Strategies to Reduce Terminal Water Consumption of Hydraulic Fracture Stimulation in the Barnett Shale

by

Jennifer Marie Secor Harold, B.S.

Thesis

Presented to the Faculty of the Graduate School of

The University of Texas at Austin

in Partial Fulfillment

of the Requirements

for the Degree of

Master of Arts

The University of Texas at Austin

August 2009

Strategies to Reduce Terminal Water Consumption of Hydraulic Fracture Stimulation in the Barnett Shale

Approved by
Supervising Committee:

Charles G. Groat

Stefan K. Schuster

Jason S. Fialkoff

Dedication

I would like to dedicate this body of work to my loving husband, Matthew Robert Harold, whose faithful support and encouragement made this possible. I would also like to thank my dear friend and mentor, Robin Brinkley Dick, who taught me the virtues of professionalism.

Acknowledgements

I would like to express my gratitude to Dr. Chip Groat and Stefan Schuster for their time, talent, and regard in cultivating my interest of water resources. Who knew water was so interesting and complex? I also offer my sincere thanks to Jason Fialkoff whose support and organizational skills were vital in the preparation of this work.

August 2009

Abstract

Strategies to Reduce Terminal Water Consumption of Hydraulic Fracture Stimulation in the Barnett Shale

Jennifer Marie Secor Harold, M.A.
The University of Texas at Austin, 2009

Supervisor: Charles G. Groat

Horizontal drilling and hydraulic fracture stimulation have enabled the economic development of unconventional resource plays. An average horizontal well in the Barnett Shale requires 3 to 4 million gallons of fresh water, 90% of which is used for hydraulic fracture stimulation. While the water consumption of Barnett Shale operations is less than 1% of total Region C consumption, extended drought conditions and competing demands for water resources are placing pressure on operators to reduce terminal water consumption. Strategies which reduce water requirements associated hydraulic fracture stimulation without compromising the efficiency and cost of energy production are essential in developing a comprehensive policy on energy-water management.

Recycling and reuse technologies were evaluated on the basis of performance, cost, and capacity to treat reclaimed flowback water and oilfield brine. Recycling

flowback fluids for future hydraulic fracture applications is the most practical repurposing of oilfield waste. The low TDS content of flowback derived from water-based fracs permits multiple treatment options. Mobile thermal distillation technology has emerged as the prevailing technique for recycling flowback water, yielding maximum water savings and reduced operating costs. The estimated cost of recycling flowback water by thermal distillation is $3.35/bbl. Compared to the current cost of disposal, recycling provides an opportunity to minimize waste and reduce the fresh water requirements of hydraulic fracture stimulation at an incremental cost.

The stewardship role of the Texas Legislature is to protect the water resources of the state and to facilitate the Regional Water Planning Process, ensuring future water needs are met. The support and participation of the Legislature and other planning entities is critical in advancing the energy-water nexus. As operators pursue innovative water management practices to reduce terminal water consumption in the oilfield, the Barnett Shale positions itself as a model for sustainable water use in the development of unconventional shale resources.

The cost of recycling and reuse technology limits the participation of small and mid-size operators who possess the greatest market share of the Barnett Shale. Funding for research and implementation of water-conscious strategies such as shared recycling facilities, CO_2 capture and storage, and pipeline infrastructure would create multi-user opportunities to promote conservation and reduce net consumption of fresh water supplies. Through the integration of technology and policy, terminal water consumption in the Barnett Shale can be greatly diminished.

Table of Contents

List of Tables

List of Figures

I: Introduction

Fresh water use in the oilfield has significantly increased with expanding development of unconventional shale resource plays. Horizontal drilling and hydraulic fracturing technology have allowed low-permeability reservoirs such as the Barnett Shale (Figure 1) to become commercially recoverable. The average fresh water consumption by a single hydraulic fracture application, or “frac job”, is between 3 and 4 million gallons (Galusky, 2007). As of March 2009, the Railroad Commission of Texas (RRC) reports more than 10,539 gas wells have been drilled in the Barnett Shale and an additional 5,037 are permitted. The Texas Water Development Board (TWDB) projects 1% of surface water and 10% of groundwater supplies in Region C Regional Water Planning Area (Region C) (Figure 2) will be consumed at the peak of Barnett Shale activity in 2010. While this anticipated consumption appears negligible, the oil and gas sector will continue to face competition from other Water User Group (WUGs) and pressure from the public to reduce consumption. Extended drought conditions could impact future water availability and limit the development of petroleum and natural gas reserves – an $8 billion source of revenue for North Central Texas (Perryman Group, 2008).

Municipal water demand in Region C is projected to increase by 92% over the next 50 years. In addition to population growth, Region C anticipates an overall loss in water storage capacity and increased demand by downstream users. The regional water plan prepared by Region C identifies 59 water management strategies to meet demand during this period (TWDB, 2007). The 2006 drought-of-record aroused public attention of water-intensive activities associated with oil and natural gas development. Despite Barnett Shale drilling activities accounting for less than 1% of total water use during 2006, public perception persists hydraulic fracture operations should be regulated. As a result, legislation approving the Upper Trinity Groundwater District was passed by the 80th Regular Texas Legislative Session. Senate Bill (SB) 1983 provided for the creation of a Groundwater Conservation District (GCD) to monitor and regulate groundwater withdrawals within Hood, Montague, Parker and Wise counties. Other legislation was also proposed during this Session to curtail Barnett Shale development through the regulation of hydraulic fracturing operations during periods of drought. These initiatives prompted the collaboration of the energy sector and interest groups to address the issue of terminal consumption of fresh water supplies in the Barnett Shale. The Barnett Shale Water Conservation and Management Committee (BSWCMC), under the direction of Gas Technology Institute and 14 member companies, engages in research to quantify water consumption associated with Barnett Shale development and identify best management practices for reducing terminal water consumption through the use of recycling, reuse and reduction technologies.

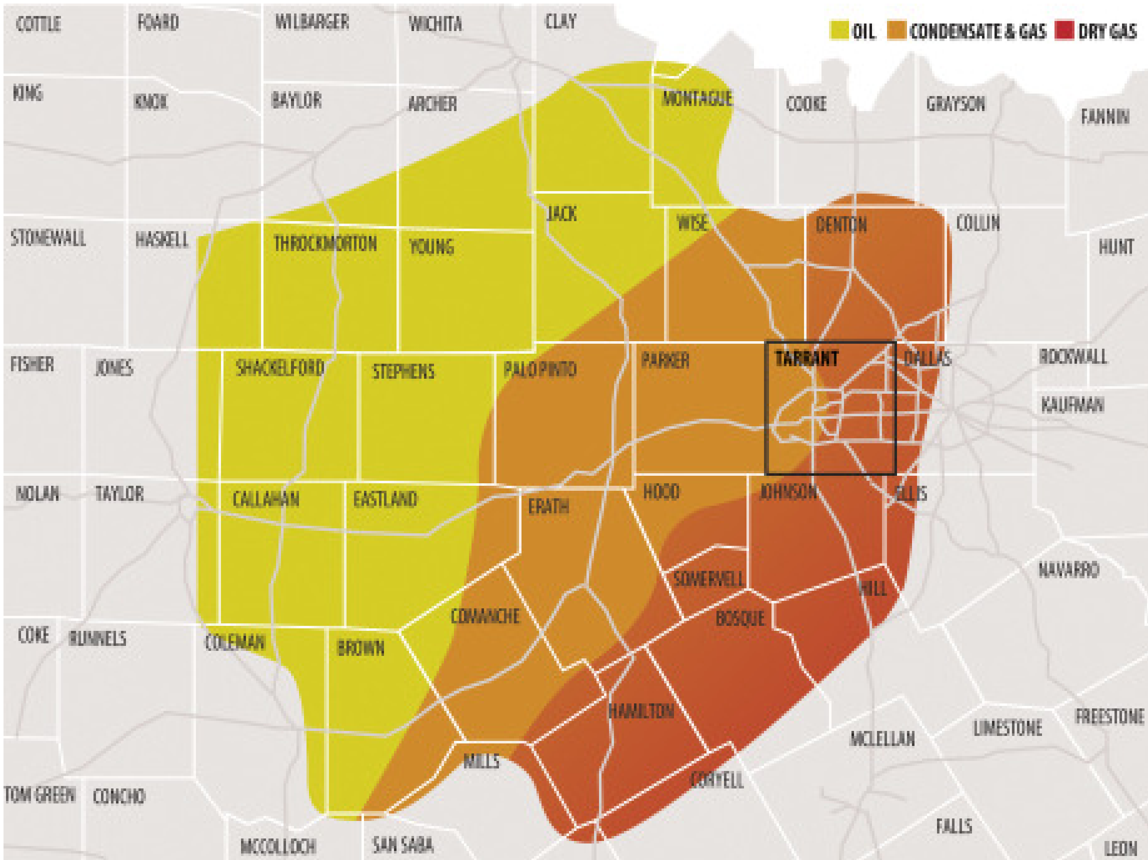


Figure 1: Barnett Shale Development Area (Oil Shale Gas)

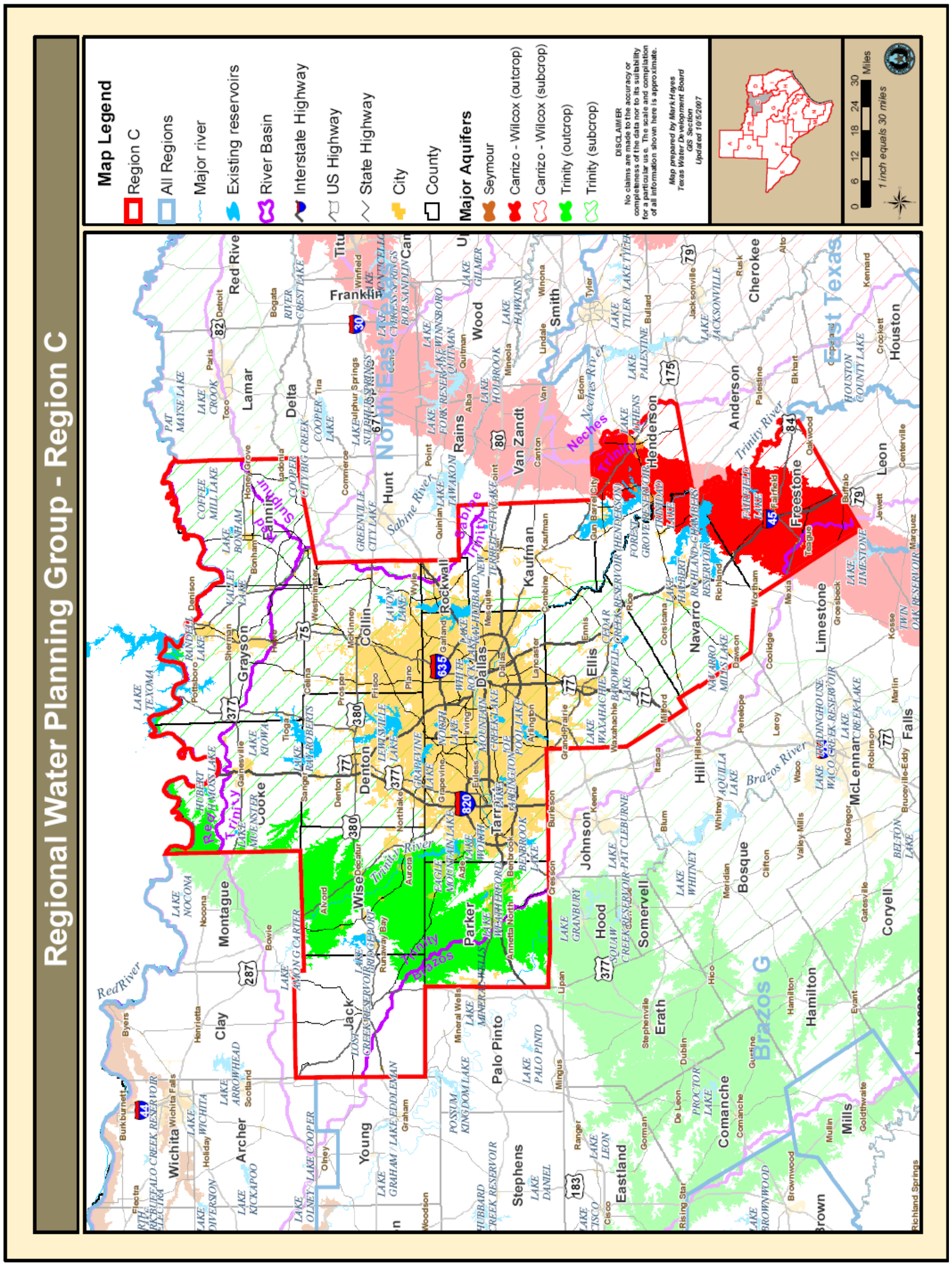


Figure 2: Region C Regional Planning Area (TWDB, 2007)

In a February 2009 report, State Comptroller Susan Combs highlighted the effects extended drought may have on the economic future of Texas. The anticipated cost of not meeting the statewide water demand is $9.1 billion per year in 2010 and $98.4 billion per year in 2060. Barnett Shale development provides more than 84,000 jobs and $8 billion in annual revenue to the state; therefore, it is in the prudent interest of all stakeholders to adopt feasible water management strategies for oil and natural gas production (Perryman Group, 2008). The momentum of prior drought legislation carried into the 81st Regular Legislative Session as Barnett Shale water consumption remained at an all time high in 2007. Heightened concerns about the integrity of saltwater disposal wells led some municipalities to issue moratoriums on new Class II injection wells within their jurisdictions. SB 273, SB 274 and SB 275 sponsored by Senator Robert Nichols (District 3), and companion bills filed in the House by Representative Brandon Creighton (District 16), proposed new requirements for permitting and monitoring injection wells. Stricter notification requirements for informing residents and GCDs, and increased monitoring of injection wells would discourage the drilling of new injection wells. Along with conservation and recycling, injection well legislation could dramatically decrease the volume of waste injected into the subsurface and allow the 141 existing Class II wells in the Newark East field (50,000+ statewide) to remain operational for a greater period of time (Tronche, 2008).

Advanced drilling and completion technologies pioneered in the Barnett Shale have accelerated the development of other shale systems including the Marcellus gas shale, the Haynesville gas shale, and the Bakken oil shale. Like the Barnett Shale, these reservoirs are located in populated, hydrologically-sensitive environments and lack a defined strategy for water conservation in conjunction with oil and natural gas extraction. Through the use of oilfield recycling and reuse strategies, the Barnett Shale is poised to become a model for sustainable water use in the pursuit of unconventional resource development.

1.1 PROBLEM STATEMENT

Competing demands for water resources in North Central Texas highlight a need for a comprehensive strategy on energy-water management. How can water-conscious technologies and policies be integrated to offset the future water needs of Region C without compromising the efficiency and cost of energy production in the Barnett Shale?

1.2 METHODOLOGY

This report investigates options for reducing and recycling oilfield waste and provides recommendations for best water management practices and policies in the Barnett Shale. Practices and processes for the recycling and reuse of oilfield waste were evaluated on the basis of cost, capacity and efficiency. Where available, results of implementation are used to support the conclusions. A summary of the 2009 81st Regular Legislative Session is included in this report to illustrate the role of the Texas Legislature in the Regional Water Planning Process. Recommendations of this report are directed to the Texas Legislature, water planning entities and operators evaluating technologies and policies to reduce water consumption in the Barnett Shale. This report also serves as a model for other unconventional shale resources affected by water supply issues.

II. Background

2. 1 HYDRAULIC FRACTURING

Hydraulic fracturing is an artificial stimulation technique used by the oil and gas sector to enhance production rates and maximize the Estimated Ultimate Recovery (EUR) of oil and natural gas wells (Wright et al, 1999). In hydraulic fracture stimulation, pressurized fluids and proppant—usually sand or engineered particles—are injected into a subsurface formation to enhance the natural fracture network. The primary components of a hydraulic fracture application are water, proppant, and chemical additives to improve viscosity (API, 2008). Water represents the greatest percentage of fracture fluids—over 99% of the liquid component (API, 2008). Fracture fluids are pumped into the wellbore at pressures capable of cracking the rock and creating channels through which hydrocarbons can pass. Proppant entrained in the fluid remains in the reservoir to preserve the fracture matrix after fluid is recovered. As a result, greater reservoir surface area is exposed, improving reservoir permeability and increasing the rate of recovery and EUR (Warpinski et al., 2005).

Hydraulic fracturing is responsible for the recent shift to develop unconventional resource plays such as coal-bed methane, tight-gas sands, and gas shales. Prior to 1995 unconventional resources were not included in the USGS national assessment of oil and gas resources. Today, unconventional reservoirs account for more than 20% domestic gas production (USGS, 1994). As the industry continues to optimize oil and gas production by hydraulically fracturing reservoirs, the effects on water quality and availability will attract greater attention. Efforts to minimize well completion costs by reducing water requirements for hydraulic fracture stimulation are already in effect, and the scope of research has expanded to address greater issues of regional water conservation.

2.2 THE BARNETT SHALE

The Mississippian Barnett Shale is an unconventional natural gas play located in the Bend Arch-Fort Worth Basin Province and extends from southwestern Oklahoma to North Central Texas (Ball and Perry, 1996). The Barnett Shale is the largest active onshore natural gas discovery in the United States. Its most prolific field, the Newark East field, spans 19 counties and roughly 400 square miles including the Dallas-Fort Worth Metroplex. Since 1997, the Newark East field has produced over 3.8 TCF of gas from more than 10,000 wells (RRC, 2008). A 2004 assessment by the USGS estimates 98.5 MBO, 1.1 BBNGL and 26.7 TCFG of technically recoverable reserves lie undiscovered in the Bend Arch-Fort Worth Basin, of which 98% of the gas is classified as a continuous accumulation associated with the Barnett Shale (USGS, 2004).

The Barnett Shale is an organic-rich black shale possessing a complex lithology of calcareous shale with intervals of clay, chert and dolomite (Jarvie, 2003). Its designation as a source, seal and reservoir make it unique among other producing gas shales (Montgomery, et al., 2005). The average thickness in the Newark East field is approximately 400 feet and productive intervals occur from a depth of about 7,500 feet. At its thickest point near the Muenster Arch, the pay interval exceeds 1,000 feet. Although naturally fractured, the Barnett Shale is predominately sealed with calcite and therefore requires hydraulic fracture stimulation to produce economic quantities of gas (Montgomery, et al., 2005). A survey of wells drilled in the Barnett Shale in 2006 concludes an average of 6.02 ac-ft of water was used for each vertical well completion, and 9.38 ac-ft for each horizontal completion. Of the 1,202 wells drilled in 2006, 91% were horizontal completions. The total estimated volume of water used in 2006 for Barnett Shale drilling and completion activities is 13,608 ac-ft. (Texerra, 2007).

2.3 WATER RESOURCES OF NORTH CENTRAL TEXAS

The TWDB estimates in 2010 the Trinity and Woodbine aquifers will provide 5% of total water supplies to Region C which spans 16 counties and includes the Dallas-Fort Worth Metroplex (TWDB, 2007). Figure 2 illustrates Region C, its major and minor aquifers and surface water bodies. According to a report by the U.S. Census Bureau, Dallas-Fort Worth is the fastest growing metropolitan area in the U.S. and by 2010, is projected to contain 27% of the state population (U.S. Bureau of the Census, 2008; TWDB, 2007). Municipal use is the region's largest WUG, accounting for 85% of total demand in 2010. Influenced by population growth, other WUGs will also encounter heightened demand during the 50-year planning period. The steam-electric WUG which uses water for electricity generation is expected to increase by 149%; and demand by the mining WUG, which includes Barnett Shale activity, is expected to rise by 52% between 2010 and 2060 (TWDB, 2007). Pumping of groundwater and insufficient recharge of the Trinity and Woodbine aquifers has led to the greatest aquifer drawdown in recorded state history. Counties located on the edge of aquifer boundaries have a greater dependency on groundwater; therefore, further drawdown of the Trinity and Woodbine aquifers will disproportionately affect those living along the western margin, and will create a future burden to provide surface water to rural areas (Bene et al., 2007).

Approximately 56% of Barnett Shale water use in 2006 was sourced from groundwater supplies. Slightly more than 43% was sourced from surface water supplies and less than 1% was sourced from recycled supplies (Texerra, 2007). The Trinity River basin is the primary source of surface water for Region C as well as the Dallas-Fort Worth and Houston metropolitan areas (TWDB, 2007). The TWDB projects Region C will encounter a total need of 336,390 ac-ft./yr of water in 2010 while demands by downstream users increase (2007).

2.4 SUMMARY OF THE TEXAS 81ST REGULAR LEGISLATIVE SESSION (2009)

Between legislative sessions, House and Senate Interim Study Committees convene to research interim charges and prepare recommendations for the next legislative session. The House Natural Resources Committee Interim Report to the 81st Legislative Session was delayed approximately three months, the committee office citing changes in leadership and budget deficits as being responsible for its late release. Among the nine interim charges prescribed to the House Natural Resources Interim Study Committee, five were addressed in the House Interim Report. Overall, the committee treaded lightly on the five charges for which it did offer recommendations and ignored other charges critical to water resources planning.

Twelve charges were commissioned by the Senate Interim Study Committee of the 80th Legislature. The variety of topics assigned reflect the breadth of water need throughout the state. Of the charges studied by the Senate Interim Study Committee, seven charges were highlighted in the Senate Interim Report. In its report, the Senate Interim Study Committee examined the safety of dams and flood control devices in the state, and evaluated the effects of aging infrastructure and diminishing reservoir capacity. As opposition increases against new dams and reservoirs, the state must evaluate new water sources to support its municipal and industrial growth. The success of brackish groundwater desalination in El Paso and Brownsville led the Senate to investigate the regional and statewide impacts of its use as a source of supply. Progressive technology and the abundance of brackish groundwater make desalination plants an appealing solution for meeting the future water needs of Texas. Disposal of concentrated brine produced by desalination is regulated the EPA and in Texas, also by the Texas Commission on Environmental Quality. Class II injection wells are those wells associated with the injection of fluids for the purpose oil and natural gas production, and include wells used for CO_2 enhanced recovery operations. Class V injection wells, including the three disposal wells permitted for use by the Kay Bailey Hutchinson Desalination Plant in El Paso, is broad category which governs injection of non-hazardous wastes, as well as long-term CO_2 geological sequestration (Hutchinson, 2008).

Opposing legislative agendas emerged in this Session to both ensure the continuation and curtail the use of Class II injection wells. A suite of bills passed into law designates CO_2 sequestration as a critical component for enhanced recovery of oil and natural gas and for the development of clean coal initiatives. SB 1387 (Seliger) and House Bill (HB) 469 (King, et al.) create a regulatory framework and provides tax incentives for large-scale implementation CO_2 capture and sequestration, placing Texas in a position to expand its unconventional resource base and manage greenhouse gas emissions currently under federal review. Already named as a successor to Barnett Shale production, the Woodford Shale in North Central Texas and Oklahoma has a history of success using CO_2 enhanced recovery techniques and will further benefit from the recently approved CO_2 legislation.

Each session, the Texas Alliance of Groundwater Districts (TAGD) prepares a summary recommending groundwater policy areas to be examined by the Legislature. In its 2009 report, TAGD emphasized a need to improve relationships between regional water planning entities and GCDs, and advised caution in considering amendments to the Rule of Capture Doctrine (TAGD, 2009). The current Managed Available Groundwater (MAG) process requires all available groundwater within a GCD to be appropriated; however, the process of meeting future groundwater needs within the GCD is unclear (TAGD, 2009). Several pieces of legislation this Session addressed groundwater appropriations and hinted at the inclusion of the Beneficial Use Doctrine. Similar to that which governs surface water use, the Beneficial Use Doctrine as it applies to groundwater under SB 1714 (Hegar) would define the term “beneficial use” and would require documented historical use data prior to approving groundwater withdrawals. SB 2008 (Hegar) which complements the Beneficial Use legislation seeks to require the disclosure all groundwater withdrawals within a GCD, including those previously exempt under Chapter 36 of the Water Code. While both bills died in committee, the awareness of limited groundwater availability is influencing legislators and planners to consider changes to the groundwater permitting process. In drafting changes to the Rule of Capture and Beneficial Use Doctrines, the House and Senate Natural Resource Committees demonstrate an exclusive ability to shape the future of oil and natural gas development in Texas.

The Rule of Capture permits landowners to pump groundwater without restriction provided the withdrawal is not malicious or wasteful. Summarizing TAGD, GCDs are responsible for managing groundwater supplies and legislative power granted to GCDs allows for the regulation of groundwater withdrawals within GCD jurisdiction. Rescinding the Rule of Capture would create standing for landowners seeking damages against those whose pumping of groundwater has diminished the landowner’s right to the resource (TAGD, 2009). The Beneficial Use Doctrine is designed to limit waste, and where the value of oil and natural gas extraction has not been defined by the state, its extension to groundwater would eliminate the exemption for oil and gas operations under Chapter 36 of the Water Code. Incorporating the Beneficial Use Doctrine would allow GCDs to permit groundwater withdrawals based upon the benefits of use. More than half of the fresh water supplies used in hydraulic fracture operations are sourced from groundwater and are discharged as waste to injection wells. Amendments to the Rule of Capture and Beneficial Use Doctrines threaten to further limit groundwater withdrawals and the amount of groundwater available for hydraulic fracture operations.

III: Practices and Processes

Water conservation is a growing challenge for Texas. Anticipated shortages could cost the state as much as $98.4 billion per year in 2060 (Texas Comptroller of Public Accounts, 2009). Region C estimates a capital cost of $13.2 billion to implement all of its recommended water management strategies. This amount represents 43% of the state's total capital expenditures and emphasizes the immediate and substantial need for water management in this area of the state. The overall water demand of Region C is projected to increase 87% by 2060. Among the 59 water management strategies recommended by the Region C planning group are the construction of four new reservoirs and a variety of conservation and reuse strategies (TWDB, 2007). While Barnett Shale activity represented less than 1% of total Region C water consumption in 2006, public pressure to reduce the water requirements of hydraulic fracture stimulation is influencing operators and policymakers to adopt water conservation practices. In 2006, state legislators considered a bill to limit hydraulic fracturing operations during periods of drought. While this bill did not become law, its support has not waned. In the 2009 81st Regular Legislative Session a multitude of bills relating to the powers of GCDs, the regulation of groundwater, and disposal of oilfield waste were introduced.

The success of horizontal drilling and hydraulic fracturing in the Barnett Shale has inspired the exploration of other unconventional resource plays once considered uneconomic to produce. As development continues, the oil and gas industry will be expected to play an explicit role in regional water conservation. Although the oilfield use is a fraction of overall consumption, water management practices can play a significant role in conservation and reducing net water use. Economic barriers are the greatest challenge to implementing regional water management strategies in the Barnett Shale.

Successful water conservation in the oilfield is dependent upon the cost, efficiency and mobility of recycling technologies. The integration of recycling, reuse and reduction strategies in hydraulic fracture stimulation and produced water management can mitigate the need for new sources of supply and minimize waste disposal.

3.1 RECYCLING

Recycling is the prevailing strategy for reducing the water requirements of hydraulic fracture stimulation. Untreated flowback water can cause scale and corrode well tubing and equipment, preventing its direct reuse in hydraulic fracture operations. Operators have traditionally opted out of recycling flowback water based on the expense and inefficiency of the available technologies. Instead, flowback is discharged into disposal wells which isolate waste in subsurface formations below the depth of usable water quality. Water acquisition represents 30-50% of well stimulation costs (Oil & Gas Journal, 2009). Existing technology capable of treating high TDS waters for hydraulic fracture reuse can offer a 50% reduction in fresh water requirements and a significant savings in acquisition, chemical, transportation and disposal costs (Gupta, et al. 2009).

Recycling produced water presents a greater challenge for operators. Produced water, or “oilfield brine”, represents the largest portion of oilfield waste but also the greatest opportunity by volume for recycling and reuse. The recycling of any oilfield fluid requires filtration and desalination to remove high concentrations of dissolved solids, salts and organic matter. The salinity of produced water is dependent upon the reservoir and has a direct impact on the efficiency of recycling. Figure 3.1 illustrates a sample distribution of produced waters and associated total dissolved contents in Texas. Based on the sample population, TDS content in North Central Texas is equally distributed between < 10,000 ppm and > 50,000 ppm.

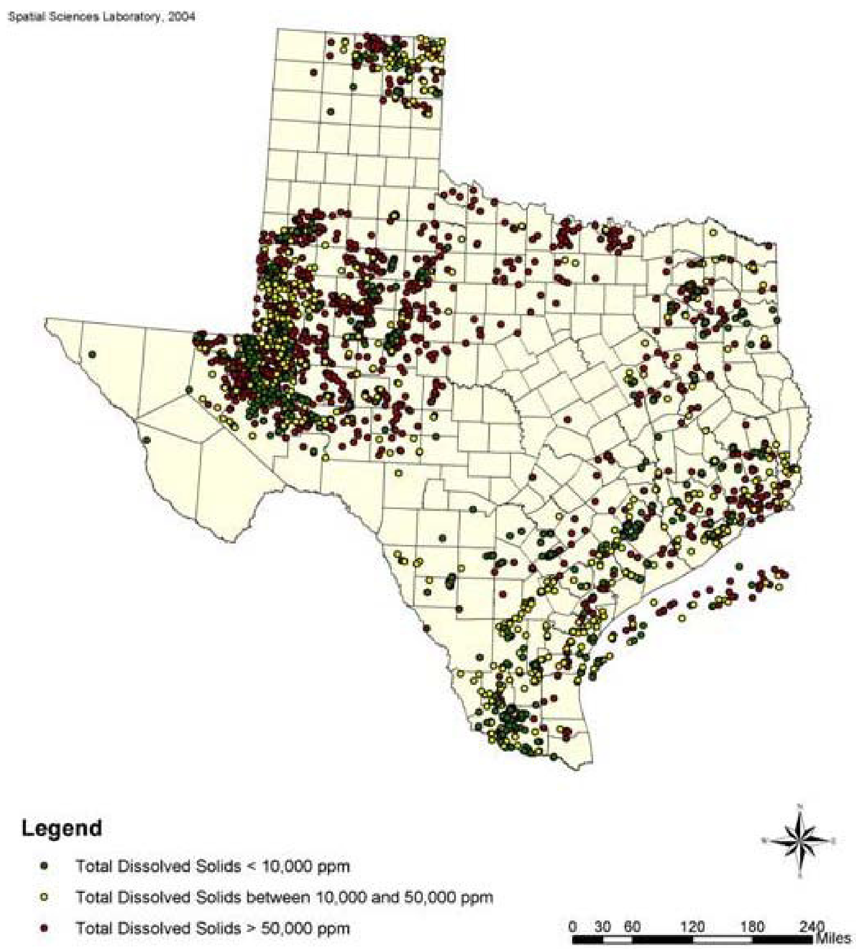


Figure 3.1: TDS Distribution in Produced Water Samples (USGS)

Successful recycling and reuse of produced water would reduce transportation and disposal costs. Aging wells tend to produce greater volumes of oilfield brine making produced water management is a significant factor in determining the future lease operating expense of a well. Produced water is mostly used on-lease by reinjecting it into the reservoir to maintain sufficient pressure for hydrocarbon production. The per barrel ratio of water to oil production in Texas is 7:1 (Burnett and Pankratz, 2004). While economic and technological limitations of treatment can prevent the use of high TDS waters—like oilfield brine—for future hydraulic fracture stimulations, treated produced water can be marketed to industrial, agricultural and irrigation users who might otherwise employ non-recycled sources. Treatment thresholds for non-potable use of recycled supplies vary with application, and ambiguous state regulations regarding the off-lease use of reclaimed water could expose operators to greater liability (Burnett, 2004). Nonetheless, recycling produced water has the potential to significantly reduce the volume of waste sent to disposal wells and to satisfy the need to conserve water and limit the drilling of new disposal wells in Region C. The primary technologies adapted for commercial recycling of flowback and produced waters are membrane filtration and thermal evaporation condensation. Both methods possess unique strengths and barriers discussed in the following sections. Successful recycling initiatives have been modeled in other unconventional resource deposits throughout Canada and the U.S. As the largest producing onshore natural gas field in the U.S., the Barnett Shale has the potential to define best water management practices for large-scale implementation in water-fatigued areas.

3.1.1 Reverse Osmosis

Reverse Osmosis (RO) is a type of membrane filtration capable of separating contaminants from water. Unlike normal osmosis in which solvent passes from a low-solute environment to a high-solute one, reverse osmosis applies pressure to the solution forcing it through a semi-permeable membrane. Only the solution is permitted through the pores of the membrane while the solute is retained.

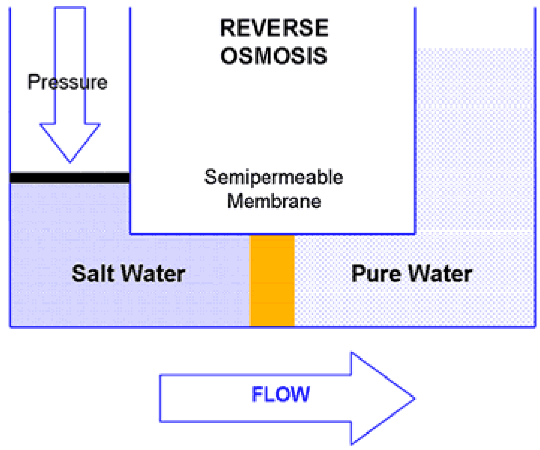


Figure 3.1.1: Illustration of Reverse Osmosis (Vertex Hydropore)

Many water treatment systems and desalination plants rely on RO to produce or supplement drinking water supplies using seawater and brackish groundwater sources. The salinity of seawater is approximately 35,000 ppm – or 35,000 mg/l TDS. According to experimental research, RO may be used to process water with salinities up to 40,000 ppm; however, at this rate higher transmembrane pressure is required thereby increasing the energy requirement (Barrufet, et al., 2005; Gaudlip, et al., 2008). The total dissolved solids (TDS) of post-frac flowback water ranges from 1,000 ppm to 50,000 ppm. Produced water may possess a much higher TDS content, up to or exceeding 250,000 ppm (Barrufet, et al., 2005). While the physical limitations of RO preclude high TDS waters from being recycled as drinking water supplies, water possessing concentrations above the 40,000 ppm threshold may be purified using RO for non-potable uses including irrigation, agriculture and meeting instream flow requirements. The greatest barrier to entry in the oilfield is the cost and energy requirements of operation. Operating costs and energy requirements associated with RO are highly correlated with influent quality and represent 70-80% of the total cost (Dow, 2009). The lower the feed salinity, the less pretreatment and energy is required to process the influent. According to David Burnett of the Global Petroleum Research Institute at Texas A&M University, RO can be used to treat Barnett Shale water for as little as $0.85 per barrel (Burnett, 2007). This cost fluctuates depending upon the variables of facility design. Initial results indicate a 3:1 brine reduction rate; however, membrane sensitivity to oil and dissolved solids leads to a fouling and sharp decline in efficiency (Gaudlip, et al., 2008).

Appropriate membrane selection is the key to RO success. Extensive research has been performed to optimize membrane selection for the purpose of processing produced water. The Texas Water Resources Institute has compared the treatment of brackish groundwater to that of oilfield brine. Results indicate oil present in brine degrades membrane quality, impairing the ability to reject dissolved solids and making membrane replacement cost a critical element in the cost-effectiveness of RO (Burnett, 2004). Pretreatment of feed has been shown to extend membrane life. Deoiling and demineralization modeling using adsorption may increase brine reduction rates, allowing as much as 90% recovery depending upon feed salinity (Barrufet, et al., 2005).

Mobility is another important factor in evaluating RO technology. To realize a savings in transportation costs, treatment must be performed at or proximate to the wellsite. The capacity to provide wellsite RO on the scale of Barnett Shale water production is not an economically viable option for operators. The capital-intensive cost of plant construction, plus and operation and maintenance costs, more than exceed disposal costs. The per barrel cost of disposal in the Barnett Shale is expected to rise as drilling activity peaks and the production of oilfield brine trends upward. The current cost for disposal in the Barnett is $2 to $3/bbl, but has exceeded $6/bbl during periods of high demand. (Burnett, 2007).

3.1.2 Thermal Distillation

Thermal distillation, or thermal evaporation distillation, is also used in the desalination of seawater to provide and supplement drinking water supplies. Recent improvements to technology have enabled the inland processing of high TDS waters, including flowback and produced waters. In thermal distillation, influent is heated to produce steam and remove dissolved solids. The steam is then condensed to produce distilled water. Thermal distillation is a mature technology with relatively new application in the oilfield water management. Like RO, thermal distillation can be used to treat both flowback and produced water for future hydraulic fracture stimulation projects or non-potable use. Thermal distillation outperforms RO in the treatment of treat high TDS waters.

Mechanical Vapor Recompression (MVR), illustrated in Figure 3.3.1, is an emergent technology in thermal evaporation distillation. MVR uses compression and heat recycling to produce distilled water from feed containing up to 80,000 mg/l TDS. The MVR process removes background heat by passing feed through a series of heat exchangers and then through a de-aerator to remove dissolved gases. Feed is then delivered to evaporator exchanger in which steam and liquids are separated. The steam is compressed, resulting in a temperature increase, then passed again through the evaporator exchanger. The steam condenses yielding distilled water. Because heat is recovered and reapplied throughout the process, MVR uses 1/40th of the energy required by traditional direct-fired distillation techniques (Aqua-Pure Ventures, Inc.). The capacity to treat higher concentration feed along with the significant energy savings over traditional distillation furthers the suitability of MVR as an oilfield tool.

MVR is best suited for the treatment of waters possessing TDS ≤ 80,000 mg/l and can achieve a 60-90% reduction in disposal volumes depending upon feed salinity (Aqua-Pure Ventures, Inc.). The primary advantages of MVR over RO treatment include mobility and flexible fuel requirements. The NOMAD 2000 Mobile Oilfield Evaporator produced by Aqua-Pure Ventures and operated by Fountain Quail Water Management is capable of processing 2,500 bbls of feed per day, converting roughly 2,000 bbls into distilled water. The NOMAD can be operated using natural gas which makes it a practical choice for Barnett Shale operations. Results from Devon Energy's NOMAD pilot program indicate an 80% efficiency rate distilling 90-100% of captured flowback water (Ewing, 2008). As GCDs in North Central Texas seek to regulate withdrawals for water-intensive operations such as oil and natural gas development, Devon and others are investing in recycling and reuse technologies to reduce dependence on groundwater and surface water supplies.

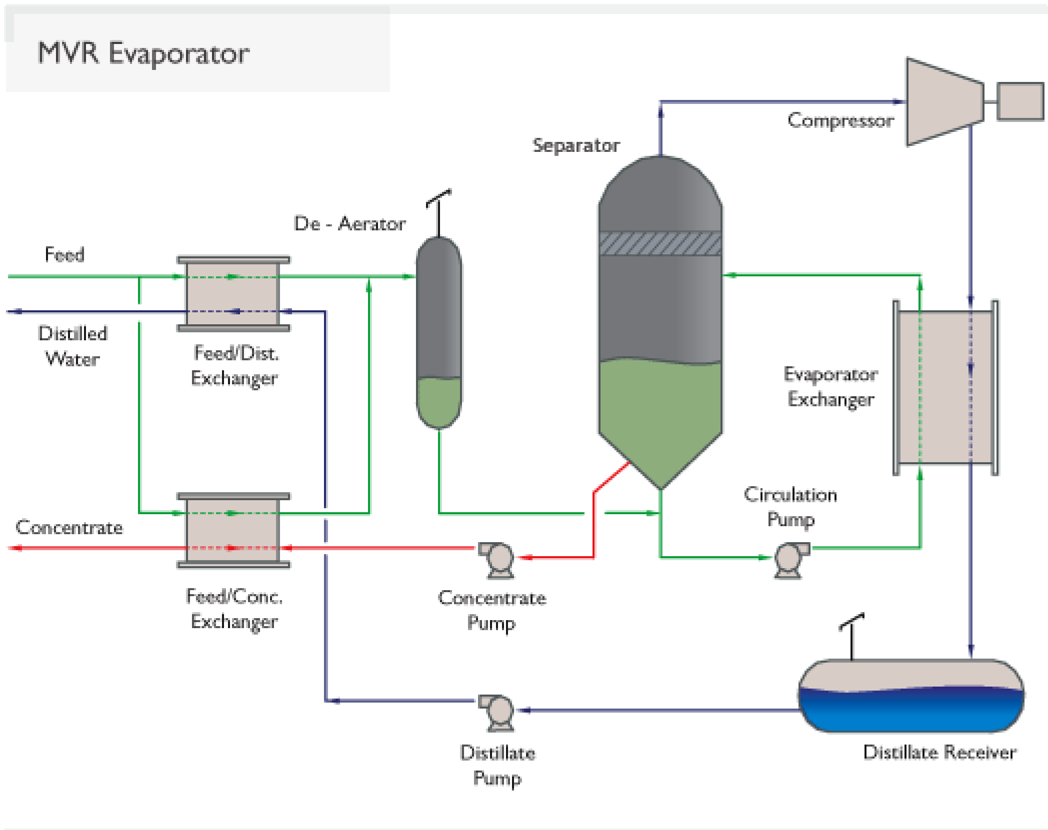


Figure 3.1.2: Illustration of MVR Process (Aqua-Pure Ventures, Inc)

The NOMAD unit is skid-mounted for easy transport and occupies roughly 50’ x 50’ of space. Its mobility makes MVR a superior choice for recycling flowback water; however, the compressor component makes it a less desirable option for use in an urban environment. Efforts to reduce noise emissions and improve the efficiency of treatment are already in process. Aqua-Pure is refining its NOMAD system to accept higher TDS feed in order to compete with 212 Resources’ semi-mobile POD facility which processes feed up to 110,000 ppm and produces a concentrated waste stream up to 260,000 ppm (Waits, 2008). The POD, produced by Vacom, has a demonstrated success both in and outside the oilfield and is preparing to expand its operations to the Barnett Shale. its footprint is comparable to the NOMAD and the enclosed design lends itself to urban use. Limited mobility and the capacity to process higher TDS waters suggest the POD may be better utilized as a permanent facility for treating produced water. Both technologies reduce disposal costs, but the NOMAD mobility advantage provides greater savings of transportation costs. The cost to recycle flowback water using thermal distillation presently exceeds the cost of disposal; however, Devon's application of evaporator technology in the Barnett Shale is a valuable tool in the evolving regulatory climate of Texas water resources.

3.1.3 Ion Exchange

Ion Exchange (IX) is the process by which dissolved solids are removed from water using a "softening" process. In the recovery of oil and natural gas, salts are removed by exchange resins capable of removing particular ions from the feed (IOGCC and ALL, 2006). IX is commonly used in conjunction with RO to treat water produced from coal-bed methane operations. The energy requirements and capital costs associated with IX limit its functionality as an economic solution for large-scale implementation (Dow, 2009).

3.1.4 Humidification-Dehumidification

The importance of small-scale recycling technology must not be overlooked in pursuit of oilfield water management. Researchers at the New Mexico Institute of Mining and Technology have received funding from the U.S. Department of Energy to provide wellsite desalination using renewable energy sources. For less than $1/bbl, produced water can be desalinated at the wellsite using geothermal and solar energy. The humidification-dehumidification process builds on thermal distillation technology to purify water for non-potable use. Effluent can be repurposed to produce drilling fluids, provide enhanced recovery operations, or used for irrigation (Bourouni, et al. 2000). The extension of recycling water on an individual well basis highlights the necessity to reduce terminal water consumption on every operational level.

3.2 OTHER OPTIONS

Oilfield recycling and reuse strategies present multiple options for sourcing alternative supplies for hydraulic fracture stimulation. In 2006, more than 1,202 Barnett Shale wells were drilled consuming an estimated 13,608 ac-ft of fresh water. 90% of the fresh water used was for hydraulic fracture operations (Galusky, 2007). Water-based fracs have prevailed as the preferred stimulation technique for exploiting unconventional resource plays, offering results comparable to traditional gel-based treatments but at a significant reduction in cost. Today, as acquisition costs and groundwater regulation increase, water-conscious operators and service companies are reconsidering oilfield technologies aimed at reducing the fresh water requirements of hydraulic fracture stimulation.

3.2.1 Alternative Sources of Supply for Hydraulic Fracture Stimulation

While the economics of treating flowback for future use alone does not support the cessation of injection-based disposal, concerns about securing future supplies is influencing planners to consider the construction of pipeline infrastructure to transport treated municipal waste to areas of North Central Texas for non-potable uses such as irrigation and energy production. The 166 mgd of effluent produced by the Village Creek sewage plant in Fort Worth is the target of a new strategy to reduce fresh water consumption by irrigation, industrial and mining WUGs. Transporting reclaimed municipal supplies via pipeline would eliminate hundreds of daily trips by trucks hauling fresh water supplies to the wellsite, and could provide a new source of revenue for municipally-owned wastewater facility operators. The City of Fort Worth has approved a contract to study the feasibility of transporting treated wastewater from the Village Creek sewage plant to end users like golf courses and oilfield consumers. The design will cost the city an estimated $1.8 million (Lee, 2008); however, if successful, this prototype may serve as a model for other water utilities seeking to finance Purple Pipe projects.

The concept of using municipal waste for hydraulic fracture stimulation is not unique to the Barnett Shale. Water scarcity in Alberta, Canada led the provincial government to adopt stringent water conservation and allocation policies. The Water for Life Strategy is a plan by the Alberta Ministry of the Environment to secure drinking water supplies, promote environmental quality and meet industry water needs through research, partnerships and conservation. The Water for Life Strategy desires a 30% improvement in water conservation efficiency and outlines oilfield injection guidelines requiring operators to reduce or eliminate disposal of non-brine fluids through recycling and reuse technologies. According to the guidance for oil and natural gas production, flowback water is used to prepare new hydraulic fracture fluids. Since the volume of flowback fluid is insufficient to adequately stimulate future wells, the integration of alternative supplies to meet fresh water requirements is recommended: produced water, brackish groundwater, non-water based frac fluids, and municipal and industrial effluents. In Alberta, membrane filtration is the dominant technology for producing frac-quality recycled supplies. (Newalta, 2008). Over time, competition has decreased the cost of membrane filtration and improved efficiency (Alberta Ministry of the Environment, 2003).

Even with sophisticated membrane filtration, the Water for Life Strategy would not be successful without flexible fracture fluids. Cooperating with water conservation measures, oilfield service providers have engineered salt-tolerant frac fluids to respond to a broader range of salinity. Traditional crosslinked gels used in early fracture stimulation required extensive treatment to return flowback fluid to usable quality. Surfactant gel fracture fluids independently developed by BJ Services and Halliburton were first deployed in the Western Canadian Sedimentary Basin in 1999. Surfactant gel frac fluid can accept component water with higher salinities than linear and crosslinked fluids. Results of use indicate a 52% reduction in makeup water where reclaimed surfactant gel frac fluid is used (Russell, 2001). Research and development of salt-tolerant frac fluids is increasing in areas like Alberta where policy mandates conservation. The use of salt-tolerant frac fluids has expanded to the domestic Bakken oil shale which extends across the Williston Basin from South Dakota to Canada, and west into Montana. BJ Services has successfully fractured over 1200 frac stages in more than 150 wells (Rieb, et al., 2009). Surfactant gel fracture treatments have been widely used in shallow shale gas plays across Canada and the northern U.S. Successful hydraulic fracture stimulation is dependent upon reservoir characteristics including pressure, porosity, temperature, water saturation and the natural fracture matrix. Wide use of surfactant gel fracs has not yet occurred in the Barnett Shale where the reservoir characteristic differ significantly from those in the Western Canadian Sedimentary and Williston Basins.

Pressure to conserve water is encouraging some state regulatory agencies to develop waste and water management strategies. In Texas, the Railroad Commission is diligently promoting its waste minimization proposal to Barnett Shale operators. Source reduction is the first tenet of waste minimization and refers to any process that eliminates or reduces oilfield waste. Recycling and reclamation of oilfield waste is the second concept of the waste minimization program and applies to drilling fluids, flowback and produced waters. Sourcing alternative supplies is a promising solution in reducing the water requirements of oilfield operations. In recent history, Barnett Shale operators have optimized the process of water-based fracs and used fewer gel fracture treatments. The cost of using reclaimed waters for hydraulic fracture stimulation has been prohibitive. However, with new sources of supply and improved treatment options, terminal water consumption associated with hydraulic fracture operations can be effectively reduced.

3.2.2 Applications of Reclaimed Flowback and Produced Waters

Where reclaimed flowback and produced waters cannot be used to offset the water requirements of future hydraulic fracture treatments, other WUGs in North Central Texas could potentially benefit from new sources of supply. Population projections estimate 27% of the state's population will reside in the Region C by 2010. By 2060, the population of Region C could increase by as much as 98% (TWDB, 2007). Municipal demand for water supplies in Region C is expected to increase by 92% during the next 50-year planning period which has legislators and planners rapidly permitting the construction of four major reservoirs to provide water to North Central Texas. Unpredictable population growth and extended drought conditions have placed pressure on Region C to make a choices between supporting future municipal demand and the meeting the established needs industrial and agricultural users which have been a financial boon for the area.

North Central Texas has a critical need to secure future water supplies. Cooperation by Barnett Shale operators furthers the development of a sustainable water-energy nexus. The value of repurposing flowback and produced water for applications beyond the oilfield is largely symbolic. Reuse of the 13,608 ac-ft. of fresh water used for Barnett Shale operations (2006) will not eliminate the water burdens of Region C; however, this volume is equal to 70% of projected demand by livestock, or 30% of projected demand by irrigation users in 2010. Whereas water consumption by the mining WUG is expected to increase over the 50-year planning period, livestock and irrigation projections remain flat (TWDB, 2007).

Recycling flowback and produced waters for off-lease use is limited by risks associated with the use of industrial reclaimed water. Industrial reclaimed water is regulated under Chapter 210 of the Texas Administrative Code and is subject to extensive water sampling and analysis requirements. This added layer of compliance has discouraged operators from implementing recycling for non-potable use. Using treated flowback and produced waters to meet instream flow requirements could contribute to a reduction of net water consumption in Region C if equal discharge requirements applied to all surface water bodies in the state. Rather, discharge permits are subject to existing stream qualities which would require a range of treatment capacities (Burnett, 2004). Barnett Shale development responds rapidly to shifts in natural gas commodity prices. Depressed prices discourage drilling and therefore variable stimulation operations would affect the ability to maintain consistent instream discharge. Further, whereas recycled oilfield fluids are an uncertain, but marketable product, treating oilfield waste to meet instream flow requirements is an economic disincentive for operators. It is fair to assume public skepticism would be present in any program which allowed the discharge of reclaimed industrial water into public waterways, a potential source of conflict that could limit the pursuit of sustainable water practices by the energy industry.

3.3 TECHNOLOGY TO REDUCE WATER REQUIREMENTS

Efforts to reduce water requirements of hydraulic fracture stimulation have also materialized in the exploration environment. Horizontal drilling and hydraulic fracturing stimulation have made possible commercial recovery of once uneconomic unconventional resource plays and vastly expanded domestic oil and natural gas reserves. Reservoir modeling is used to identify and map the geological and petrophysical characteristics of a reservoir. In recent years, reservoir modeling has provided insight to the complexity of fracture networks enabling optimization of hydraulic fracture treatments.

3.3.1 Microseismic Monitoring

Microseismic monitoring is derived from traditional seismic technology and was first used by the mining industry to monitor subsurface disturbances. Early research of microseismic monitoring was performed by Los Alamos National Laboratory in the 1970s and 1980s to measure microseisms created by subsurface fluid injection (Warpinski, 2009). While microseisms from hydraulic fracture stimulation are too small to be measured by surface monitoring systems, the placement of downhole data recorders has expanded the ability to quantify the effects of hydraulic fracture stimulation. Microseismic monitoring adds significant value to reservoir modeling in reservoirs where fracture behavior is unknown. As more infield drilling occurs in the Barnett Shale, operators can use microseismic monitoring to increase knowledge of fracture orientation and length resulting in optimum development of the field (Warpinksi, 2009). Likewise, understanding fracture growth generated by hydraulic fracturing can guide operators to orient hydraulic fracture treatments to maximize well performance in a multi-well field.

3.3.2. Hydraulic Fracture Diagnostic Tools

The development of specialized tools capable of providing for real-time data has immeasurably improved hydraulic fracturing results. Immediate feedback of wellbore conditions and hydraulic fracturing results allows operators to adjust the amount of frac fluid and proppant delivered to the wellbore during stimulation. Whereas early hydraulic fracture stimulation was performed as a single event, the process has evolved to include multiple stages of fracture treatments using downhole tools to isolate objective zones and control fluid delivery. Well logging performed before and after stimulation can measure the effectiveness of the frac job and allows operators to optimize future hydraulic fracture treatments. The integration of diagnostic tools and reservoir modeling provides operators with valuable information for planning successful drilling programs. The ability to model a reservoir using precise wellbore data allows operators to maximize the results of hydraulic fracture stimulation while identifying ways to reduce material costs of well completion.

Untapped unconventional resource plays present a multitude of uncertainty. A data-sharing trend has emerged among operators hoping to gain reservoir knowledge beyond the scope of their wellbores. Arrangements to share proprietary information have formed on many levels from agreements between operators to trade production information to consortiums of operators, researchers and regulatory bodies pooling financial and intellectual capital to characterize entire reservoirs and optimize production. These collective arrangements often provide independent operators access to state-of-the-art technology for a fraction of the cost. Applying the data sharing model to hydraulic fracture monitoring enables industry and regulators to exchange information about the water requirements of hydraulic fracture stimulation across a greater distribution of wells.

A larger data set can help identify and evaluate techniques for reducing the water requirements and improving the efficiency of hydraulic fracture stimulation.

IV. Findings

Barnett Shale activities account for less than 1% of total water consumption in Region C. Roughly half of 1% is sourced from groundwater and half of 1% is sourced from surface water. Less than 1% of Barnett Shale water is derived from recycled supplies (Galusky, 2007). Recycling flowback water for future hydraulic fracture operations is the best strategy for reducing terminal water consumption in the Barnett Shale. The influent thresholds of current recycling technologies permit the treatment of high TDS waters up to 80,000 ppm (the content of flowback water ranges from 1,000 to 50,000 ppm). Since 90-100% of frac fluids can be recovered within one to two weeks following stimulation, recycling flowback water offers a semi-renewable supply of water for future hydraulic fracture operations available on demand. While savings generated by reduced acquisition, transportation and disposal costs are not competitive with the costs of recycling, they can partially offset the capital expense and operating costs of treatment facilities.

Of the available recycling technologies, thermal distillation is best suited for recycling flowback water. Table 5.1 compares the performance and cost of thermal distillation technology to RO and injection well disposal. Thermal distillation technology can yield up to 80% efficiency with minimal energy inputs and flexible fuel requirements. Recent advances in MVR technology have increased influent thresholds and waste concentration capacity which allow greater feed salinities and provide maximum distillate production. The Barnett Shale provides an abundant supply of natural gas for operation; and compact, skid-mounted units enable the rapid deployment of thermal distillation units to the wellsite. Pilot operations have already reduced the number of daily truck trips hauling fresh water and brine to and from the wellsite.

	Disposal	Reverse Osmosis	Thermal Distillation
Capacity	50,000+ wells in Texas	Dependent on feed quality and capacity	2,500 bbl/day
Influent Requirement	Exempt under RCRA	≤ 40,000 ppm	≤ 80,000 ppm
Effluent Quality	n/a	Dependent on feed quality	Concentrates waste ≤ 260,000 ppm
Energy Requirements	Transportation	Electricity	Natural Gas (25-28 BTU/lb.)
Mobile Technology	n/a	▼	▲
Per Barrel Cost (est).	\$2 - \$3	\$0.85	\$ 3.35
Incentives for Use	• Inexpensive	• Reduce OPEX • High Capacity	• Maximum Distillate Production • Reduce OPEX
Barriers to Market Entry	• Public Criticism • Limited Capacity	• Capital Cost • High Energy Requirement • Membrane Fouling	• Expensive • Limited Capacity
Efficiency	n/a	• Correlated with influent quality • 3:1 brine reduction (initial rate)	• 80% avg. (flowback)
Effluent Marketability?	n/a	Yes	Yes
Public Opinion	▼	▲	▲

Table 5.1: Performance of Flowback Recycling Technologies

The cost of thermal distillation facilities can limit recycling opportunities for smaller and mid-size independent operators. Under this situation, supplemental water management strategies can be used to reduce consumption. Advanced frac fluids and diagnostic tools can yield improved well performance and significant water savings for incremental investment. Multiple approaches to conservation allow operators to maximize water savings without penalty. Shared recycling facilities to treat flowback and produced waters in the greater Barnett Shale area can reduce terminal water consumption while allocating the capital and operating costs. Possible future legislation to limit water use for hydraulic fracture operations during periods of drought, or the increased regulation of Class II injection wells, could incentivize operators to consider constructing shared facilities.

V. Conclusions

5.1 General Conclusions

There is a compelling symmetry in the goals of the TWDB and the Barnett Shale Water Conservation and Management Committee (BSWCMC). A desire for responsible water management practices, education, and consensus-based solutions are among the principles that guide the TWDB, BSWCMC, and others to reduce waste and promote conservation. Horizontal drilling and hydraulic fracture stimulation have made the economic recovery of shale reservoirs possible. The Barnett Shale has produced more than 2.5 TCF of natural gas to date and contains more than 27 TCF of additional natural gas reserves. A USGS assessment of the Bakken oil shale indicates an estimated 3.0 to 4.3 billion barrels of technically recoverable oil making it the largest onshore domestic oil find to date (2008). The Haynesville/Bossier gas shale along the border of Texas and Louisiana extends more than 9,000 square miles and contains an estimated 251 TCF of technically recoverable reserves (DOE, 2009). The Marcellus gas shale, which has not yet been studied by the USGS, covers six states and contains an estimated 262 TCF of technically recoverable reserves. These figures do not include the vast reserves of other shale systems, tight-gas sands and coal-bed methane currently under development using similar water-intensive extraction techniques.

Soft commodity prices are advancing natural gas to levels competitive with coal, which has historically dominated the U.S. electricity market. Commercial extraction of unconventional resource plays will require an indefinite volume of water. This places the Barnett Shale experience in a unique position to test the economic and physical limits of reducing water requirements for hydraulic fracture stimulation while complying with greater oversight by regional planners. Under the direction of the TWDB, Regional Planning Groups (RPGs) are required to develop water plans with respect to regional aquifers, surface water bodies and unique demand matrices. Because the State of Texas treats surface water and groundwater as separate entities, independent regulatory structures exist for managing supplies which are hydrologically linked. Thus, cooperation among RPGs, GCDs, WUGs is required to advance the goals the planning process. As Barnett Shale operators pursue innovative water management practices it brings the energy-water nexus into greater focus and provides a valuable opportunity to resolve the water issues of North Central Texas. Strategies which reduce terminal water consumption associated hydraulic fracture stimulation without compromising efficiency and cost energy production will become an integral part comprehensive policy on energy-water management.

5.1 SPECIFIC CONCLUSIONS

Aging wells generate greater volumes of produced water. The current cost for disposal in the Barnett Shale remains stable at $2 to $3/bbl, but has exceeded $6/bbl during periods of high demand (Burnett, 2007). The per barrel cost of disposal in the Barnett Shale is expected to rise as drilling activity peaks and the production of oilfield brine trends upward. The likelihood additional disposal wells will be drilled in the Barnett Shale is low; therefore, industry will be required to implement water management strategies to advance exploration and development.

Recycling flowback fluids for future hydraulic fracture applications is the most practical repurposing of oilfield waste. The low TDS content of flowback derived from water-based fracs permits multiple treatment options. Barnett Shale lithology is unique among other gas shales in that 90-100% of frac fluids may be recovered (Hayes, 2009).

While multiple recycling techniques are capable of processing reclaimed flowback water, thermal distillation is the predominant technology. Mobile distillation treatment facilities are ideal for recycling flowback water which is produced for a limited period of time following hydraulic fracture stimulation. Once flowback water is reclaimed, units may be dispatched to other locations and the distillate applied to future hydraulic fracture treatments. Devon Energy's nine unit NOMAD program has yielded a 78% rate of efficiency distilling 90-100% of total flowback water recovered in 2007 (Ewing, 2008). The 2008 treatment cost per barrel of recycled flowback fluid was $4.43/bbl. Factoring in the market value of the distillate produced, the net disposal cost for 2008 was $3.35/bbl (Ewing, 2008).

Unlike Alberta, the inexpensive disposal costs in the Barnett Shale have kept the price of RO treatment high and restrained efforts to improve efficiency. Membrane selection significantly impacts the efficiency of RO treatment. As membrane quality diminishes, its ability to reject dissolved solids declines. Pretreatment to remove dissolved oils can extend membrane life and reduce the cost of membrane replacement; however, the capital cost, immobility and energy demands of RO limit its potential as a tool for cost-effective recycling of hydraulic fracture fluids.

VI. Recommendations

6.1 SHARED RECYCLING FACILITIES

The volume of produced water generated from Barnett Shale wells poses significant disposal responsibility and environmental liability that will only increase in future years. The cost to acquire and the capacity to operate treatment facilities are beyond the abilities of most operators. A study examining the feasibility of shared recycling facilities is recommended to evaluate the impacts large-scale recycling facilities would have on reducing disposal volumes, lower operating costs, and the production of a marketable water supply for future hydraulic fracture treatments and non-potable use. Funding for the TWDB and the RRC to expand research on commercial recycle technology, or to construct shared recycling facilities, would incentivize operators and water planning entities to participate in the process.

6.2 AMENDMENTS TO THE RULE OF CAPTURE AND BENEFICIAL USE DOCTRINES

The proposed changes to the Rule of Capture expose operators and other users to increased liability for pumping groundwater. Extending the Beneficial Use Doctrine to groundwater will enable GCDs to determine whether groundwater use for hydraulic fracture stimulation is considered a beneficial use. Further, determinations of beneficial use could vary by GCD creating inequitable development opportunities. Both measures would effectively restrict the use of groundwater for oilfield operations at the cost of limiting Barnett Shale development and the development of other unconventional resources. Further evaluation by the Legislature and water planning entities is needed to determine how the structure of groundwater ownership and groundwater permitting requirements can be aligned with the DFC process while preserving GCD-WUG relations.

6.3 CO_2 CAPTURE AND SEQUESTRATION

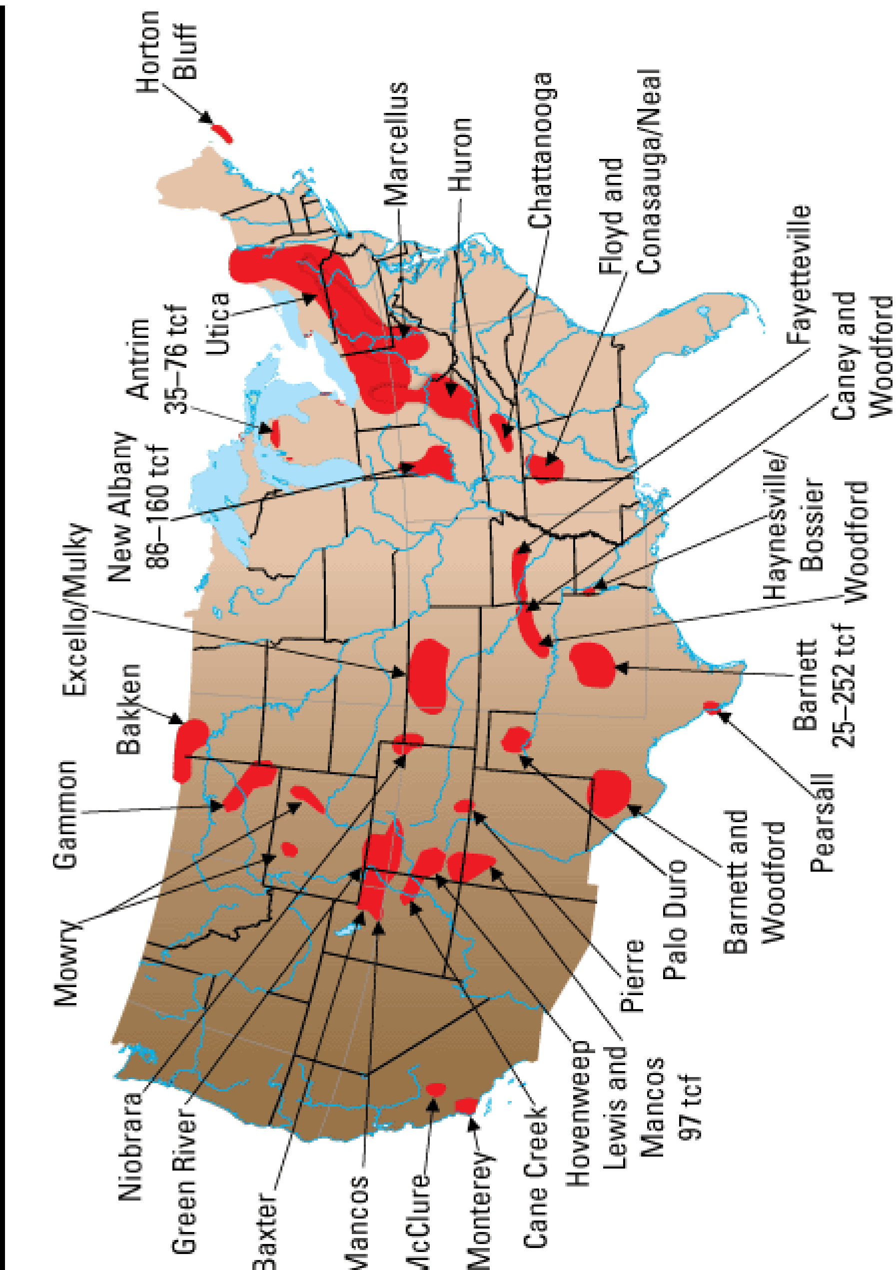
In addition to reducing greenhouse gas emissions, CO_2 capture and sequestration could further the goal of reducing terminal water consumption in the Barnett Shale. Enhanced recovery of oil and natural gas using CO_2 technologies is expected to expand as a result of new tax incentives and defined regulatory framework. CO_2-based stimulation could displace the use of water-based fracs in the development of gas shale systems. More research is needed to evaluate the effectiveness and environmental impacts of CO_2-based stimulation and the application of CO_2 capture and storage in enhanced recovery operations.

6.4 MUNICIPAL PIPELINE INFRASTRUCTURE

Current technology permits the use of treated municipal waste in the preparation of hydraulic fracture fluids. The construction of the Village Creek sewage plant pipeline represents a significant effort by the City of Fort Worth to reduce terminal water consumption in the Barnett Shale by delivering treated wastewater to users for non-potable use. The Legislature should consider opportunities to expand funding for similar pipeline projects which would provide WUGs access to alternative and recycled supplies, reducing dependence on groundwater and surface water supplies. The support and participation of the Legislature is critical in advancing the water-energy nexus for the purpose economic development, and to protect and conserve the state's water resources.

Appendix A

MAJOR U.S. SHALE BASINS



Major US shale basins.

Appendix B

81ST REGULAR LEGISLATIVE SESSION ACTIVITY

Interim Charges to House Committee on Natural Resources (80th)

1. Monitor ongoing efforts related to joint planning in GMAs, including setting DFCs.

2. Review and evaluate model for investor-owned water and sewer utilities specifically: rates, fees, ownership of multiple systems, and financing development.

3. Monitor of implementation of HB 2876 relating CCNs for water and sewer systems.

4. Monitor implementation of HB 3, HB 4 and SB 3 enacted by 80th Session.

5. Create uniform template for MUD creation to expedite process.

6. Examine rules of resignation for members of water and soil conservation district in order to serve on GCD council.

7. Study efficacy of flood control infrastructure, liability thereof and legal authority and financing authority to make repairs.

8. Review TCEQ fee structure and determine scope of services funded by TCEQ, and the allocation of resources including personnel.

9. Monitor agencies and programs under committee's jurisdiction.

Interim Charges to Senate Committee on Natural Resources (80th)

1. Study the safety of dams, levees and other flood control devices and assess cost to repair aging infrastructure.

2. Review Texas air emissions inventory and identify areas in need of improvement.

3. Study and assess new technology for identifying point source identification technology for pollution emissions.

4. Assess the impact of new electricity generation technology and examine the energy-water nexus as it pertains to the State Water Plan.

5. Identify and evaluate saline water bodies in the State and identify options and needs for desalination.

6. Monitor implementation of HB 1763 (79th).

7. Investigate groundwater issues in areas without a defined aquifer such as the Barnett Shale, and evaluate GCD fee authority.

8. Review the authority and powers of river authorities.

9. Study and assess mercury and arsenic emissions in the state.

10. Evaluate the need for water quality standards in critical areas including the Edwards and Barton Springs recharge zones.

11. Monitor progress of the EAA Recovery Implementation Plan.

12. Monitor implementation of legislation passed in the 80th Session and discuss means to transfer historic parks and properties from TWPD to THC.

Texas Water News
81st Legislature Regular Session

Session Begins: 1/13/2009

Session Ends: 6/1/2009

Stages:
1 Filed
2 Out of Chamber 1 Committee
3 Voted on by Chamber 1
4 Out of Chamber 2 Committee
5 Voted on by Chamber 2
6 Sent to Governor
7 Bill Becomes Law

Bill No.		Sponsor	Filed	Stage
	Regional Water Planning			
HB 3494	Relating to the establishment of desired future conditions of groundwater resources and revision of those conditions by the Texas Water Development Board.	Corte	3/11/09	1
SB 2119	Relating to desired future condition requirements for certain groundwater conservation districts.	Seliger	3/13/09	1
SB 2296	Relating to the timing of submittal of groundwater management plans.	Duncan	3/13/09	4
SB 2318	Relating to the use and management of surface water resources.	Averitt	3/13/09	2
SB 2319	Relating to the creation of a groundwater conservation district in a priority groundwater management area.	Averitt	3/13/09	4
HB 4656 (SB 2120 identical)	Relating to the management, operation, and review of groundwater conservation districts.	Smithee (Seliger)	3/13/09	1
SB 2120 (HB 4656 identical)	Relating to the management, operation, and review of groundwater conservation districts.	Seliger (Smithee)	3/13/09	3
HB 4655 (SB 1386 identical)	Relating to priority groundwater management areas.	Smithee (Seliger)	3/13/09	1
SB 1386 (HB 4655 identical)	Relating to priority groundwater management areas.	Seliger (Smithee)	3/13/09	4
HB 2340 (SB 1209 identical)	Relating to the Middle Trinity Groundwater Conservation District.	Miller (Fraser)	3/04/09	2
SB 1209 (HB 2340 identical)	Relating to the Middle Trinity Groundwater Conservation District.	Fraser (Miller)	2/27/09	7
HB 1082 (SB 715 companion)	Relating to the North Texas Municipal Water District.	Laubenberg (Shapiro)	2/05/09	3
SB 715 (HB 1082 companion)	Relating to the North Texas Municipal Water District.	Shapiro	2/06/09	7
SB 1544	Relating to the creation of the Prairielands Groundwater Conservation District; providing authority to issue bonds; granting a limited power of eminent domain.	Averitt	3/09/09	4
	Financing Supply and Infrastructure			
HB 3542 (SB 2284 identical)	Relating to the issuance of grants by the Texas Water Development Board for water and wastewater system improvements in economically distressed areas.	Lucio III (Lucio)	3/13/09	2
SB 2284 (HB 3542 identical)	Relating to the issuance of grants by the Texas Water Development Board for water and wastewater system improvements in economically distressed areas.	Lucio (Lucio III)	3/13/09	4
HB 3527 (SB 2283 identical)	Relating to the use of the state participation account of the water development fund.	Callegari (Lucio)	3/11/09	2
SB 2283 HB 3527 identical)	Relating to the use of the state participation account of the water development fund.	Lucio (Callegari)	3/11/09	4
HB 3526	Relating to the adoption of rules by the Texas Water Development Board regarding supplemental funding resulting from federal economic recovery legislation.	Callegari	3/11/09	5
SJR 50	Proposing a constitutional amendment relating to the issuance of additional general obligation bonds by the Texas Water Development Board.	Averitt	3/13/09	4
SB 2311	Relating to Texas Water Development Board surveys for water infrastructure financing.	Averitt	3/13/09	4
SB 2320	Relating to the authority of a groundwater conservation district to assess production fees.	Averitt	3/13/09	1
SB 2313	Relating to the creation of the water plan projects fund to assist the Texas Water Development Board in the funding of certain projects identified in the state and regional water plans.	Averitt	3/13/09	4
SB 2314	Relating to the administration of the Clean Water State Revolving Fund and the Drinking Water State Revolving Fund.	Averitt	3/13/09	7
	Supply, Demand, Availabilty and Allocation Management			
SB 1406	Relating to the consideration of the effects of climate variability on water supplies in regional and state water plans.	Sharpleigh	3/05/09	3

Texas Water News
81st Legislature Regular Session

Session Begins: 1/13/2009
Session Ends: 6/1/2009

Stages:
1 Filed
2 Out of Chamber 1 Committee
3 Voted on by Chamber 1
4 Out of Chamber 2 Committee
5 Voted on by Chamber 2
6 Sent to Governor
7 Bill Becomes Law

Bill No.		Sponsor	Filed	Stage
	Water Law, Regulation and Appropriations			
HB 3335	Relating to the powers and authority of water districts.	Callegari	3/11/09	5
SB 2006	Relating to groundwater permitting considerations of the adopted water plans.	Hegar	3/12/09	3
HB 4258	Relating to the regulation by groundwater conservation districts of the drilling of certain water wells.	Hilderbran	3/13/09	2
HB 1434	Relating to the use of money in the watermaster fund.	Lucio III	2/18/09	1
SB 2008	Relating to consideration of water produced from exempt wells.	Hegar	3/12/09	3
SB 1714	Relating to the evidence of beneficial use in the permitting of groundwater.	Hegar	3/10/09	3
HB 4028	Relating to testing requirements for certain commercial injection wells.	Christian	3/12/09	1
HB 177 (SB 273 identical)	Relating to testing reqs. for certain commercial injection wells.	Creighton (Nichols)	11/12/08	1
SB 273 (HB 177 identical)	Relating to testing reqs. for certain commercial injection wells.	Creighton (Nichols)	11/12/08	1
HB 178 (SB 274 identical)	Relating to limitations on the locations of injection wells.	Creighton (Nichols)	11/12/08	1
SB 274 (HB 178 identical)	Relating to limitations on the locations of injection wells.	Creighton (Nichols)	11/12/08	1
HB 179 (SB 275 identical)	Relating to the application for new reqs. For commercial underground injection control wells to be adopted by the TCEQ.	Creighton (Nichols)	11/12/08	2
SB 275 (HB 179 identical)	Relating to the application for new reqs. For commercial underground injection control wells to be adopted by the TCEQ.	Nichols (Creighton)	11/12/08	4
HB 433	Relating to the procedures for acting on applications for certain permits under the Solid Waste Disposal Act.	Lucio III	12/18/08	2
	Conservation Efforts			
HB 225 (HJR 25 enabling leg.)	Relating to an exemption from ad valorem taxation of the portion of the appraised value of a person's porpoerty attrubutable to the implementation on the property of water conservation intiatives, desalination and brush control.	Aycock (Aycock)	11/14/08	1
SB 2489	Relating to the authority of the San Jacinto River Authority to implement a groundwater reduction plan for the conservation of groundwater and the reduction of groundwater withdrawals in Montgomery County, and to issue bonds of the authority; providing administrative penalties.	Williams	4/02/09	2
	Water and the Environment			
HB 323	Relating to the establishment of a program for detecting and giving notice of an unauthorized discharge of industrial, municipal, or other waste into any water in the state.	Raymond/Guillen	11/20/08	1
HB 595 (SB 822 identical)	Relating to a restriction on permits authorizing discharges of sewage effulent into any water in the contributing or recharge zone of the San Antonio or Barton Springs segment of the Edwards Aquifer.	Leibowitz/Rodriguez	1/14/09	1
SB 822 (HB 595 identical)	Relating to a restriction on permits authorizing direct discharge of waste or pollutants into water in certain areas where associated with Barton Springs segment of Edwards Aquifer.	Van de Putte	2/12/09	1
HB 1508 (SB 1099 identical)	Relating to a restriction on permits authorizing direct discharge of waste or pollutants into water in certain areas where associated with Barton Springs segment of Edwards Aquifer.	Bolton	2/19/09	2
SB 1099 (HB 1508 identical)	Relating to a restriction on permits authorizing direct discharge of waste or pollutants into water in certain areas where associated with Barton Springs segment of Edwards Aquifer.	Watson	2/19/09	1
HB 1553 (SB 988 identical)	Relating to the development of a climate adaptation plan by certain entities.	Burnam	2/20/09	2
SB 2328	Relating to the development of environmental flow regimes by the Environmental Flows Advisory Group and Texas Commission on Environmental Quality.	Hegar	3/13/09	1
SB 988 (HB 1553 identical)	Relating to the development of a climate adaptation plan by certain entities.	Ellis	2/19/09	1

Texas Water News
81st Legislature Regular Session

Session Begins: 1/13/2009
Session Ends: 6/1/2009

Stages:
1 Filed
2 Out of Chamber 1 Committee
3 Voted on by Chamber 1
4 Out of Chamber 2 Committee
5 Voted on by Chamber 2
6 Sent to Governor
7 Bill Becomes Law

Bill No.		Sponsor	Filed	Stage
	Administrative Processes			
SB 1190 (HB 2063 identical)	Relating to the enforcement of rules by a groundwater conservation district.	Duncan/Averitt/Seigler	2/26/09	2
HB 2063 (SB 1190 identical)	Relating to the enforcement of rules by a groundwater conservation district.	Callegari/Creighton	3/02/09	7
HB 1890	Relating to notification of applications for permits for certain injection wells.	Creighton	2/26/09	4
HB 1664	Relating to an exemption for groundwater used for certain purposes from production fees assessed by the Upper Trinity Groundwater Conservation District.	King, et al.	2/23/09	7
SB 540	Relating to notice of an application for a permit to dispose of oil and gas waste in a commerical disposal well.	Davis/Nichols	1/26/09	3
HB 569	Relating to notice of an application for a permit to dispose of oil and gas waste in a commerical disposal well.	S. Miller	1/12/09	2
HB 4027	Relating to limitations on the location of Class II injection wells.	Christian	3/12/09	1
HB 4026	Relating to the application of new requirements for Class II injection wells to be adopted by the Railroad Commission of Texas.	Christian	3/12/09	1
HB 1669	Relating to certificates of public convenience and necessity for water or sewer services.	Callegari	2/23/09	3
HB 2658 (SB 2098 identical)	Relating to the release of certain property from a certificate of public convenience and necessity for water service and sewer service.	Kuempel (Wentworth)	3/06/09	1
SB 2098 (HB 2658 identical)	Relating to the release of certain property from a certificate of public convenience and necessity for water service and sewer service.	Wentworth (Kuempel)	3/13/09	1
SB 718	Relating to certificates of public convenience and necessity to provide water or sewer utility service.	Nichols	2/06/09	1
HB 4318	Relating to allowing certain landowners to request that land be decertified from the service area of a holder of a certificate of public convenience and necessity.	Callegari	3/13/09	1
HB 4043	Relating to notifications to certain purchasers of real property that may be located in an area subject to a certificate of convenience and necessity for water or sewer service.	Callegari	3/12/09	7
HB 43	Relating to permitting reqs. for GCDs, including permits to transfer water	Corte	11/10/08	1
HB 2254 (SB 752 identical)	Relating to the authority of a local government to prohibit the Railroad Commission of Texas or the Texas Commission on Environmental Quality from issuing a permit for a disposal well.	Hancock	3/03/09	1
SB 752 (HB 2254 identical)	Relating to the authority of a local government to prohibit the Railroad Commission of Texas or the Texas Commission on Environmental Quality from issuing a permit for a disposal well.	Davis/Nichols	2/10/09	4

Texas Water News
81st Legislature Regular Session

Session Begins: 1/13/2009
Session Ends: 6/1/2009

Stages:
1 Filed
2 Out of Chamber 1 Committee
3 Voted on by Chamber 1
4 Out of Chamber 2 Committee
5 Voted on by Chamber 2
6 Sent to Governor
7 Bill Becomes Law

Bill No.		Sponsor	Filed	Stage
	Regulatory Takings			
HB 2685	Relating to the landowner's bill of rights.	Callegari	3/06/09	7
HB 1432	Relating to a landowner's repurchase of real property from an entity that acquired the property through condemnation.	Jackson	2/18/09	1
HB 1424	Relating to the procedure for the disannexation of territory from a municipality.	Leibowitz	2/18/09	2
HB 1389	Relating to the acquisition of real property for public use.	Davis	2/18/09	2
HB 1385	Relating to the assessment of damages to a property owner from condemnation.	Davis	2/18/09	1
HJR 96	Proposing a constitutional amendment to define a public use for which property may be taken, damaged, or destroyed.	Christian, et al.	3/10/09	1
SB 2122	Relating to a limitation on the use of the power of eminent domain by certain water districts.	West	3/13/09	1
SB 1180	Relating to regulatory takings.	Patrick	2/26/09	1
SB 1023	Relating to the exercise of eminent domain authority.	Ogden	2/20/09	3
HB 4 (SB 533 identical)	Relating to eminent domain, including certain limitations, procedures, and standards relating to the use of eminent domain.	Orr, et al.	1/05/08	1
SB 533 (HB 4 identical)	Relating to eminent domain, including certain limitations, procedures, and standards relating to the use of eminent domain.	Duncan	1/23/09	1
HB 1483 (HB 402 duplicate)	Relating to the use of eminent domain authority.	Pitts	2/19/09	1
HB 402 (HB 1483 duplicate; SB 18	Relating to the use of eminent domain authority.	Woolley	12/15/08	1
SB 18 (HB 402 similar)	Relating to the use of eminent domain authority.	Estes	2/10/09	4
HB 417	Relating to the acquisition of and compensation for real property, incl. blighted property, for public purposes through condemnation or certain other means.	Callegari	12/16/08	2
HJR 14	Relating to the limiting the taking of private property.	Corte	11/10/08	7
HB 369	Relating to assessment of damanages in a condemnation proceeding.	B. Brown	12/04/08	2
HJR 65	Proposing a constitutional amendment to require compensation for certain property taken where the use is public and necessary.	Davis	2/18/09	1
SB 219	Relating to prohibiting the use of eminent domain to take private property for recreational purposes.	Nichols	11/10/08	1
HJR 31	Relating to prohibiting the state of a political subdivision of the state from taking private property for the primary purpose of economic development or to benefit a particular private party.	Anderson	12/03/08	1
	Other Issues of Interest			
HB 2811 (SB 2111 identical, enables HJR 123)	Relating to the implementation of and incentives for projects involving the capture, transportation, injection, sequestration, geologic storage, or abatement of carbon dioxide.	P. King	3/09/09	2
SB 2111 (enables SJR 39, HB 2811 identical)	Relating to the implementation of and incentives for projects involving the capture, transportation, injection, sequestration, geologic storage, or abatement of carbon dioxide.	Averitt	3/13/09	4
HB 2872	Relating to the establishment by the State Soil and Water Conservation Board of a carbon dioxide sequestration or emissions offset program.	Chisum	3/09/08	1
HB 469	Relating to the establishment of incentives by this state for the implementation of certain projects to capture and sequester in geological formations carbon dioxide that would otherwise be emitted into the atmosphere.	P. King	12/22/08	7
SB 483	Relating to the establishment of incentives by this state for the implementation of certain projects to capture and sequester in geological formations carbon dioxide that would otherwise be emitted into the atmosphere.	Seliger	1/15/09	1
HB 2669 (SB 1387 identical)	Relating to the injection and geologic storage of anthropogenic carbon dioxide.	Crownover	3/06/09	2
SB 1387 (HB 2669 identical)	Relating to the injection and geologic storage of anthropogenic carbon dioxide.	Seliger	3/05/09	7
SB 940 (HB 2821 identical)	Relating to the regulation of the public practice of geoscience.	Wentworth	2/18/09	7
HB 2821 (SB 940 identical)	Relating to the regulation of the public practice of geoscience.	Chisum	3/09/09	2
SB 941 (HB 2820 identical)	Relating to contracts by governmental entities for professional services relating to geoscience.	Wentworth	2/18/09	3
HB 2820 (SB 941 identical)	Relating to contracts by governmental entities for professional services relating to geoscience.	Chisum	3/09/09	6
HB 638	Relating to the use of direct recording electronic voting equip.	Leibowitz	1/15/09	1
HB 381	Relating to the use of certain voting equip. in an election that does not involve a federal office.	Callegari	12/08/08	1
HB 419	Relating to the use of certain voting equip. in a city election that is not held jointly with an election in which a federal office appears on the ballot.	B. Brown	12/16/08	1
SB 628	Relating to immunity of the state and state agencies and employees of the state and state agencies from suit by certain public entities.	Ogden	2/02/09	1

Glossary

ac-ft	1 acre foot equals approximately 325,851 gallons of water
BBNGL	Billion barrels of natural gas liquids
DFCs	Desired Future Conditions
EUR	Estimated Ultimate Recovery
Flowback water	Recovered fluids used in hydraulic fracture stimulation
GCD	Groundwater Conservation District
HB	House Bill
IX	Ion Exchange
MAG	Managed Available Groundwater
MBO	Million barrels of oil
mg/l	Milligrams per liter
MVR	Mechanical Vapor Recompression
ppm	Parts per million
Proppant	Natural or man-made particles used in hydraulic fracturing
RPG	Regional Planning Group
RO	Reverse Osmosis
SB	Senate Bill
TAGD	Texas Alliance of Groundwater Districts
TCF	Trillion cubic feet
TCFG	Trillion cubic feet of gas
TDS	Total Dissolved Solids
TWDB	Texas Water Development Board
WUG	Water User Group

References

Alberta Ministry of the Environment. Government of Alberta. 2003. Water for Life: Alberta's Strategy for Sustainability (November 2003). Edmonton, Alberta. http://www.waterforlife.alberta.ca/documents/wfl-strategy_Nov2003.pdf [accessed May 3, 2009].

API Creative Services. Hydraulic Fracturing at a Glance. API. http://www.api.org/policy/exploration/upload/HYDRAULIC_FRACT_INDIVID_PAGES.pdf [accessed October 10, 2008].

Aqua-Pure Ventures, Inc. Wastewater Solutions: MVR Evaporation. http://www.aqua-pure.com/wastewater/MVR_evaporation.html [accessed June 30, 2009].

Ball, M. M. and W.J. Perry. 1996. Bend Arch-Fort Worth Basin Province (045). Quoted in D. L. Gautier, G. L. Dolton, K.I. Takahashi, and K. L. Varnes. 1995 National Assessment of United States Oil and Gas Resources – Results, Methodology, and Supporting Data. U.S. Geological Survey Digital Data Series DDS-30, Release 2, CD-ROM.

Bene, J., Harden, B., Griffin, S.W., and J.P. Nicot, 2007. Northern Trinity/WoodbineAquifer Groundwater Availability Model: Assessment of Groundwater Use in the Northern Trinity Aquifer Due to Urban Growth and Barnett Shale Development. Report prepared for the Texas Water Development Board, Austin, Texas, under contract number 0604830613.

Bourouni, K., M.T. Chaibi, and L. Tadrist. 2000. Water Desalination by Humidification and Dehumidification of Air: State of the Art. Paper Desalination 137 (2001) 167–176 presented at the conference on Desalination Strategies in South Mediterranean Countries, Jerba, Tunisia, September 11-12.

Burnet, D.B. Potential for Beneficial Use of Oil and Gas Produced Water. 2004. The Future of Desalination in Texas. Volue 2 Biennial Report on Seawater Desalination. Texas Water Development Board. http://www.twdb.state.tx.us/iwt/desal/docs/The%20Future%20of%20Desalination%20in%20Texas%20-%20Volume%202/documents/B3.pdf [accessed March 10, 2009].

Burnett, D.B., Texas A&M Global Petroleum Institute quoted in Mike Lee, 2007. Well Plan Injects Pressure Into Wastewater Dispute. Fort Worth Star-Telegram. November, 18, 2007. Metro, B1.

Burnett, D.B, and C.J. Vavra. 2008. Energy Development and Water Needs in Texas: The Next 20 Years. Global Petroleum Research Institute. Presented at 2008 Unconventional Gas International Conference and Exhibition, Fort Worth, Texas, September 30-October 2.

Burnett, D.B. and T.A. Pankratz. 2004. Recovery of Fresh Water Resources from Desalination of Brine Produced during Oil and Gas Production Operations. Report to the Texas Water Development Board, September 2004.

Dow Chemical Company. Dow Water Solutions. 2009. Ion Exchange or Reverse Osmosis? http://www.dow.com/liquidseps/design/ix_ro.htm [accessed March 10, 2009].

Ewing, J., Devon Energy Corporation. 2008. Taking a Proactive Approach to Recycling Water in the Barnett Shale. Presented at the Fort Worth Business Press Barnett Shale Symposium. Fort Worth, Texas. February 29, 2008.

Galusky, P.L. 2007 Fort Worth Basin/Barnett Shale Natural Gas Play: An Assessment of Present and Projected Fresh Water Use. Prepared by Texerra under the direction Gas Technology Institute and commissioned by the Barnett Shale Water Conservation and Management Committee. Midland, Texas. April 3, 2007.

Gaudlip, A.W., L.O. Paugh, SPE, Range Resources Appalachia LLC, T.D. Hays, Gas Technology Institute. 2008. Marcellus Shale Water Management Challenges in Pennsylvania. SPE paper 119898-PP presented at the 2008 Shale Gas Production Conference, Fort Worth, Texas, November 16-18.

Gupta, D.V.S, SPE and B.T. Hildek, SPE, BJ Services Company. 2009. Frac Fluid Recycling and Water Conservation: A Case History. SPE paper 119478 presented at the 2009 SPE Hydraulic Fracturing Technology Conference, The Woodlands, Texas, January 19-21.

Harold, J. 2009. Texas Water News: 81st Legislature Regular Session. Presented at The University of Texas at Austin for CRP 387C, Water Resources Planning. Austin, Texas, May 5.

Hays, T., interview by author, February 16, 2009.

Hays, T. and A. Arthur. 2004. Overview of Emerging Produced Water Treatment Technologies. Proceedings of the 11th Annual International Petroleum Environmental Conference. October 12-15.

Hutchinson, W. R., El Paso Water Utilities. Deep-Well Injection of Desalination Concentrate in El Paso, Texas. Southwest Hydrology, March/April 2008. 30. University of Arizona - SAHRA. http://www.swhydro.arizona.edu/archive/V7_N2/feature7.pdf [accessed July 12, 2009].

Hydrolink Water Treatment Equipment. http://www.hydrolink.com.pk/osmosis.html [accessed March 9, 2009].

IOGCC and ALL, 2006, "A Guide to Practical Management of Produced Water from Onshore Oil and Gas Operations in the United States," prepared for U.S. Department of Energy, National Energy Technology Laboratory, by the Interstate Oil and Gas Compact Commission and ALL Consulting, Oct. Available at http://www.all-llc.com/IOGCC/ProdWtr/ProjInfo.htm. [accessed July 12, 2009].

Jarvie, D. 2003. The Barnett Shale as a Model for Unconventional Shale Gas Exploration. Humble Geochemical Services.

Lee, M, 2007. Well Plan Injects Pressure Into Wastewater Dispute. Fort Worth Star-Telegram. November, 18, 2007. Metro, B1.

Montgomery, S.L., D.M. Jarvie, K.A. Bowker, and R. M. Pollastro. 2005. Mississippian Barnett Shale, Fort Worth Basin, North-Central Texas: Gas-Shale Play with Multi-Trillion Cubic Foot Potential. E&P Notes. AAPG Bulletin. V. 89, No. 2. February, 2005. 155-175.

Newalta. 2008. Oilfield and Municipal Water Recovery and Reuse in SE Alberta. Presented at APEGGA PD Seminar, Alberta, Cananda, April 17.

Oil Shale Gas. Barnett Shale Map of Texas. What is the Barnett Shale Area Formation? http://oilshalegas.com/barnettshale.html [accessed on August 9, 2009].

Perryman Group. 2008. Economic Impact Study. Presented at the Barnett Shale Expo, March 2008. http://www.barnettshaleexpo.com/docs/2008_Summary.pdf [accessed April 25, 2008].

Railroad Commission of Texas. Oil and Gas Division. Newark, East (Barnett Shale) Statistics. http://www.rrc.state.tx.us/data/fielddata/barnettshale.pdf [accessed March 7, 2009].

Reib, B., S. Allen and J. Hogan, BJ Services Co. 2009. The Benefits of Recycle-Produced Water for Fracs. E&P Magazine. March, 2009. 61-63.

Russell, D. Recycling of Water and Minimizing Fresh Water Usage. 2001. Presented at PTAC Forum on Shallow Gas, Calgary, Canada, June 21.

Senate Committee on Natural Resources. 2009. Interim Report to the 81st Legislature: Dam Safety, February 2009. Austin, Texas.

Senate Committee on Natural Resources. 2009. Interim Report to the 81st Legislature: Salinity of Surface Waters and Groundwaters in Texas, February 2009. Austin, Texas.

Texas Alliance of Groundwater Districts. Groundwater in Texas 2009. 2009.

Texas Comptroller of Public Accounts. Liquid Assets: The State of Texas' Water Resources. 2009.

Texas Water Code, 2007. Chapter 36.

Texas Water Development Board. Regional Water Planning Area Map – Region C. 2007. http://www.twdb.state.tx.us/mapping/maps/pdf/rwpg/letter_size/Region%20C%208x11.pdfTexas [accessed January 14, 2009].

Tronche, J.L. Water Recycling Debate Has Many Sides. Fort Worth Business Press. March 24, 2008. http://www.fwbusinesspress.com/display.php?id=7232 [accessed January 2, 2009].

Vacom. http://www.vacomllc.com/ [accessed March 9, 2009].

U.S. Department of Commerce. U.S. Census Bureau. 2008. Dallas-Fort Worth Leads Metro Areas in Numerical Growth Prepared by Robert Berstein and Public Information Office. Washington, D.C: Government Printing Office.

U.S. Department of Energy. Office of Fossil Energy and National Energy Technology Laboratories. 2009.Modern Shale Gas Development in the United States: A Primer. Prepared by Ground Water Protection Council and ALL Consulting under contract DE-FG26-04NT15455. Washington, D.C. April, 2009.

U.S. Department of the Interior. U.S. Geological Survey. 2008. 3 to 4.3 Billion Barrels of Technically Recoverable Oil Assessed in North Dakota and Montana's Bakken Formation—25 Times More Than 1995 Estimate—. USGS News Release. http://www.usgs.gov/newsroom/article.asp?ID=1911 [accessed June 29, 2009].

U.S. Department of the Interior. U.S. Geological Survey. 2004. Assessment of Undiscovered Oil and Gas Resources of the Bend Arch-Fort Worth Basin Province of North-Central Texas and Southwestern Oklahoma (2003). Fact Sheet 2004-3022. http://pubs.usgs.gov/fs/2004/3022/fs-2004-3022.htm [accessed January 16, 2009].

U.S. Department of the Interior. U.S. Geological Survey. 1995. 1995 National Assessment of United States Oil & Gas Resources: Overview of the 1995 National Assessment of Potential Additions to Technically Recoverable Resources of Oil and Gas—Onshore and State Waters of the United States. Prepared by U.S. Geological Survey National Oil and Gas Resource Assessment Team. U.S. Geological Survey circular 1118. Washington, DC: Government Printing Office.

Vertex Hydropore. What is Reverse Osmosis? http://www.reverseosmosis.com.au/reverse_osmosis_definition.htm [accessed January 21, 2009].

Waits, R., 212 Resources. Quoted in J.L. Tronche. 2008. Water Recycling Debate Has Many Sides. Fort Worth Business Press, March 24, 2008. http://www.fwbusinesspress.com/display.php?id=7232. [accessed January 21, 2009].

Warpinski, N. 2009. Microseismic Monitoring Emerges in Step with Rise of Unconventional Plays. The American Oil & Gas Reporter, January, 2009, 101.

Warpinski, N.R., R.C. Kramm, J.R. Heinze, and C.K. Waltman. 2005. Comparison of Single- and Dual-Array Microseismic Mapping Techniques in the Barnett Shale. SPE paper 95568 presented at the 2005 ATCD, Dallas, Texas, October 9-12.

Wright, C.A., L. Weijers, E.J. Davis, M. Mayerhofer, and Pinnacle Technologies, Inc. 1999. Understanding Hydraulic Fracture Growth: Tricky but Not Hopeless. SPE paper 56724 presented at 1999 Annual Technical Conference and Exhibition, Houston, Texas, October 3-6.

Vita

Jennifer Marie Secor Harold was born in Katy, Texas on June 30, 1982, the daughter of Maria DeRose Secor Gill and William Joseph Secor. After earning her diploma from Katy High School, Katy, Texas, in 2000, Ms. Harold entered The University of Houston-Downtown, Houston, Texas, where she received the degree of Bachelor of Science in 2006. Ms. Harold received the National Science Foundation Scholars Award for Math and Sciences in 2000. From 2003 to 2007, Ms. Harold was employed with Sterling Exploration and Production Co., LLC, an independent oil and gas firm in Houston, Texas. In August 2007, Ms. Harold entered the University of Texas at Austin to earn her master's degree in Energy and Earth Sciences from the Jackson School of Geosciences under the supervision of Dr. Charles G. Groat. Ms. Harold is currently employed with Brigham Oil and Gas, LP, in Austin, Texas, since 2007.

Permanent address: 12202 Tanglewild
Austin, TX 78758

This thesis was typed by the author.