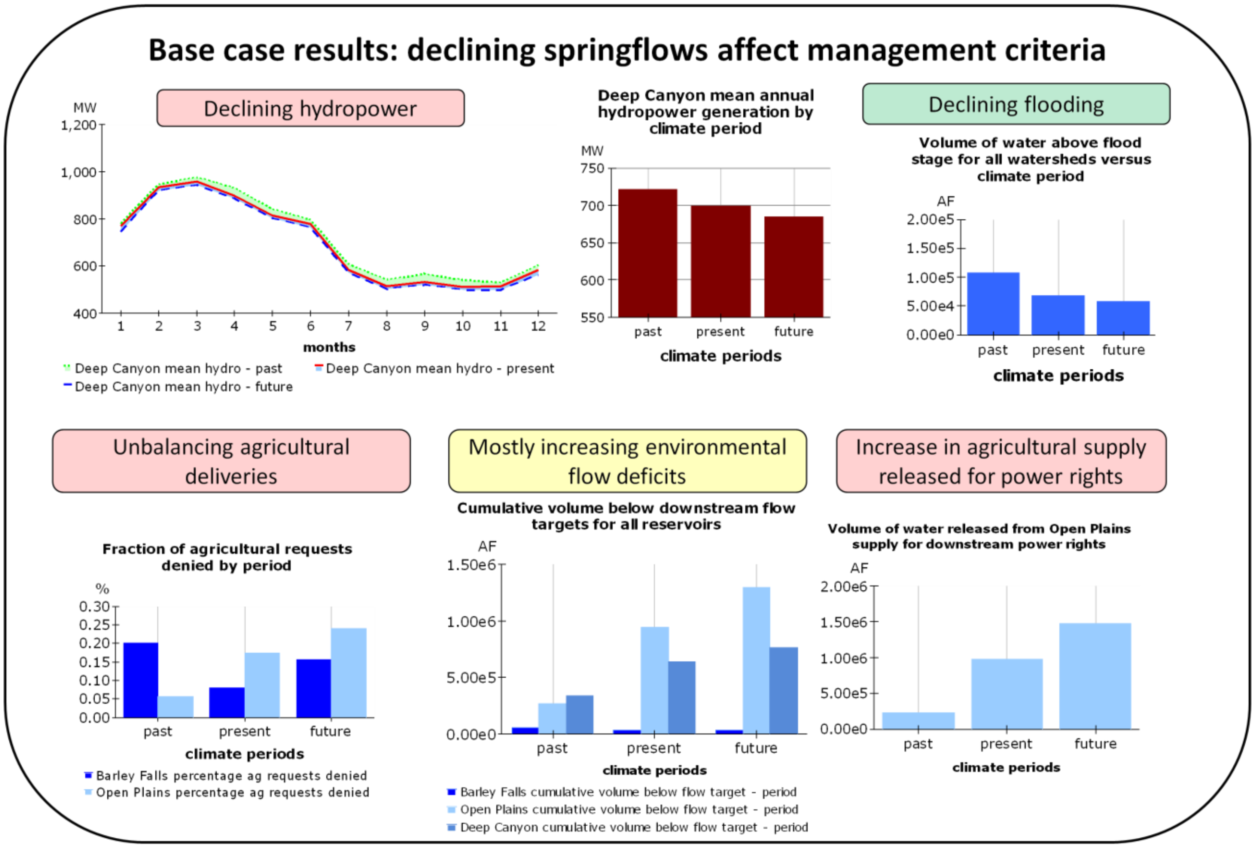


Figure 4. Due to the declining springflows, a number of management criteria exhibit negative outcomes. These undesirable outcomes are shown in red, while desirable outcomes are in green and mixed outcomes in yellow.

Testing Proposed Policies

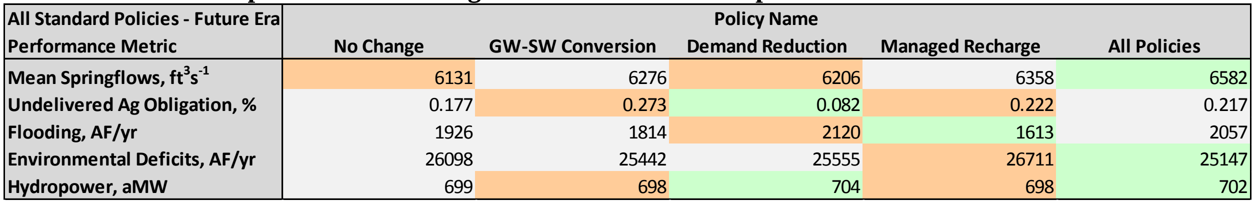
The results of the base case indicate that, with no action, declining springflows will lead to an increase in the number of years with competition for water between agricultural and energy users, as well as among agricultural users themselves. This behavior has been suggested on the Snake River for some time (Darrington et al., 2009). Table 3 outlines the CAMP policies that IDWR have suggested and the Idaho legislature has approved for reversing the declining springflows from the Eastern Snake Plain Aquifer. These three policies were designed to recover springflows, but to be truly comprehensive they should account for all five of the management criteria. Each policy was implemented in the Cutthroat River Model, and the absolute average of each criterion for the future area is shown in Table 4. Notably, the groundwater to surface water conversion policy is the worst performer in the agricultural delivery and hydropower categories, and it is the best performer in none of the categories. This information weeded out conversion as a potential "worst" policy. Also, each policy only has a minor impact on hydropower generation, about 1% at the most in the future era.

Table 3. Comprehensive Aquifer Management Policies

Policy Name	Description
Groundwater to surface water conversion	Approximately 100 kAF/yr by transitioning groundwater pumpers to surface water use
Agricultural demand reduction	Reducing withdrawal by 250-350 kAF/yr between surface and groundwater users by means of contractual agreements, crop mix changes, fallowing, land purchases, or other mechanisms
Managed aquifer recharge	Increasing the aquifer water budget by 150-250 kAF/yr by diverting from surface water to managed recharge sites, nominally in spring and fall when demand is low
Weather modification	A pilot program to increase precipitation through cloud seeding. Not simulated in the Cutthroat River model.

After removing the conversion policy, the performance metrics were normalized by the business-as-usual case and plotted on the radar diagram shown in figure 5. Values toward the edge of the radar diagram indicate desirable performance, while values toward the origin indicate undesirable performance. In this way, shapes with higher area are likely better at more criteria than shapes with smaller area. Notably, springflow recovery appears to be as good as the sum of its parts, as indicated by the case with all policies in place. Agricultural deliveries become less reliable with any policy other than demand reduction. Demand reduction also improves environmental flow deficits and hydropower production quite well. Only managed recharge is able to curb flooding more than the business-as-usual scenario. The scenario with all policies in place appears to be a good middle ground between improving springflows and satisfying the hydropower interests.

Table 4. Average values in the future era for the five performance metrics under standard policies. Orange indicates undesirable performance while green indicates desirable performance.



All Standard Policies - Future Era	Policy Name				
Performance Metric	No Change	GW-SW Conversion	Demand Reduction	Managed Recharge	All Policies
Mean Springflows, ft^3s^{-1}	6131	6276	6206	6358	6582
Undelivered Ag Obligation, %	0.177	0.273	0.082	0.222	0.217
Flooding, AF/yr	1926	1814	2120	1613	2057
Environmental Deficits, AF/yr	26098	25442	25555	26711	25147
Hydropower, aMW	699	698	704	698	702

Conclusions

If the CAMP policies outlined in table 3 are not enacted, the results of the Cutthroat River Model suggest that the basin will not be as productive as the historic period of 1970-1999. Surface water irrigators, especially those in the Open Plains region, would find decreasing delivery reliability because they are more dependent on the upper Barley Falls Reservoir due to the decreased flow from Barley Springs. Because Open Plains surface water diverters have senior rights in general compared to Barley Falls diverters, this scenario could result in more calls for curtailment of groundwater pumpers and Barley Falls diverters. Courts would continue to face problems with futile calls and may need to curtail water users out of priority. At the same time, Idaho Power shareholders may notice the 6% decrease in average hydropower generation and call for more water to be released from Open Plains Reservoir to meet the Swan Falls instream right. Environmental interests around the Deep Canyon Complex may also notice that less water is being released in spring and fall for anadromous fish passage downstream because Idaho

Power is trying to hold water back for peak electricity demand season. Flood control downstream of Open Plains will be more effective due to the decreased springflows. This may be the new normal if no CAMP policies are enacted.

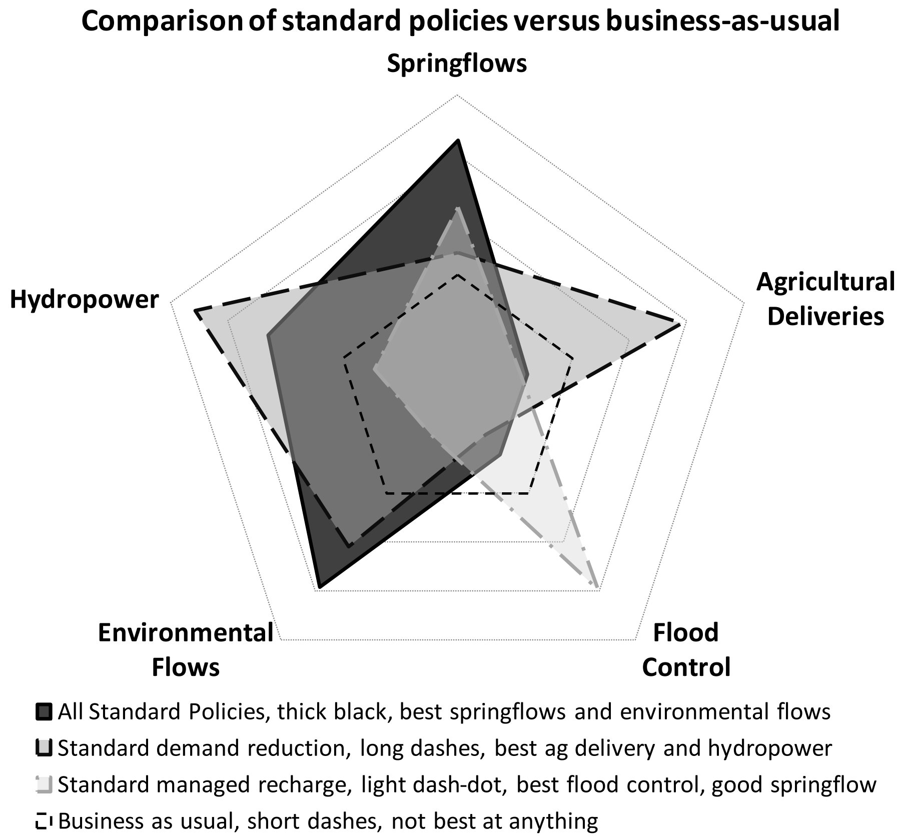


Figure 5. A radar diagram showing the relative performance of selected policies compared to business-as-usual. All policies together do well on several fronts, but are somewhat undesirable in terms of flood control and agricultural deliveries.

If CAMP provisions are implemented as-is, they won't improve all water and energy management goals in the Snake River Basin. Namely, groundwater to surface water conversion policies help springflow by 2.4% compared to business as usual, but put additional stress on agricultural deliveries, hydropower, and environmental flows. Managed recharge helps springflows by 3.7%, but can negatively impact environmental flows and hydropower. This result is somewhat counterintuitive. The hydropower is down even though springflows are higher because surface water is being removed from the system for recharge, and the springflows take around 40 years to fully come to a new equilibrium. Demand reduction helps the most criteria, but it also has the highest potential to decrease agricultural production and leaves more potential for downstream flooding.

This paper has introduced WESTs ability to model the water and energy planning criteria of the Snake River Basin. It shows the ability of WEST to be calibrated to historic conditions in the Snake River Basin and summarizes the important behavioral elements of the Cutthroat River Model. The performance metrics that reflect basin management criteria are currently changing through time, and the CAMP policies that IDWR has designed to alleviate the problem of declining springflows are evaluated holistically. The recommendation to IDWR is that CAMP policies of managed recharge and agricultural demand reduction should be enhanced beyond their current levels, while the policy of groundwater to surface water conversion should be considered as a less desirable option for holistic management.

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Utilizing Produced Water and Hydraulic Fracturing Flowback as a New Water Resource

David R. Stewart, R. Forbes Guthrie, Andrew D.R. Stewart
Stewart Environmental Consultants, LLC

The statements made during the workshop do not represent the views or opinions of the EPA. The claims made by the participants have not been verified or endorsed by the EPA.

Introduction

The energy industry has an issue with produced water and its associated costs. Produced water and hydraulic fracturing flowback water (referred to as produced water throughout this paper) is generally mineralized and contains particulate and dissolved organics. This water is brought to the surface during an oil and gas operation. These operations consist of conventional and unconventional oil and gas wells. Depending on the source of the produced water, the amounts of water can be significant, such as tight sands or coal bed methane water.

This paper will discuss the research regarding the use of produced water as a new water resource. We will cover four different facilities and different types of produced water from both conventional and unconvential sources. The treatment and discharge of produced water is specifically applicable to the western United States where a continuing draught is occurring. Produced water will provide new water in the surface streams. Due to water law, prior appropriation doctrine (first in use is first in right), this will allow energy companies a new income stream if the proper treatment is performed to allow discharge of this produced water. We also believe that produced water can be part of the portfolio of water rights that can assist with less dependence of agricultural to urban water rights transfers. It is important to note that agriculture will require an increase in water in order to meet the requirements of the market and the goals of the USDA. Therefore, the treatment and discharge of produced water will help to meet the needs of agriculture as well as allow for the increase in domestic energy development by removal of the constraint of injection wells on energy production.

Volumes of Produced Water

Approximately 21 to 25 billion barrels of produced water are generated from more than 1 million wells in the United States. This equates to 3.2 million acre feet of water annually. This will support over 10 million people annually based on 0.3 af/home per year.
Population growth, drought in the western United States and climate change have substantially increased the demand for water in the arid west. This lack of water is creating a water crisis in the west. The areas of high demand was highlighted in the US Bureau of Reclamation Study – Water 2025. In reviewing this report, we combined data from the USGS on the location of produced water and the projected water short areas of the western US. This information is found in Figure 1. As shown in this figure, the produced water generation is either directly in the area of a water short location, such as the front range of Colorado or can be delivered through a stream system such as the lower Colorado River area of Las Vegas, the Central Arizona Project and the Metropolitan Water District Colorado River Aqueduct.

Water – Energy – Agriculture Nexus

There is a water – energy - agriculture nexus that needs to resolved in order to help in the development of domestic energy and also the development of water resources in the western US. Currently, it is estimated that between 20% to 30% of our energy in both electricity and natural gas in the west is for the movement of water. This is a significant number that needs to be improved.

For produced water, it is estimated that 30% of the energy that was brought to the surface in the form of oil or natural gas is being expended in the reinjection of this produced water back into the subsurface through Class II injection wells.

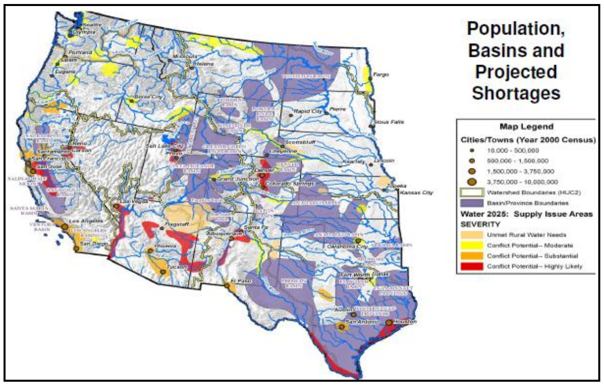

Figure 9. Produced Water Generation overlain on Water Short Areas

Energy producers will save a considerable amount of costs associated with reinjection through a Class II injection well with this proposed program of beneficial use of the produced water. When comparing the energy needed for reinjection of 30% to the cost of treatment of 5% to 8%, there is a significant savings in the energy needed for disposal.

Beneficial Use of Produced Water – Colorado River Basin

Figure 2 provides a profile of the Colorado River basin, which shows both the upper and lower basin under the seven state compact. As shown, this figure shows that the projects in the upper basin will deliver water to the natural stream system. The system is then capable of delivering water to the lower basin through the Colorado River system.

In order for this to occur, there will need to be studies by the Colorado River Seven States Commission regarding the use and application of this water. However, based on the existing water shortages that are projected for this area, it appears that the timing is correct for this to proceed in a study and analysis phase.

Figure 10. Colorado River Basin

It is estimated that the amount of produced water that could be generated during production of unconventional energy resources, such as CBM or tight sands gas well fields could range from 500,000 to 1,000,000 acre feet per year. At the present time, the need for this water is being discussed by the Upper Colorado River Basin Commission.

The Raton Basin has a considerable amount of produced water that can be delivered to the Arkansas River near Pueblo Colorado. Through exchanges and utilization of the various ditch systems in the area, we can deliver this water to Pueblo, Colorado Springs and southern Denver/Aurora areas.

Who Owns this Produced Water

Historically, produced water has been re-injected through a Class II injection well, placed in an evaporation pit or disposed of through a direct discharge. All of these techniques have some adverse environmental impacts.

We have worked with various energy companies to turn this wastewater into an asset. This marketable product is achieved through a treatment system that achieves discharge standards through an NPDES permit system. We then go through the regulatory and legal hurdles to be able to take this treated water and sell it as an augmentation water.

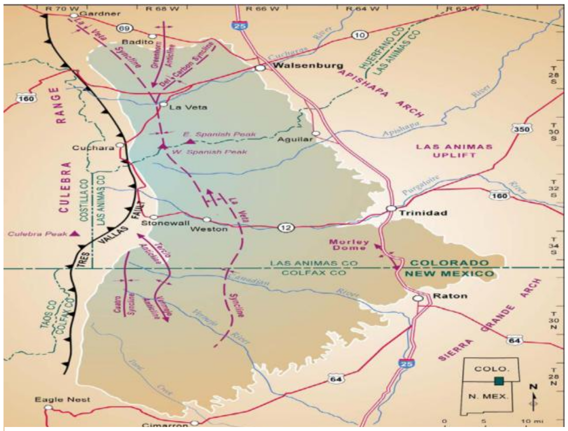

Figure 11. Raton Basin for CBM Production

Colorado has the most complicated and controlled system of water rights in the west. It is the only state which has their own water court system. In Colorado, the groundwater is classified as either tributary to a stream or non-tributary. Most produced water, due to the geologic formation, is likely non-tributary. This will allow for the complete consumption or utilization to exhaustion of this water.

Recently, Colorado passed HB 1303 and SB 165, which are a result of a produced water case in southwest Colorado (Vance vs Simpson/Wolfe). In this particular case, the produced water had a tributary component. Due to this factor, the State Engineer was required to classify the withdrawal of this produced water as a beneficial use. This required the energy company to obtain a permit from the State Engineer's office.

The Wellington Colorado case (Wellington Water Works vs. Dumont) is a case where the water right was obtained and is consistent with the Colorado Supreme Court decision in the Vance case. Specifically, if the energy company wants to utilize the produced water beneficially, they need to do the following:

1. Obtain a beneficial use permit from the State Engineer
2. Contact the Colorado Department of Public Health and Environment for a preliminary effluent limit determination for discharge to a surface water.
3. Obtain a discharge permit from the Colorado Oil and Gas Conservation Commission.
4. Apply to Water Court to obtain a vested right in the produced water for beneficial use.

We followed this path in the Wellington case and were able to obtain the water court ruling in March 2008. As stated above, other states are not as burdensome with their requirements and likely will follow the prior appropriation doctrine which would allow the first in use to have the first in right.

Wellington Colorado Production Water Plant

The first produced water from a conventional oil and gas field project to beneficially use this water is near Wellington, Colorado. This project is treating oil production water as a new water resource. This new water resource will be used to augment shallow water aquifers to prevent injury to senior water users. The oil company is embarking on this project to increase oil production. A separate company will then purchase and utilize this water as an augmentation water source. This water is under a preliminary contract to allow the Town of Wellington and northern Colorado water users to increase their drinking water supplies significantly. In this example, the Town of Wellington can increase their water supply by 300 percent due to this new water source.

The overall process of this project was to accomplish the following:

- Obtain concurrence with the State Engineer that this water was non-tributary. This was accomplished in 2004.
- A discharge permit was required from the Colorado Oil and Gas Conservation Commission with a technical review by the Colorado Department of Public Health and Environment. This permit was obtained in December 2005.
- A water court ruling is required to allow this water to be used in perpetuity. This was granted in March 2008.

As shown by the above timeline, this project has taken a significant amount of time. One of the issues in this project is being the first entity to accomplish these tasks. Now that a precedent has been set, we believe that this will proceed in a more timely manner in the future.

The economic reasons for this plant are as follows:

- The cost of the production water treatment plant is approximately $2,000 to $3,000 per ac-ft of capacity. The operational cost for this plant is approximately $350 per ac-ft.
- The cost of the reverse osmosis plant for the drinking water portion of the plant is $2,000 to $3,000 per ac-ft.
- For the two plants, the cost for capacity is $4,000 to $6,000 per ac-ft.
- The market for this water is $15,000 to $20,000 per ac-ft for the non-tributary water, and the market for the finished water is an additional $15,000 per ac-ft.
- Therefore, for an investment of $4,000 to $6,000 per ac-ft, the return is close to $35,000 per ac-ft.

In addition, the energy company is able to expand their production by over 50 percent based on the capacity of the treatment facility.

We believe that the economic value will only increase in the future. This is due to the lack of water in the western United States.

Utah Facility

The Upper Colorado River Basin represents a considerable opportunity for appropriation of produced water, as previously discussed. In 2010, we commissioned a produced water treatment facility in Westwater Utah. Water treated at this facility originates from produced waters within a 75-mile radius, primarily from oil and CBM operations in the Uinta and Piceance basins. Prior to the commissioning of the plant, primary the disposal method for this water was evaporation. Increased regulatory pressures on evaporative pits with regards to VOC emissions and disposal of RCRA regulated hazardous sludge placed question on the long-term viability of disposal at the regional evaporative pit, providing validity to the operation of a centralized mechanical treatment facility.

The service area of the Westwater Utah facility is approximately 75miles in radius, with most of the energy companies producing small to moderate volumes of water. Though the individual volumes of produced water are relatively small, the potential aggregate for that radius totals over 60,000bbl/day or roughly 22,000,000bbl/yr. The plant facilities have been designed to modularly expand to treat up to that volume in 5000bbl/day increments.

The first phase of this facility is currently on line, with treatment capacity of 10,000bbl/day via two Class II injection wells. The disposal water is treated prior to injection to remove constants harmful to the injection formation, also preserving integrity of a large helium dome underlying the facility. The second phase of the facility, treating water for reuse and stream discharge will come on line in the Fall of 2013, transitioning the Class II injection wells to brine disposal wells.

As this is a centralized facility, the primary economic driver for use of this facility is cost. These economics are broken into three components: disposal, transport and exploration water acquisition. Due to volumes, the disposal cost is on-par with local evaporative disposal rates, additionally removing any uncertainty around long-term viability of disposal by evaporation and the associated liability issues. Transportation cost is addressed in providing the disposal haulers with outbound loads of exploration water, treated to their standards for exploration. This model represents a considerable savings, in that their trucks are now fully loaded both inbound and outbound, decreasing hauling cost, road use and carbon footprint in the area. Exploration water is provided to energy companies through processing of the produced water to standards required in their process. The exploration water is sold at prices on-par with their traditional sources, usually agricultural water, but with higher consistency and long-term availability.

Processing produced water to standards of reuse provides economic and strategic benefits to energy producers as well as environmental sustainability. Aside from economic and long-term water management benefits to the energy producers, the environmental benefits from this project are significant, namely, use-avoidance of fresh water. The pressure on regional fresh water supplies, traditionally sourced from agricultural water rights is considerably mitigated in this business model. Consumptive use water is preserved for flow into the Colorado River Basin. Additionally, as the plant capacity expands, more water will be treated than can be sold for energy exploration. The balance of this water will be treated NPDES standards for surface-discharge and appropriated as a senior water right as agricultural augmentation water, further taking pressure off fresh water consumption in the Colorado River Basin.

Coal Bed Methane Project - Wyoming

A third example is the CBM production waters that are being developed in the west. We performed a study of CBM waters in southwest Wyoming. These waters need to be removed in order to develop the resource of CBM. This is a difficult water to dispose of due to the organics and mineral content of the water. Technologies have been developed to treat this water, but the beneficial use of this water has not been researched or developed. Potential uses of this water are for municipal augmentation of a new water resource, industrial and agricultural interests as well as environmental enhancement through the creation of wetlands and in-stream flows.

The typical CBM project produces approximately 10,000 ac-ft per year. The cost of a treatment facility will be approximately $8 to $12 million. This will include a membrane treatment facility as well as brine management and treatment.

We are currently going through the determination of the tributary/non-tributary status of the groundwater. Based on our most current analysis, we believe that the water will be totally non-tributary. This water will have a projected value between $500 to $5,000 per ac-ft per year on an annual basis.

The cost of treatment of this water for CBM production water has been estimated between $0.25 to $0.75 per barrel. The cost of deep well injection has been as high at $2.00 per barrel. This translates into a cost of $2,000 to $8,000 per ac-ft for treatment and $16,000 per ac-ft for disposal. The market price for this water is close to $20,000 per ac-ft for a long-term lease. If the energy companies are currently paying $2.00 per bbl for disposal, then treatment would lower their overall costs. In addition, the first activity at a CBM facility is the dewatering phase. If the water could be sold at this point, then the cost of development is greatly reduced.

Tight Sand Project – Central Wyoming

In 2011 we were engaged by a major energy company to design and perform an on-site pilot study to validate the technical efficiencies and costs to process high volumes of their tight sands produced water at a centralized collection facility in Freemont County, Wyoming. Previous disposal was via evaporation. Increased volumes and tightening regulations of evaporative pits necessitated the company to explore mechanical treatment options. At full capacity, treatment volumes would total over 90,000,000bbl/yr, with discharge into tributaries of the Wind River. The discharge volume from this facility alone will total over 11,000af/yr.

Both regulatory compliance and treatment cost were primary drivers in this project. Arguably, evaporative disposal is a low-cost solution. Regulatory scrutiny and tightening regulations of evaporative pits, primarily with regards to VOC emissions and hazardous sludge generation, have substantially shifted disposal strategies for producers of large volumes of water. This project is a very good example. Additionally, the volumes of water generated allow for very high economies of scale in the deployment of mechanical treatment processes. Our study showed that this water could be treated to discharge standards at under $0.30/bbl, which was on par with costs for evaporative disposal rates in the area. These economics present considerable savings to energy companies by removing transportation costs. Additionally, this type of centralized water filtration facility addresses liabilities with regards to disposal of RCRA regulated solid waste sludge and also allows for long-term water management planning, removing from the equation uncertainties relative to the ability to obtain disposal contracts in evaporative pits.

It is interesting in that the volume of treated water, totaling over 11,000af/yr was not considered as an asset by the energy company, but only as a liability. The disposition of this water into the Wind River basin, ultimately into the Boysen Reservoir and Bighorn River represents a considerable water rights asset and a drought-proof volume of water maintaining in-stream flow. If appropriated as non-tributary water, this water has a value of $5,500,000 to $55,000,000 per year in addition to the environmental benefits of providing consistent temporal stream flows.

Conclusions

The conclusions of this work are that produced water can be an asset to the company if treated correctly. In order to achieve this asset, treatment to meet discharge standards needs to be part of the engineering process. Also, water rights need to be a consideration. If these are done, then this wastewater can be sold, typically at a profit and result in a favorable income to the company.

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