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Hydraulic fracturing and water use in Dallas, Texas

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HYDRAULIC FRACTURING AND WATER USE IN DALLAS, TEXAS

A Thesis

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Abstract

Dallas, Texas is located in North Texas and sits above the eastern portion of the Barnett Shale natural gas formation. Hydraulic fracturing, or “fracking”, was introduced to the region as a means to access previously inaccessible natural gas within the formation. This fracking concerns many because it requires large amounts of fresh water, an average of over 4 million gallons per well within Dallas Water Utilities’ service area. This thesis examines whether water use for fracking will have a negative effect on the water supply for the city of Dallas and its wholesale water customer cities. The water is typically removed from the water cycle because chemical additives required for fracking are difficult to remove and the water is often disposed of underground. Methods of recycling and treating this water are being pursued but are not currently employed at a high rate in the Barnett Shale area. Water is of special concern in this region due to drought, increasing population, and the recent discovery of Zebra Mussels in the water supply. Texas is experiencing the worst drought other than the 1950s drought of record which is reducing the available water supply, through both evaporation and lack of recharge. The population in the area is also projected to nearly double by 2060 which will lead to increased water demand. Zebra Mussels have been found in Dallas’ supply system and these mussels are impossible to remove and can clog pipes, reducing the flow of water and so potentially reducing the available supply. Future water plans are prepared to address these issues, focusing on conservation as well as increasing available supplies. Based on this analysis, hydraulic fracturing in Dallas, Texas and within Dallas Water Utilities’ wholesale customers should not significantly affect Dallas’ water supply in the

near term. Other methods of conservation, such as limiting landscape watering, should be considered as more beneficial ways to save water.

Introduction

The combination of horizontal drilling with hydraulic fracturing, or “fracking,” has dramatically increased domestic oil production. With these techniques, operators can produce a form of natural gas known as “shale gas” because it has been trapped within shale formations below ground (EIA, 2013). In 2011 about 95% of the natural gas used in the United States was produced domestically (EIA, 2013) and accounted for roughly 25% of overall energy consumption (EIA2, 2013).

This growing energy independence and the associated boost to the economy are certainly some benefits of hydraulic fracturing; however there are drawbacks as well. As the name implies, hydraulic fracturing requires the use of water which is one of the concerns many have with its use, particularly in arid regions. The amount of water needed for fracking varies depending on the particular formation and even the particular location of the well within the formation (Jenkins, 2012). According to Mantell (2010), “Hydraulically fracturing a typical Chesapeake [Energy] deep shale natural gas well requires an average of 5 million gallons of water” with an additional 600-650,000 gallons used for drilling the well. This water use typically occurs one-time per well, it is very rare for a well to need to be hydraulically fractured beyond the initial job (Mantell, 2010). The water injected into the well is mixed with additives that require extensive treatment of any water that flows back to the surface and often removes it from the water cycle indefinitely, the water remaining in the well is also lost (Chesapeake, 2013; Jenkins, 2012).

The Barnett Shale, located beneath North Texas, is possibly the largest natural gas formation in the United States (RRC, 2013) and produces about 6% of the natural gas

produced in the continental United States (Rahm, 2011). A portion of the Barnett lies below Dallas County and Dallas Water Utilities' (DWU's) service area. Dallas lies on the eastern edge of the Barnett Shale and at this point not much drilling has occurred within Dallas County. However, Trinity East Energy, LLC, is requesting permission to drill in Dallas, and Chesapeake Energy has already fractured two wells in Dallas County since June, 2013 (FracFocus, 2013) with plans to fracture wells in Coppell, TX as well as perhaps other locations in Dallas County in the near future.

Due to the relatively insignificant amounts of groundwater below Dallas County most water used for fracking these wells will come through the local municipal supplier (Nicot and Scanlon, 2012). As Dallas and other cities within DWU's service area consider these permits the wisdom of this water use must be a leading factor in the decision. DWU has already allocated most current water supplies, with a projected reserve in 2010 of 601.52 million gallons per year after conservation strategies (TWDB, 2010).

Dallas is located in a region that is growing and the population within DWU's service area is projected to double by 2060 (City of Dallas, 2013). A growing population will require more water so DWU will have to both increase conservation measures and acquire more sources. The state of Texas is also in the midst of a severe drought comparable to or worse than the drought of record in the 1950s (Young, 2013). The drought has not been as severe near Dallas as in other regions of the state, but DWU's reservoir levels are still down and are subject to higher evaporation rates due to the increased heat thought to be caused by the drought (Nielson-Gammon, 2011; Young, 2013). DWU has also been dealing with the recent invasion of Zebra Mussels in some of

their reservoirs, which may reduce pumping capacity and thus reduce water availability (Cataldo, 2001; Scott, 2013).

Each of these factors must be carefully weighed as these permit applications are considered. Water must always be available for essential water uses, or those “required for the protection of public health, safety, and welfare” (Drought, 2010). However, techniques are available that could potentially allow reuse of water that flows back to the surface and so would reduce the amount of freshwater required to frack subsequent wells. From extraction to electricity production, natural gas requires less water than coal (Mantell, 2010). As these applications are examined, both present and future water conditions and water use should be considered. Other methods of conservation should also be considered and may ultimately save more water and be more beneficial than limiting fracking. This thesis will examine the effect of water use for hydraulic fracturing on the water supply of Dallas Water Utilities and its customer cities in the coming decades.

Geography

The city of Dallas is located within Dallas County (Figure 1) in the region commonly known as North Texas (Figure 2). North Texas consists of the sixteen counties (Collin, Dallas, Denton, Ellis, Erath, Hood, Hunt, Johnson, Kaufman, Navarro, Palo Pinto, Parker, Rockwall, Somerval, Tarrant, and Wise) which are members of the North Central Texas Council of Governments (NCTCOG, 2013).

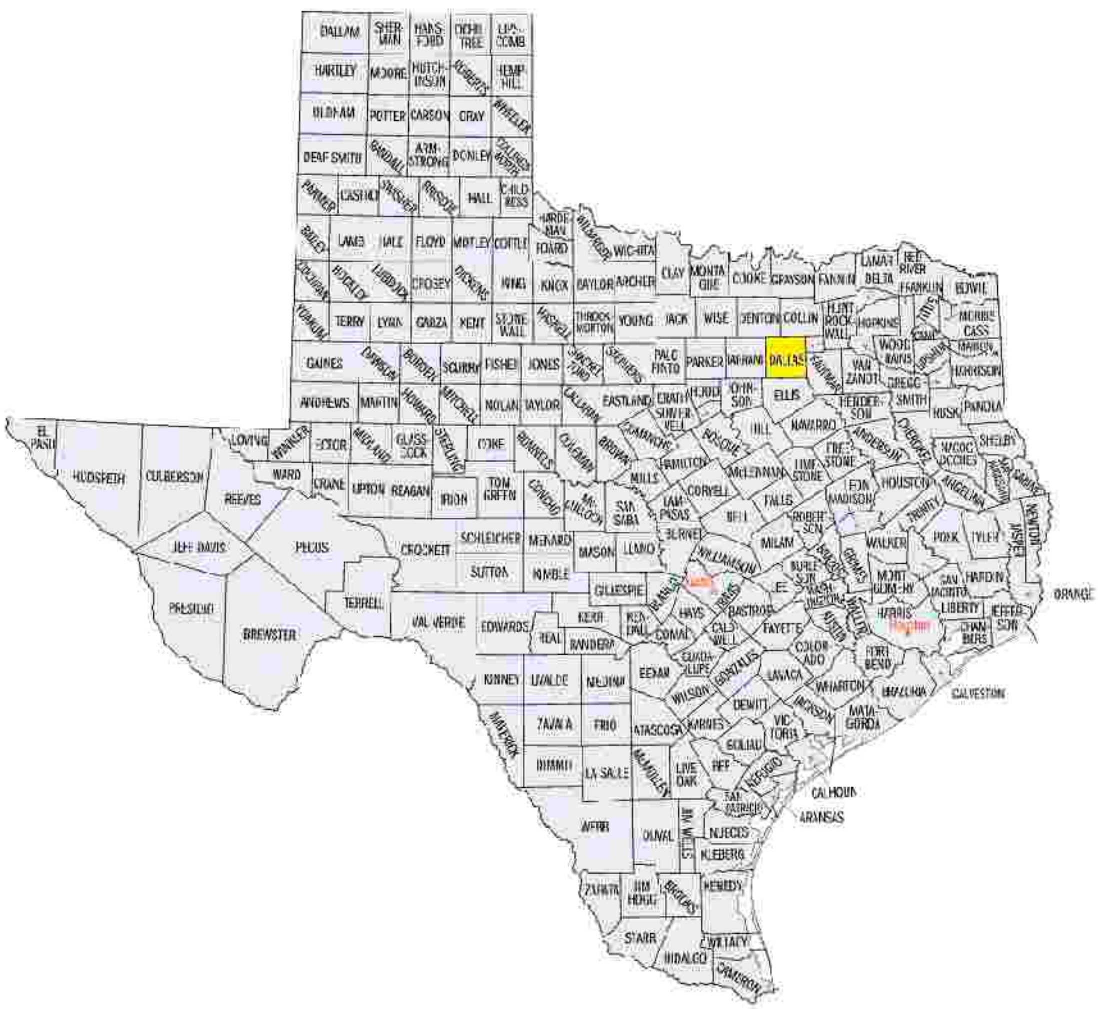

Figure 1 – Texas Counties (Adapted from USCB 2013)

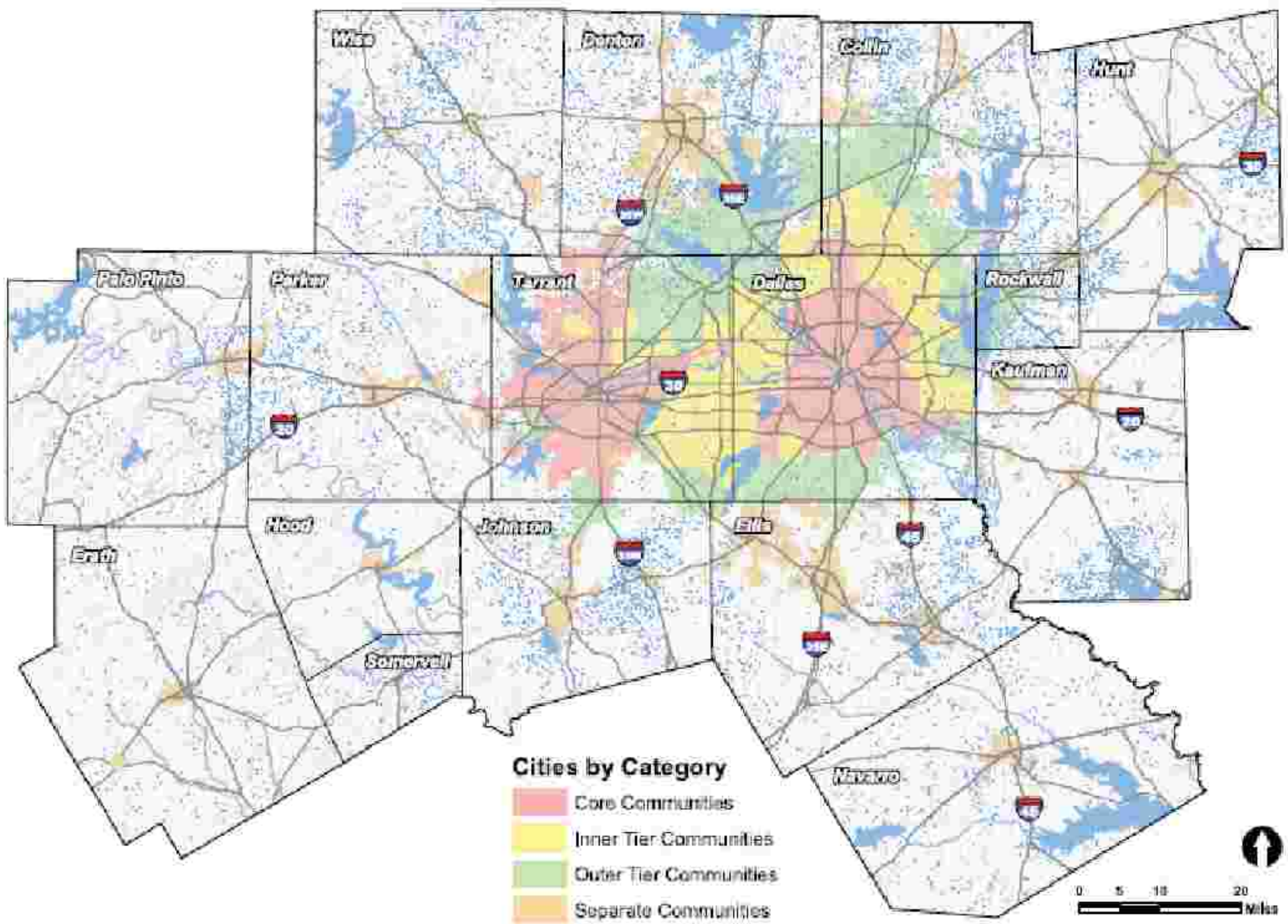

Figure 2 – North Texas Counties (VNT, 2013)

Dallas is also part of the Dallas-Fort Worth Metroplex, commonly referred to as DFW, which includes Dallas and Fort Worth as well as much of the surrounding area. DFW is a smaller sub region of North Texas and can be seen in Figure 2 as the highlighted “Core,” “Inner Tier,” and “Outer Tier” Communities.

All surface water in the state of Texas is owned by the state and users must acquire water rights. In the 1950s Dallas became a water supplier and has continued to add wholesale customers due to agreements made in obtaining Dallas’ water rights (Dallas, 2010). According to the DWU *Memorandum of Agreement with Wholesale Treated Water Customers* (2010), “Dallas has been granted extensive water rights by the State in return for its promise to serve as a defined area approved by Council and included in the State water plan which includes customer cities.”

Each contract lasts for a period of 30-years and all customers must enforce the water restrictions imposed when DWU deems them necessary due to water shortages (Dallas, 2010). Each contract also includes a Memorandum of Agreement which “spells out the rate-setting methodology for determining wholesale treated water rates for customer cities” and implements cost-sharing among Dallas and customer cities for new water resources and infrastructure (Dallas, 2010).

Dallas Water Utilities (DWU) is operated by the City of Dallas but also works with twenty three wholesale contracts (City of Dallas, 2006). Wholesale customers for treated water in 2011 were: Addison, Carrollton, Cedar Hill, Cockrell Hill, Combine WSC, The Colony, Coppell, Dallas County Water Control and Improvement District (WCID) #6, D/FW International Airport, DeSoto, Duncanville, Farmers Branch, Flower

Mound, Glenn Heights, Grand Prairie, Hutchins, Irving, Lancaster, Lewisville, Ovilla, Red Oak, and Seagoville with the addition of Dallas County Park Cities Municipal Utilities District (DCPCMUD) in 2012 (DWU, 2013). DWU also has a contract with Irving for water treatment services (City of Dallas, 2006).

DWU currently relies solely on surface water sources for its water supply. According to the Texas Commission for Environmental Quality (TCEQ) (2009), "[s]urface water in Texas is owned by the state and held in trust for citizens of the state. The state grants the right to use this water to different people, such as farmers or ranchers, as well as to cities, industries, business, and other public and private interests." The water rights granted to DWU were deemed acceptable for both the city of Dallas and DWU's wholesale customers (City of Dallas, 2006). At the present time the state has granted DWU water rights to: Lake Grapevine, Lake Lewisville, Lake Tawakoni, Lake Palestine, Lake Ray Hubbard, Lake Ray Roberts, and Lake Fork (City of Dallas, 2006). All of the lakes, except Lake Fork, are man-made and were built largely due to the City's planning (City of Dallas, 2006).

Lake Grapevine is located northwest of Dallas in both Denton and Tarrant counties and was the first of the reservoirs constructed when the Grapevine dam was completed in 1952 (U.S., 2007). Lake Lewisville lies to the north of Dallas in Denton County and was completed in 1955 as an expansion of what was originally Lake Dallas (City of Dallas, 2006). Lake Tawakoni, located far to the east, was constructed in 1964 (City of Dallas, 2006) in Hunt and Rains Counties bordering Van Zandt County. Lake Palestine was next constructed in Henderson County, far southeast of Dallas, and is not yet connected to DWU's supply (City of Dallas, 2006). Lake Ray Hubbard, the only lake

constructed even partially in Dallas County, to the east of the city, was built in 1973 and also extends into Collin and Rockwall Counties (City of Dallas, 2006). In 1981 Dallas acquired the rights to Lake Fork in Rains and Wood Counties, slightly further east than Lake Tawakoni, assuming the water rights of the Texas Utilities Generating Company (now TXU) (City of Dallas, 2006). Most recently, in 1989, Lake Ray Roberts was constructed to the far north in Cooke, Denton, and Grayson Counties (City of Dallas, 2006).

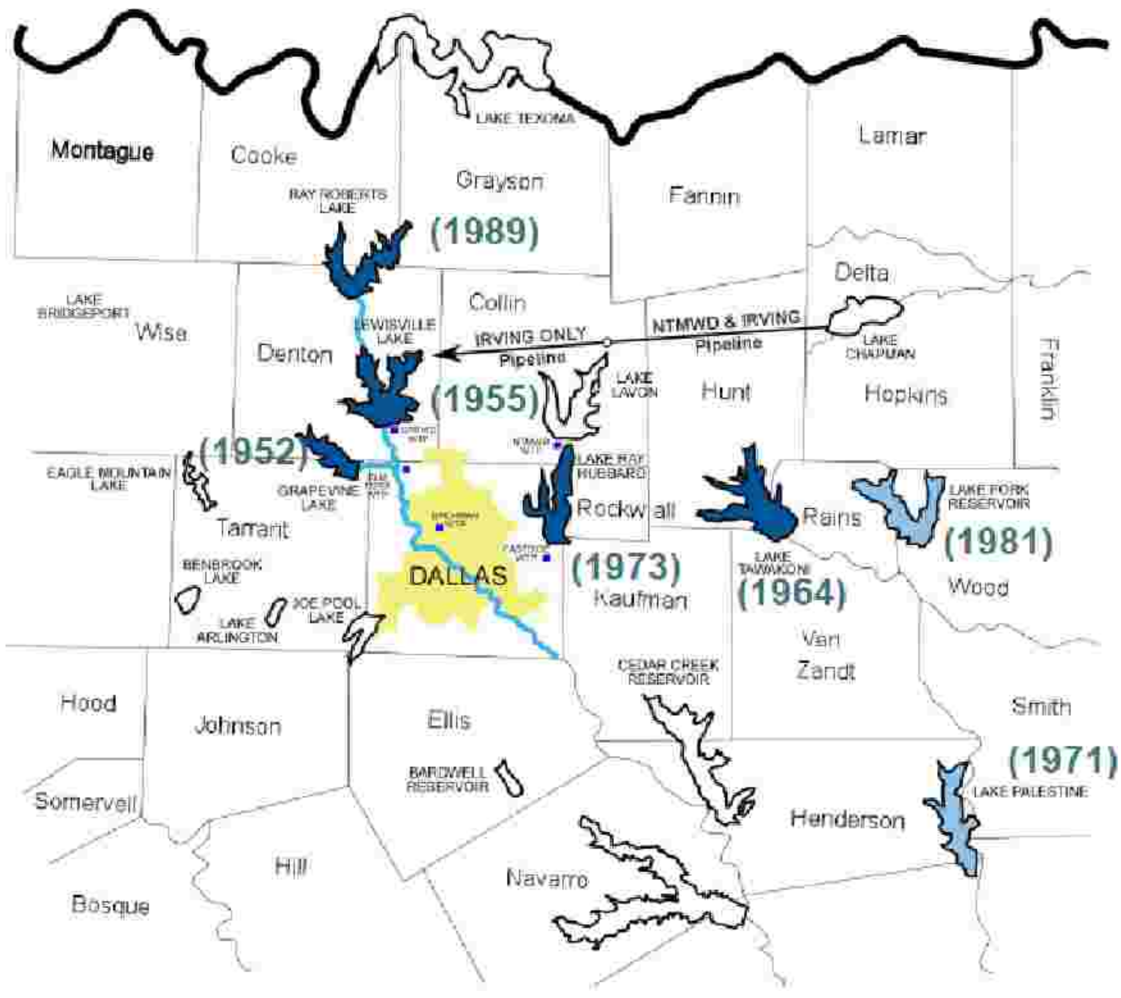

Figure 3 – Current DWU Water Supplies (City of Dallas, 2006)

Lakes Ray Roberts, Lewisville, Grapevine, and Ray Hubbard are the only reservoirs actually located within Texas Water Development Board's (TWDB) Region C (TWDB, 2010). All except Lake Ray Hubbard, which is owned by Dallas, are owned by the Corps of Engineers (TWDB, 2010). All four of the lakes are within the Trinity River basin and Lakes Ray Roberts, Lewisville, and Ray Hubbard are along the Elm Fork Trinity River Stream (TWDB, 2010). Lake Grapevine is located along Denton Creek (TWDB, 2010).

The water rights for Lake Ray Roberts and Lake Lewisville are shared between Dallas and Denton (TWDB, 2010). Lake Grapevine water rights were given to Dallas County Park Cities Municipal Utilities District – now a wholesale customer of DWU – along with Dallas and Grapevine (TWDB, 2010). Lake Ray Hubbard water rights belong to Dallas exclusively (TWDB, 2010). Lake Tawakoni and Lake Fork rights are shared with the North Texas Municipal Water District (NTMWD) (TWDB, 2010). The Sabine River Authority (SRA) has rights to Lake Tawakoni for local municipal users (Sabine, 1999). SRA also has water rights to Lake Fork, as well as an agreement to purchase the portion of DWU's contracted amount which cannot be transferred out of the Sabine Basin (Sabine, 1999).

Barnett Shale

The Barnett Shale is a natural gas formation that lies beneath North Texas. The formation has more than 5,000 square miles of surface area and is located about a mile and a half below ground (Barnett Shale, 2013). The Barnett Shale is beneath twenty four counties in Texas, including Dallas County along the far east side of the play. Parts of Denton and Tarrant Counties which are served by DWU lie above the formation as well. When

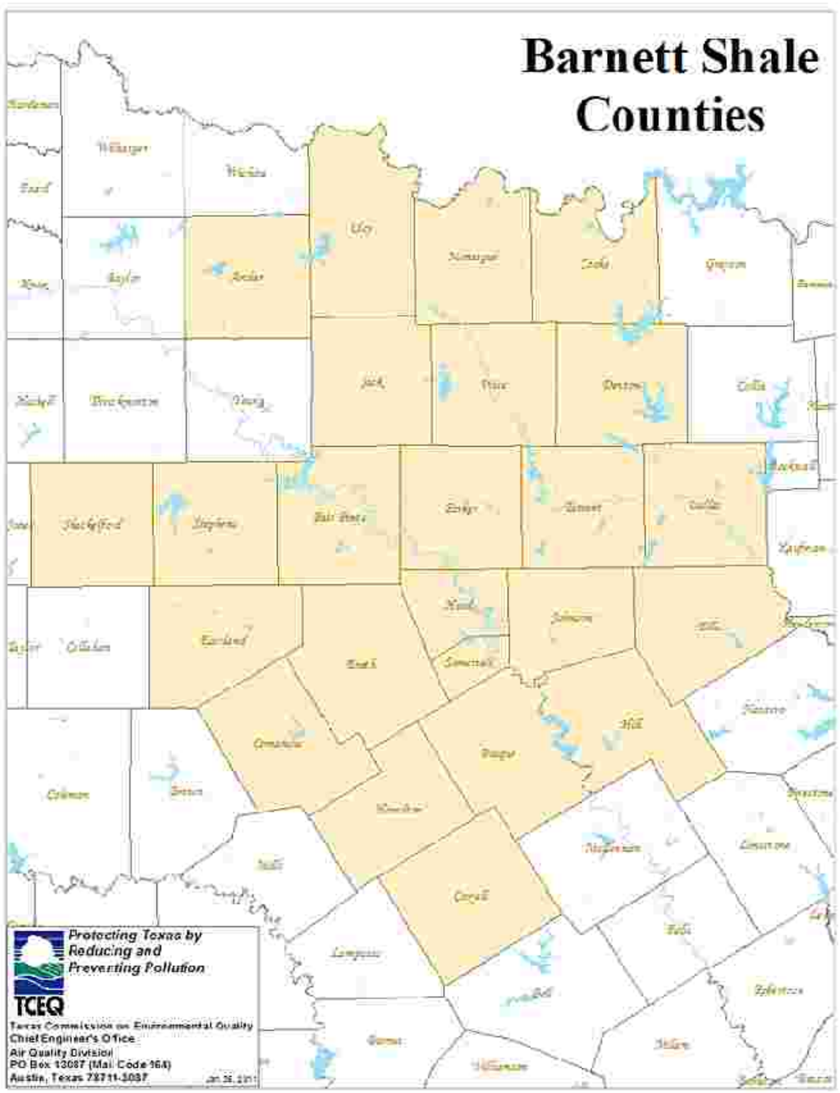

Figure 4 – Barnett Shale Counties (TCEQ, 2013)

vertical wells were the only available method of extracting natural gas, wells in the Barnett Shale were not productive enough to be economical or worth pursuing (Barnett Shale, 2013). In 2001, horizontal drilling was introduced to the area and, when paired with hydraulic fracturing, created a dramatic increase in the production of natural gas (Barnett Shale, 2013).

According to Lynn Helms (2013) “[h]orizontal drilling is the process of drilling a well from the surface to a subsurface location just above the target oil or gas reservoir called the ‘kickoff point’ then deviating the well bore from the vertical plane around a curve to intersect the reservoir at the ‘entry point’ with a near-horizontal inclination, and remaining within the reservoir until the desired bottom hole location is reached.” This technique is useful for the Barnett Shale not only because it increased productivity but because so much of the formation lies beneath urban areas where many people do not want drills. Horizontal drilling allows the well pad to be located in more remote areas while still enabling the producer to reach gas in otherwise inaccessible locations, such as beneath neighborhoods or downtown centers.

Horizontal drilling is paired with hydraulic fracturing to access the natural gas in the formation. According to the United States’ Office of Fossil Energy (DOE, 2013), “[h]ydraulic fracturing is a technique in which large volumes of water and sand, and small volumes of chemical additives are injected into low-permeability subsurface formations to increase oil or natural gas flow. The injection pressure of the pumped fluid creates fractures that enhance gas and fluid flow, and the sand or other coarse material holds the fractures open.” While much of the water does return to the surface eventually

the water is often not recoverable due to the chemicals added before injection and mixture with salt and other contaminants underground.

Fracking and Water Use

According to Chesapeake Energy, currently one of the largest producers in the Barnett Shale area, “hydraulically fracturing a typical Chesapeake Barnett horizontal deep shale gas well requires an average of 2.5 million gallons per well” (Chesapeake, 2012).

During 2011, thirty-nine wells were drilled within Dallas Water Utilities’ service area and one well was drilled in 2012 (FracFocus, 2013). The wells drilled and hydraulically fractured in 2011 used a total of 162,617,632 gallons of water, an average of 4,169,683 gallons of water per well, and the well drilled and hydraulically fractured in 2012 used 4,558,932 gallons of water. These numbers are higher than those that Chesapeake claims as their average in the area, but these numbers include wells drilled not only by Chesapeake but also Titan Operating, Williams Production Gulf Coast LP, WPX Energy, and XTO Energy. All of these numbers include only water used for hydraulically fracturing the wells, not the additional water required to drill the wells (FracFocus, 2013). According to Chesapeake drilling the well “requires between 65,000 and 600,000 gallons of water” (Chesapeake 2, 2012).

Chesapeake drilled and hydraulically fractured a total of seventeen wells within DWU’s service area in 2011. On average these wells used 4,321,765 gallons of water. The least amount of water was used in Barnes 3H, in Grand Prairie, Tarrant County, which required 2,382,408 gallons of water. The most water was used for UPRR 5H, also in Grand Prairie, Tarrant County, which required 6,444,900 gallons of water. All wells in

the DWU service area, aside from Barnes 3H, used over 3 million gallons of water, higher than what Chesapeake lists as their average water use in the Barnett Shale (refer to Table 1).

Williams Production Gulf Coast LP drilled six wells in DWU's service area in 2011. These wells averaged 5,115,596 gallons of water to hydraulically fracture. The least amount was used by Dr. Bob Smith C East #5H, in Flower Mound, Denton County, which used 4,132,967 gallons of water. Dr. Bob Smith C West 1H, also in Flower Mound, Denton County, used 5,982,220 gallons of water for the most water used in a well by Williams Prod. Gulf Coast LP (refer to Table 1).

Titan Operating drilled and hydraulically fractured five wells within DWU's service area in 2011 and drilled the only well within DWU's service area in 2012. On average Titan Operating's wells required 3,701,931 gallons of water per well. Prologis Northwest Unit 1H, in Lewisville, Denton County, used 2,331,546 gallons of water. Prologis Southeast Unit 1H, the only well drilled in 2012, also located in Lewisville, Denton County, used the most amount of water: 4,558,932 gallons of water (Refer to Table 1).

In 2011 XTO Energy drilled and hydraulically fractured four wells in DWU's service area with an average use of 2,734,970 gallons of water per well. Lowest use was in Joe Pool Gee Unit 5H: 2,186,960 gallons of water and highest use was Joe Pool Gee Unit 3H: 3,507,352 gallons of water. Both wells are located in Grand Prairie, Tarrant County (Refer to Table 1).

WPX Energy drilled and hydraulically fractured seven wells within DWU's service area in 2011 and used an average of 4,265,930 gallons of water per well. The lowest water use was at Ace Unit C12H, in Lewisville, Denton County: 3,484,256 gallons of water. Ace Unit B5H, also in Lewisville, Denton County, required the most water: 4,754,269 gallons (Refer to Table 1).

XTO Energy had the lowest average water use per well and even the well requiring the most water, 3,507,352 gallons, was not as high as the average water use for any of the other drilling operators in the area. Williams Production Gulf Coast LP had the highest average water use per well, a value surpassed only by four other individual wells in the area: Duke United 2H, Harvey 2H, Harvey 3H, and UPRR 5H, all drilled by Chesapeake in Grand Prairie, Tarrant County (Refer to Table 1).

In 2011 the city of Dallas used a total of 155,163,286,520 gallons of water: 4,883,065,594 gallons for industrial purposes, 1,073,922,252 for irrigation, and 149,206,298,674 gallons for municipal use (City of Dallas, 2013). DWU sent 47,691,471,000 gallons to their 22 wholesale customer contracts in 2011 (DWU, 2013). For 2011 DWU's total water expenditures were 202,854,757,520 gallons of water. The 162,617,632 gallons of water used in drilling and hydraulically fracturing natural gas wells in DWU's service region in 2011 comprised 0.0802% of overall water use by Dallas Water Utilities.

In 2012 the city of Dallas used a total of 153,276,628,284 gallons of water, slightly less than in 2011. In 2012 6,574,594,613 gallons of water were used for industrial purposes, 863,387,844 gallons for irrigation, and 148,838,645,827 gallons for municipal

Table 1 - Wells Permitted and Drilled in DWU Contract Cities (FracFocus, 2013)

City	**County**	**Lease**	**Operator**	**Frac Date**	**Water Use** (in gallons)
Flower Mound	Denton	Dr. Bob Smith B West 1H	Williams Prod. Gulf Coast LP	4/13/2011	5,562,467
Flower Mound	Denton	Dr. Bob Smith B West 3H	Williams Prod. Gulf Coast LP	4/12/2011	5,121,763
Flower Mound	Denton	Dr. Bob Smith B West 4H	Williams Prod. Gulf Coast LP	4/13/2011	5,014,673
Flower Mound	Denton	Dr. Bob Smith C East #5H	Williams Prod. Gulf Coast LP	1/10/2011	4,132,967
Flower Mound	Denton	Dr. Bob Smith C West 1H	Williams Prod. Gulf Coast LP	1/6/2011	5,982,220
Flower Mound	Denton	Hillard North #1H	Titan Operating	9/22/2011	4,431,345
Flower Mound	Denton	Hillard South #1H	Titan Operating	9/21/2011	4,517,775
Grand Prairie	Ellis	Atherton Murphy D 4H	Chesapeake	2/28/2011	4,700,766
Grand Prairie	Ellis	Atherton Murphy D 9H	Chesapeake	2/28/2011	3,619,266
Grand Prairie	Tarrant	Barnes 1H	Chesapeake	11/1/2011	3,782,772
Grand Prairie	Tarrant	Barnes 2H	Chesapeake	11/5/2011	3,765,006
Grand Prairie	Tarrant	Barnes 3H	Chesapeake	11/18/2011	2,382,408
Grand Prairie	Tarrant	Barnes 4H	Chesapeake	11/15/2011	3,156,594
Grand Prairie	Tarrant	Barnes 5H	Chesapeake	11/9/2011	4,488,918
Grand Prairie	Dallas	Barnes Assembly A 3H	Chesapeake	5/6/2011	3,716,286
Grand Prairie	Dallas	Childs Kelley A 3H	Chesapeake	9/19/2011	3,834,936
Grand Prairie	Tarrant	Duke United 1H	Chesapeake	11/28/2011	4,601,898
Grand Prairie	Tarrant	Duke United 2H	Chesapeake	11/29/2011	5,317,746
Grand Prairie	Tarrant	Harvey 2H	Chesapeake	10/24/2011	5,445,594
Grand Prairie	Tarrant	Harvey 3H	Chesapeake	10/25/2011	5,357,310
Grand Prairie	Tarrant	Harvey 4H	Chesapeake	10/25/2011	4,688,754
Grand Prairie	Tarrant	Harvey 5H	Chesapeake	8/22/2011	4,450,278
Grand Prairie	Tarrant	Joe Pool Gee Unit 2H	XTO Energy	11/17/2011	2,827,668
Grand Prairie	Tarrant	Joe Pool Gee Unit 3H	XTO Energy	12/1/2011	3,507,352

Table 1 continued – Wells Permitted and Drilled in DWU Contract Cities (FracFocus, 2013)

City	**County**	**Lease**	**Operator**	**Frac Date**	**Water Use** (in gallons)
Grand Prairie	Tarrant	Joe Pool Gee Unit 4H	XTO Energy	11/29/2011	2,417,901
Grand Prairie	Tarrant	Joe Pool Gee Unit 5H	XTO Energy	11/16/2011	2,186,960
Grand Prairie	Tarrant	UPRR 5H	Chesapeake	6/6/2011	6,444,900
Grand Prairie	Dallas	West Carpo 3H	Chesapeake	5/5/2011	3,716,580
Lewisville	Denton	Ace Unit B5H	WPX Energy	9/20/2011	4,754,269
Lewisville	Denton	Ace Unit C12H	WPX Energy	9/14/2011	3,484,256
Lewisville	Denton	Ace Unit D13H	Williams Prod. Gulf Coast LP	5/2/2011	4,879,488
Lewisville	Denton	Chen Unit A1H	WPX Energy	9/26/2011	4,644,528
Lewisville	Denton	Chen Unit A2H	WPX Energy	9/27/2011	4,740,149
Lewisville	Denton	Chen Unit B5H	WPX Energy	9/7/2011	4,038,260
Lewisville	Denton	Chen Unit B6H	WPX Energy	9/2/2011	3,682,586
Lewisville	Denton	Cobb Unit 1H	WPX Energy	8/22/2011	4,517,459
Lewisville	Denton	Prologis Northeast Unit 1H	Titan Operating	12/19/2011	4,102,938
Lewisville	Denton	Prologis Northwest Unit 1H	Titan Operating	12/11/2011	2,331,546
Lewisville	Denton	Prologis Southeast Unit 1H	Titan Operating	1/20/2012	4,558,932
Lewisville	Denton	Prologis Southwest Unit 1H	Titan Operating	12/11/2011	2,269,050

use (City of Dallas, 2013). DWU sent 47,411,767,000 gallons of water to 23 customer cities in 2012. DWU's total water expenditures in 2012 were 200,688,395,284 gallons of water. Only one well was drilled and hydraulically fractured within DWU's service area in 2012: Prologis Southeast Unit 1H in Lewisville, Denton County, which used 4,558,932 gallons of water, 0.0023% of DWU's total water expenditures in 2012.

While hydraulic fracturing comprises such a small percentage of total water use by DWU, it must be remembered that currently most water used in hydraulic fracturing is lost to the water cycle indefinitely while most other water used enters back into the system and is only temporarily appropriated. Frac Focus (2013) does not, however, differentiate between the use of recycled or produced water and fresh water in the water use totals, so the amount of water used in each well may be comprised partially of water already essentially removed from the water system by previous use in hydraulically fracturing another well. According to Nicot et al (2012), "[c]ollected information tends to suggest that the industry has been decreasing its fresh-water consumption despite the increase in water use.

Fracking requires millions of gallons of water per well which is essentially removed from the water cycle once used. However, the combustion of natural gas with oxygen creates carbon dioxide and water (Mantell, 2010):

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$$

It is estimated that "approximately 10,675 gallons of water vapor are produced with the combustion of one MMCF (million cubic feet) of natural gas" (Mantell, 2010).

According to Mantell's (2010) calculations, if a typical Chesapeake Energy well in the

Barnett play requires an average of 4,000,000 gallons of water, at the rate natural gas is produced it would take less than 6 months of natural gas production to return that amount of water to the effective hydrologic cycle. It's estimated that these wells will continue to produce gas for 20 years, without needing additional fracking, and will continue to produce water through combustion (Mantell, 2010).

Table 2 – Projected Water Demand for Dallas County Mining (Adapted from TWDB, 2010 Table 4F.59)

Values in Millions of gallons/year	**Projected Demand**					
	2010	**2020**	**2030**	**2040**	**2050**	**2060**
Projected Water Demand	971.04	990.59	987.33	987.33	987.33	987.33
Currently Available Water Supplies						
DWU Sources	89.28	74.29	70.71	66.47	61.26	54.09
Local Supplies	469.92	496.92	496.92	496.92	496.92	496.92
Trinity Aquifer	124.48	124.48	124.48	124.48	124.48	124.48
Woodbine Aquifer	105.25	105.25	105.25	105.25	105.25	105.25
Other Aquifer	167.16	167.16	167.16	167.16	167.16	167.16
Total Current Supplies	**983.09**	**968.10**	**964.52**	**960.28**	**955.07**	**947.90**
Need (Demand-Current Supply)	**0**	**22.48**	**22.81**	**27.05**	**32.26**	**39.43**
Water Management Strategies						
Additional Water from DWU	0	22.48	22.81	27.05	32.26	39.43
Supplemental Wells	0	0	0	0	0	0
Total Water Management Strategies	**0**	**22.48**	**22.81**	**27.05**	**32.26**	**39.43**
Reserve	**12.01**	**0**	**0**	**0**	**0**	**0**

Hydraulic fracturing is included in the Texas Water Development Board's mining category projections, which is actually projected to decline by 1% by 2060 (TWDB, 2011). However, "the mining category has been particularly difficult to analyze and project due to the isolated and dispersed nature of oil and gas facilities, the transient and temporary nature of water used, and the lack of reported data for the oil and gas industry" (TWDB, 2011). These projections are statewide, so actual mining use may be increased

in particular regions, such as the Barnett Shale, where hydraulic fracturing is present (TWDB, 2011). The projections also look forward to 2060. According to TWDB (2011), “the use of water for hydraulic fracturing operations is expected to increase significantly through 2020.” Hydraulic fracturing tends to use large amounts of water to initially drill and fracture the well, but does not require water past the initial fracturing (TWDB, 2011).

The 2011 Region C Water Plan projects that mining water use in the state will increase from 3,378.10 million gallons in 2006 to 13,529.35 million gallons in 2010, 12,695.50 million gallons in 2020, 13,565.19 million gallons in 2030, 14,495.83 million gallons in 2040, 15,456.76 million gallons in 2050, and 16,357.74 million gallons in 2060 (TWDB, 2010).

According to the TWDB (2010) mining use projections in Dallas County, roughly half of the water used would come from groundwater. Unlike surface water in Texas, which is owned by the state, groundwater rights generally belong to the landowner, though groundwater is also managed through groundwater conservation districts (GCDs) (Texas Water Code Section 36.002; TWDB, 2010). According to Nicot and Scanlon (2012), “groundwater withdrawal for oil and gas exploratory activities, including fracking, is exempt from GCD regulations under the State water code.” However, drilling operations would not be able to come into an area and usurp all of the ground water, they are still required to have drilling permits, etc. through the city where the well is located that likely factor in water use and how it would affect the area’s water supply.

In the Barnett Shale area it is estimated that only 11% of the water used in fracking operations is from groundwater, the remainder being municipal (Nicot and

Scanlon, 2012). This is not reflected in TWDB's (2010) projections, although these projections could signify a coming change as increasing populations demand increasing surface water resources.

Wastewater

The acquisition of natural gas from the Barnett Shale in Texas requires large amount of water for each well. Initially about 250,000 gallons of water is used to drill the well (Chesapeake, 2012), and then an average of about 4 million gallons of water (see "Fracking and Water Use") is used to hydraulically fracture, or "frack," the well. While water used for fracking in 2011 and 2012 combined within Dallas Water Utilities' (DWU) service area accounted for only approximately 0.04% of overall water use, water used in fracking is often removed from the water system indefinitely. The other uses of water (industrial, irrigation, municipal, and wholesale customer use) account for the majority of DWU's water expenditures, roughly 99.96%, but these uses only temporarily appropriate the water rather than removing it from the system.

When looking strictly at the percentage of water use accounted for hydraulic fracturing it does not appear to have a significant impact on DWU's water use and the continued use of such a small amount of water should not hinder DWU's future plans and supply needs. However, it must be considered that this water may not return to the system and over years the amount of water lost to the system could become significant. According to the Texas Water Development Board, water use for mining (mostly hydraulic fracturing in Dallas County) is expected to peak at 907.82 million gallons per year in 2020 and steadily decrease to an estimated 624.33 million gallons per year by 2060 (TWDB, 2013).

When a well is hydraulically fractured, the producer injects the well with a mixture of water and additives. According to Chesapeake Energy, water and sand (used as a proppant, maintains openness of fractures to promote gas escape) compose 99% of

the mixture while other additives compose the remaining 1% (Chesapeake, 2013). These other additives include: acid, an anti-bacterial agent, a breaker, a corrosion inhibitor, a friction reducer, a gelling agent, iron control, and scale inhibitor (Chesapeake, 2013). The acid "helps dissolve minerals and initiate cracks in the rock" (Chesapeake, 2013). The anti-bacterial agent "eliminates bacteria in the water that produce corrosive byproducts" (Chesapeake, 2013). The breaker additive delays the breakdown of the gel, it "reacts with the 'crosslinker' and 'gel' once in the formation making it easier for the fluid to flow to the borehole" (Chesapeake, 2013). Corrosion of the pipe by the injected water or produced water is prevented by the corrosion inhibitor which binds to metal surfaces (the pipe) (Chesapeake, 2013). The friction reducer "'slicks' the water to minimize friction" (Chesapeake, 2013). The gelling agent is used to "thicken the water in order to suspend the sand" and also "combines with the 'breaker' in the formation thus making it much easier for the fluid to flow to the borehole and return in produced water" (Chesapeake, 2013). The iron control agent "prevents precipitation of metal (in pipe)" (Chesapeake, 2013). Finally, the scale inhibitor "prevents scale deposits downhole and in surface equipment" (Chesapeake, 2013). Companies are not required to list each specific additive or its percentage in the mixture as these are considered "trade secrets" and protected under federal law.

Disposal

The aforementioned mixture is injected into the well from whence portions of it eventually return as "flowback". Typically, anywhere between 20 and 40% of the injected water returns as flowback, the remainder fills holes and cracks previously filled by the natural gas (Jenkins, 2012). The acid injected "reacts with minerals present in the formation to create salts, water, and carbon dioxide," so the acid is neutralized

(Chesapeake, 2013). The anti-bacterial agent is generally broken down by the micro-organisms that may be present, though a small amount may return in the flowback (Chesapeake, 2013). The breaker reacts with the “crosslinker” and gelling agent which “produces ammonia and sulfate salts” which are present in the flowback (Chesapeake, 2013). The corrosion inhibitor bonds to the pipes and the remainder is generally “broken down by micro-organisms and consumed” or is contained in the flowback (Chesapeake, 2013). The friction reducer also is frequently broken down and consumed by micro-organisms while a small amount still resurfaces in the flowback (Chesapeake, 2013). The gelling agent is involved in the reaction with the breaker and “crosslinker” and has the same products. The iron control “reacts with minerals in the formation to create simple salts, carbon dioxide and water” which are present in the flowback (Chesapeake, 2013). Most of the scale inhibitor is still present in the flowback, but some “reacts with microorganisms that break down and consume the product” (Chesapeake, 2013). Also contained in the flowback is water that may already have been present in the formation and so contains native minerals and possibly radioactive materials (Jenkins, 2012).

Traditional wastewater treatment by municipal facilities does not completely treat the water with all of these additives, so other methods must be used (Jenkins, 2012). Most frequently the water is not treated and is instead disposed of through underground injection using saltwater disposal wells (SWDs) (Chesapeake 2, 2013). According to Chesapeake Energy, “this process uses SWDs to return the water underground into porous rock formations similar to those from which it came. These formations are separated from treatable groundwater by thousands of feet of multiple layers of impermeable rock. SWDs are permitted under the Federal Safe Drinking Water Acts,

Underground Injection Control Program." This method of disposal permanently removes the water from the effective water cycle.

According to Chesapeake Energy (2012), "[w]ater used in Chesapeake Barnett deep shale gas well operations differs most notably from all other uses [municipal, irrigation, industry, power generation, and livestock] because it is temporary, occurring only once during the drilling and completion phases of each well. Use of this water does not represent a long-term commitment of the resource in the Barnett Shale geographic area." However, in 2010 Chesapeake Energy was only able to treat and reuse approximately 6% of total water needed (Mantell, 2010). The other 94% of the water needed does, then, represent a long-term commitment of this resource in the Barnett Shale as it is disposed of and removed from the water system.

Reuse

Texas has recently modified regulations on the industry to encourage reusing wastewater (Chesapeake 2, 2013). Currently available methods include reuse without treatment, processing through industrial water treatment facilities, the use of evaporation to separate wastes, filtering of the water and blending with fresh water for reuse, and chemical treatment along with distillation (Chesapeake 2, 2013). According to FracFocus.org, Class II injection wells and water recycling for reuse are the only methods currently being used to deal with flowback in the Barnett Shale (FracFocus, 2013).

Reuse would be an ideal method of dealing with wastewater as it would reduce the amount of fresh water that energy companies would continue to need to drill and fracture new wells. Reuse could form its own type of water cycle and as water is injected into one well, flows back, injected into another well, etc. Additional fresh water would

still be required as not all of the injected water returns to the surface (Jenkins, 2012). According to Mantell (2010), two factors are important in determining whether reuse of water in a particular well should be pursued: (1) quantity of produced water generated and (2) quality of produced water generated.

Quantity matters because wells that produce low amounts of flowback over long periods of time incur a greater economic cost as tanks and trucks must be kept ready to move the water for a longer period (Mantell, 2010). If a well is continuously producing water over a long period of time it economically limits the transport distance, a producer does not want to have to continue returning to a distant area to collect water (Mantell, 2010). Wells that produce large amounts of water quickly enable a quick turnover and may make it more feasible to collect and transport the water longer distances for use in another well (Mantell, 2010).

Quality is important as well in determining the availability of the water for reuse. When examining quality there are three things to look at: Total dissolved solids (TDS) (salinity), total suspended solids (TSS), and the presence of scale-causing compounds (hardness compounds) (Mantell, 2010). According to Mantell (2010), "TDS can be managed in the reuse process by blending with freshwater to reduce the TDS and TSS can be managed with relatively inexpensive filtration systems. Scale causing compounds can also be managed with chemical treatments, but note that each additional treatment step reduces the economic efficiency of the process. The ideal produced water for reuse has low TDS, low TSS, and little to no scale causing compounds." Scale causing compounds are an issue because they "readily form precipitates which rapidly block the

fractures in gas bearing formations required for economic gas production" (Kargbo et al., 2010)

These quality factors vary based on the particular formation being hydraulically fractured, and even at different locations of the same formation (Jenkins 2012). This makes it more difficult for companies to develop reuse treatment technologies and policies because methods must be specialized to the type of flowback found within each area (Jenkins 2012). Some regions may be better suited to reuse, such as those that produce water with low TDS, low TSS, and few scale causing compounds as well as those with a quick return of large quantities of flowback (Mantell, 2010).

In the Barnett Shale reuse is economically limited. Due to the high availability of SWDs near well sites the vast majority of the water is disposed of via underground injection (Mantell, 2010). This method of disposal is cheaper than developing methods of reuse as flowback from the Barnett Shale "generally has higher levels of TDS, low TSS, and moderate scaling tendency" (Mantell, 2010). Rather than blending with freshwater and performing chemical treatments it is cheaper for the operator to permanently dispose of the flowback.

Treatment Methods

Another method of dealing with flowback is processing through industrial water treatment facilities (Chesapeake 2, 2013). Several companies provide such services, often mobile so that they can move as the operator completes treatment at one drill site and moves to another. One such company is Halliburton which offers their CleanWave® Frac Flowback and Produced Water Treatment (Halliburton, 2013). According to Halliburton (2013):

> [T]he service features a mobile electrocoagulation component that uses electricity to treat flowback and produced water…The CleanWave system destabilizes and coagulates the suspended colloidal matter in water. When contaminated water passes through the electrocoagulation cells, the anodic process releases positively charged ions, which bind onto the negatively charged colloidal particles in water resulting in coagulation. At the same time: gas bubbles, produced at the cathode, attach to the coagulated material causing it to float to the surface where it is removed by a surface skimmer. Heavier coagulants sink to the bottom, leaving clear water, suitable for use in drilling and production operations.

The use of electrocoagulation does not require chemicals which reduces the cost to the operator and reduces the likelihood of environmental problems (Els and Cuba, 2013).

Another company offering industrial treatment options is Siemens which offers their FracTreat™ Mobile Produced Water Treatment System. “FracTreat systems include flotation, precipitation, [and] clarification” (Siemens, 2013). The flotation system floats “solids, oils, and other contaminates to the surface of liquids” where they are skimmed off (Siemens, 2013). The precipitation and clarification system combines several technologies commonly used in the oil field to remove metals and solids from the water (Siemens, 2013).

Ecosphere also offers onsite treatment of flowback to producers (Ecosphere, 2013). Ecosphere uses a patented Ozonix® Technology to treat water without using chemicals (Ecosphere, 2013). Ecosphere claims that their system will allow operators to recycle and reuse all of the water in their operations, significantly reducing the fresh water needed for new wells (Ecosphere, 2013). Ecosphere uses a “proprietary advanced oxidation process” to treat the water for bacteria, soluble organics, and hydrocarbons (Ecosphere, 2013). The Ozonix® system also reduces the amount of anti-bacterial agents needed as well as the level of friction reducers (Ecosphere, 2013).

There are many other companies that offer industrial wastewater treatment facilities to increase the amount of water available for reuse (Altela, 2013; GIW, 2013).

Oil companies may also place wastewater in evaporation ponds to separate the waste from the water (Boschee, 2012) as only the pure water would evaporate away, leaving the waste. This method does allow the water to return to the water cycle but then companies are left having to dispose of large quantities of dry waste (Kargbo et al., 2010), which may be toxic.

Some of these technologies now available to treat wastewater may be effective for flowback in the Barnett Shale, reducing the amount of fresh water needed to hydraulically fracture new wells.

In order to recycle produced water, in 2006 Chesapeake founded their Aqua Renew® program (Chesapeake 3, 2013). According to their website, the program was "founded under the concept of water recovery and reuse…utilizing state-of-the-art technology in an effort to recycle produced water" (Chesapeake 3, 2013). Chesapeake is seeking to expand the use of their AquaRenew® program within the Barnett Shale (Chesapeake 3, 2013). If this endeavor is successful it would reduce the amount of water permanently lost to the water cycle to Chesapeake wells in Dallas.

Trinity East was unable to be reached for comment on their proposed methods of reuse in the Barnett Shale, if any.

Electricity Generation

In Texas in 2010 36% of the state's electricity was produced in coal-fired power plants and 45% was produced in natural gas combined cycle plants (NGCCs) (Grubert et al., 2012). Water is used throughout the process of electricity generation, for both coal and natural gas. As discussed, harvesting natural gas requires the use of hydraulic fracturing which requires millions of gallons of water. Water is further used for cooling in over 90% of the NGCC in Texas while about 5% use air cooling (Grubert et al., 2012). Natural gas has low air emissions compared to coal in electricity production so water is not needed for any sort of pollution control system (Grubert et al., 2012).

Coal requires water for aquifer dewatering, or depressurization, which removes water from coal seams to allow for coal extraction (Grubert et al., 2012). Water used in coal extraction, unlike most water used in fracking, is not removed from the water cycle but "the water is generally extracted and discharged independent of potential beneficial use" (Grubert et al., 2012). Coal-produced electricity also uses water for cooling, about 60% of coal plants in Texas use once-through cooling while the rest use wet recirculation (Grubert et al., 2012). Once-through cooling uses water from a nearby source, runs it through the system to absorb excess heat, and then returns the water to the source, albeit at a higher temperature (UCS, 2013). Wet recirculation also draws water from a nearby source but then uses cooling towers to cool the water before recirculating it through the system (UCS, 2013). Additional water is only drawn to replace water lost through evaporation (UCS, 2013). Finally, coal-fired power plants require water for wet scrubbers to reduce SO_x emissions (Grubert et al., 2012). Carbon Capture Systems (CCS) are not yet utilized in Texas, but if required they would increase water use (Grubert et al., 2012).

Dry cooling systems are options for both coal-fired power plants and NGCCs, but financially they make more sense for NGCCs as “the amount of cooling necessary is much less per unit of electricity output in NGCC plants” (UCS 2, 2013). Dry cooling systems, as the name implies, do not use water (UCS, 2013). Instead, they use air to cool the steam exiting a turbine (UCS, 2013). This means that a dry cooling system in a NGCC can be much smaller than that required for a coal-fired power plant and so cost less (UCS 2, 2013).

Grubert et al. (2012) found that “Texas coal-fired power generation accounted for an estimated 90 billion gallons of freshwater consumption in 2007 from its full fuel cycle, including about 10 billion gallons from mine dewatering.” In comparison, to produce the same amount of electricity natural gas would require only 37 billion gallons of water, from extraction to cooling to emission control, only 40% of the water required for coal power (Grubert et al., 2012).

Water is saved easily in emission control as NGCCs do not require any water-utilizing pollution controls, whereas coal requires limestone scrubbers and may soon require CCSs in Texas (Grubert et al., 2012). In 2007, 5 billion gallons of water were used in sulfur control (Grubert et al., 2012). Carbon dioxide control, using current technologies, would require an estimated 86 billion gallons per year (Grubert et al., 2012). NGCCs also require less water for cooling as there is less waste heat (Grubert et al., 2012). In 2007 coal-fired plants used 75 billion gallons of water for cooling; a NGCC would need only 34 billion gallons of cooling water to produce the same amount of electricity (Grubert et al., 2012).

While the water use concern with natural gas lies in the amount of water used for extraction, coal actually requires even more water to extract enough coal to produce the same amount of electricity (Grubert et al., 2012). Coal extraction in Texas used about 11 billion gallons of freshwater in 2007 (Grubert et al., 2012). This number only includes water used to extract coal in Texas, not coal that was imported (Grubert et al., 2012). If the water used to extract the imported coal is also included, these numbers would be greatly increased. For example, in 2005 Texas imported 56.6% of its coal from out of state (Combs, 2013). To replace "both Texas-extracted and imported coal with Texas natural gas would require an estimated 3.2 billion gallons of freshwater consumption for natural gas extraction," according to Grubert et al. (2012), nearly 8 billion gallons of water less than just the coal produced in Texas.

Approximately 1,028 British thermal units (BTUs) are contained within one cubic foot of dry natural gas (Mantell, 2010). In the Barnett Shale, assuming an average of 4 million gallons of water per well and an estimated average production of 3 billion cubic feet of natural gas, water use is estimated to be 1.3 gal/mmbtu (Mantell, 2010). This number does not include, however, any water used at the NGCC plant.

Per one million British thermal units (mmbtu), coal requires 16.1 gallons of water while natural gas uses 3.0 gallons (Grubert et al., 2012). This 3.0 gal/mmbtu of natural gas includes indirect water use for additives in the fracking fluid (Grubert et al., 2012). On average coal uses 0.071 gallons per kilowatt-hour (kWh) of electricity compared to an average 0.022 gal kWh^{-1} used by natural gas (Grubert et al., 2012). For one mmbtu natural gas requires only 18% of the water that coal does, and natural gas requires 30% of the water that coal does to produce a kWh of electricity. As water reuse increases and

perhaps new technology requires less water for fracking, these estimates could decrease even further (Grubert et al., 2012).

Overall, Grubert et al. (2012) found that “lignite extraction is over three times as water intensive as the most water-intensive shale gas expected in Texas, primarily because of the need to dewater mines.” Coal extraction in Texas is more water intensive than most coal extraction in the US, but natural gas extraction is still more efficient overall (Grubert et al., 2012). As mentioned before, coal extraction for Texas-produced coal alone requires 11 billion gallons of water annually, and only about 43% of the coal used (in 2006) was produced in state. Natural gas extraction to produce the same amount of electricity as all of the coal used in Texas (both imported and locally produced) would require only 3.7 billion gallons of water (Grubert et al., 2012).

While the water use benefits of natural gas as compared to coal may seem obvious, the economics of coal extraction, transport, and use versus those of natural gas should also be considered though an analysis on this subject is outside the scope of the current project.

Drought

Texas seems to be in an almost constant state of drought, saved only by interspersed wetter years (Nielson-Gammon, 2011) which serve to partially refill reservoirs and refresh the water supply. As such, water planning is of major importance in the state. The water is not consistently renewed so reservoirs and available supplies must be carefully monitored and regulated to ensure that there is always enough water present for public health and safety.

The current Texas drought began in October 2010 (Nielson-Gammon, 2011) and according to the National Weather Service Forecast (NWS, June 5, 2013) still continued as the state enters summer 2013. The first year of the drought, from October 2010 to September 2011, is the driest year on record for much of Texas since statewide record keeping began in 1895 (Nielson-Gammon, 2011). Since September 2011 rainfall has remained below average so that in October 2013 Texas will have experienced three years of drought. Current projections indicate the likelihood of an autumn in Dallas with rainfall slightly above normal, but likely not enough to erase the effects of such a severe drought (NWS, August 4, 2013).

The worst drought on record in Texas occurred in the 1950s (Nielson-Gammon, 2011), specifically 1951-1957 (City of Dallas, 2006) and the same conditions that allowed that drought are present now. Texas weather is affected by several global climate patterns, including La Niña/El Niño, the Pacific Decadal Oscillation (PDO), and Atlantic Multidecadal Oscillation (AMO) (Nielson-Gammon, 2011).

Ocean Current Patterns

When sea-surface temperatures are below normal in the central and eastern tropical Pacific Ocean it is referred to as La Niña (NOAA, 2013). El Niño is the opposite, when sea-surface temperatures are warmer than normal (NOAA, 2013). The warm temperatures associated with El Niño typically lead to wetter-than-normal conditions in Texas, whereas La Niña patterns are tied to drier conditions (Nielson-Gammon, 2011). 2010-2011 was a very intense La Niña, while 2011-2012 was not quite as cool (Nielson-Gammon, 2011). This led to the very severe drought in 2011, and while the 2012 drought conditions may not have been as extreme they exacerbated the conditions so that Texas was unable to recover during the 2012 year. Currently conditions in the Pacific are considered El Niño/Southern Oscillation (ENSO) neutral, though some climatologists forecast slight La Niña conditions (El Niño, 2013). Again, this will not lead to a drought as severe as that of 2011 but it will not provide the wetter conditions needed to fully recharge reservoirs and the water supply.

Texas climate is also affected by the PDO (Nielson-Gammon, 2011) which is similar to El Niño patterns except that its oscillations last longer and are less variable – PDO events have been demonstrated to persist for 20-30 years (Mantua, 1999). Also differing from El Niño, PDO patterns seem to primarily affect North Pacific/North American weather patterns rather than the tropics (Mantua, 1999). Since 1998, the present PDO has been in a position that leads to drier weather in Texas (Nielson-Gammon, 2011).

Lastly, the AMO also plays a role in Texas climate patterns. The AMO has longer lasting phases similar to the PDO (AMO, 2013). The AMO concerns temperature changes in a large part of the Atlantic, between the equator and Greenland (AMO, 2013).

Since about 1995 the AMO has been in a warm phase which tends to create dry conditions in Texas (Nielson-Gammon, 2011).

The last recorded time when both the AMO and PDO had conditions leading to dry weather in Texas was between the mid-1940s to the early 1960s, when the drought of record occurred as well as another more minor drought in the 1960s (Nielson-Gammon, 2011). The AMO and PDO are difficult to forecast and it is unknown how long these drought-favorable conditions will last for Texas, with estimates ranging from three to fifteen more years (Nielson-Gammon, 2011).

Reservoir Levels

Even during the peak of the drought (approximately September-early October 2011) Dallas was one of the areas least impacted (See Figure 5) but water resources were still effected. Reservoir levels continue to decline at present (NWS, June 5, 2013) and in 2011with increased heat during the year water supplies experienced increased evaporation (Nielson-Gammon, 2011). Drought tends to lead to increased temperatures in Texas as the soil dries out and the sun heats the ground and nearby air (Nielson-Gammon, 2011). The summer of 2011 set records as one of the warmest summers ever recorded (Nielson-Gammon, 2011). As Dallas Water Utilities (DWU) currently relies solely on surface water evaporation of water supplies is a concern (City of Dallas, 2006). While reservoir levels continue to decline and not be replenished, DWU must carefully plan water use to ensure that there is enough water for necessary functions.

Though the area surrounding Dallas may not have been as severely affected as the rest of Texas, east Texas has been severely affected (Nielson-Gammon, 2011). Drought levels are most often measured using the Standardized Precipitation Index (SPI) (Table 3). “The SPI takes a particular value of accumulated precipitation (such as precipitation

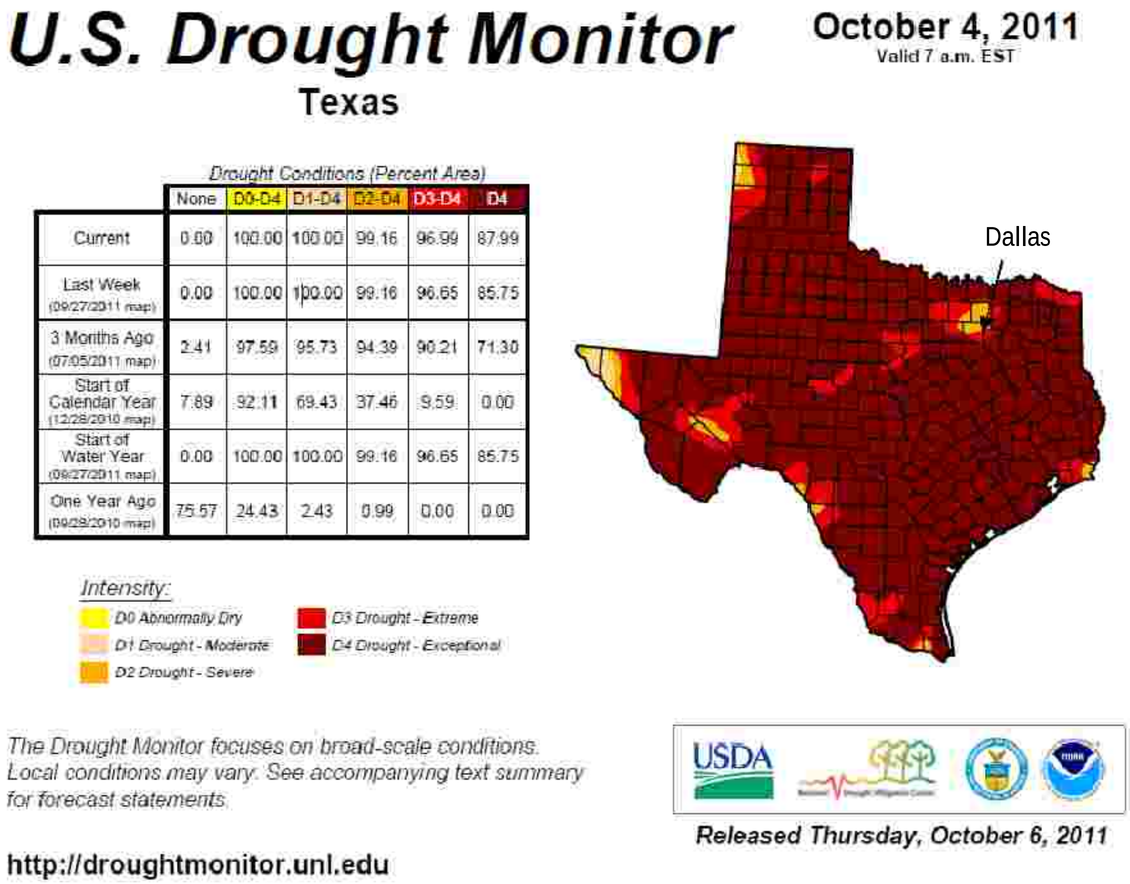

Figure 5 – Dallas drought conditions October 4, 2011 (USDM)

over the past six months) at a given location and rescales it based on the historical record of precipitation variability at that location." (Nielson-Gammon, 2011). Negative values indicate drier conditions than would be expected when examining the historical values (Nielson-Gammon, 2011).

Table 3 – SPI Index (Nielson-Gammon, 2011)

SPI Range	Expected Frequency	Designation
0.5 to -0.5	About 40% of the time	Near Normal
-0.5 to -0.7	About 10% of the time	Abnormally dry
-0.8 to -1.2	About 10% of the time	Moderate drought
-1.3 to -1.5	About 5% of the time	Severe drought
-1.6 to -1.9	About 3% of the time	Extreme drought
-2.0 to -2.5	About 1.5% of the time	Exceptional drought
Below -2.5	About 0.5% of the time	Exceptional drought

In October 2011, twelve counties in East Texas had a 24 month SPI of less than -2.5, and one county was below -3.0 (Nielson-Gammon, 2011). East Texas generally experiences higher rainfall than the rest of the state so Dallas has planned most future reservoirs in East Texas (City of Dallas, 2006).

Another method of measuring drought is the Palmer Drought Severity Index (PDSI) (Nielson-Gammon, 2011). “The PDSI attempts to assess the relative amount of water available in the soil, based upon precipitation, an estimate of evaporation based on temperature, and information regarding soil type.” (Nielson-Gammon, 2011). A PDSI value below -2 is considered drought and below -4 indicates extreme drought (Nielson-Gammon, 2011). Texas is divided into ten climate divisions, and the National Climatic Data Center calculates a PDSI value for each division (Nielson-Gammon, 2011). Dallas is part of the third climatic division, North Central Texas, which in 2010-2011 had a minimum PDSI of -5.37, with three months below a PDSI of -4 and seven months of a PDSI below -2 (Nielson-Gammon, 2011).

Drought Contingency Plan

Dallas Water Utilities adapted their most recent Drought Contingency Plan on June 9, 2010, a few short months before the current drought began (Drought, 2010). The plan applies to all DWU customers, wholesale and otherwise and defines non-essential water use as “water uses that are not essential or required for the protection of public health, safety, and welfare” (Drought, 2010). In developing this plan the city used a model examining water levels under the conditions of the drought in the 1950s (Drought, 2010). The Drought Contingency Plan is to be updated every five years (Drought, 2010).

Stage 1 drought contingency measures may be declared when less than 65% of the total raw water supply is available. Stage 1 includes some voluntary measures for customers to reduce water use as well as mandatory restrictions. The goal of Stage 1 is to reduce water use by 5% in total gallons per capita per day (GPCD). Stage 1 restrictions focus on mandatory reductions in

landscape watering and other non-essential uses such as washing cars, filling fountains and pools, etc. Commercial customers are also encouraged to voluntarily reduce water use. Wholesale customers are encouraged to implement similar measures of reduced water use when DWU declares a Stage 1 drought. (Drought, 2010)

The city manager may declare Stage 2 measures in effect when less than 55% of the total raw water supply is available. Similar to Stage 1, Stage 2 includes both voluntary measures and mandatory restrictions. Stage 2 aims to reduce water use by 15% GPCD. Stage 2 restrictions are similar to those in Stage 1 primarily including increased restrictions on the same activities. Wholesale customers are again encouraged to implement similar measures. (Drought, 2010)

Stage 3 measures are declared when the available raw water supply drops to below 45%. Stage 3 no longer includes voluntary measures as a means of control, but instead there are several mandatory restrictions to reduce water use. Stage 3 aims to reduce water use by 20% GPCD. Stage 3 measures further restrict activities mentioned above, banning some as well as providing a specific schedule of when others may occur. (Drought, 2010)

Table 4 – Dallas Drought Stages and associated restrictions by Dallas Water Utilities (Drought, 2010)

	Percent Available	Reduction Goal	Reduction Measures
Stage 1	<65%	5%	Voluntary: • Reduce watering of new landscaping • Reduce filling of ornamental fountains • Reduce frequency of washing vehicles • Reduce draining and filling of swimming pools • Reduce recreational use of watering implements • Public education campaigns • Increase leak detection efforts • Perform water use audits of high-volume customers Mandatory: • Maximum 2-days-per-week landscape watering within designated hours
Stage 2	<55%	15%	Voluntary: • Encourage further reduction of filling swimming pools • Increase use of education campaigns • Continue leak detection Mandatory: • Maximum one-day-per week landscape watering within designated hours • Ban refill of ornamental fountains, city fountains no longer operated • Ban recreational water use of watering implements • Vehicle washing restricted to hand-held bucket or hose with shutoff nozzle except at commercial car wash stations • Ban on rinsing impervious surfaces (buildings, windows, etc.) • New mains may not be flushed unless required for service

Table 4 Continued – Dallas Drought Stages and associated restrictions by Dallas Water Utilities (Drought, 2010)

	Percent Available	Reduction Goal	Reduction Measures
Stage 3	<45%	20%	Voluntary: • None Mandatory: • Maximum one-day-per-week landscape watering, all types of sprinklers banned at all times • Vehicle washing prohibited except at commercial car washes during restricted hours • Filling of pools banned • No new permits issued for swimming pools or ornamental ponds or fountains • Restricted hours of foundation watering • Ornamental fountain use banned • 10% rate increase for high volume users • Wet street sweeping and washing of city vehicles banned
Stage 4	<30%	25%	Voluntary: • None Mandatory: • No landscape watering • No vehicle washing • Continued restriction of foundation watering hours

The final stage, Stage 4, is declared when less than 30% of the total raw water supply is available. Stage 4 also includes only mandatory restrictions to reduce water use. Stage 4 restrictions are designed to reduce water use by 25% GPCD. Stage 4 prohibits most uses of water that are not essential to public health, safety, and welfare. (Drought, 2010) Stages 2, 3, and 4 allow for DWU to increase water rates for retail customers in an attempt to lessen water use (Drought, 2010).

Climate Change

Climate change is a complicated issue and a full discussion and study of its possible impacts on DWU's water supply is outside the scope of this thesis. However, as study on climate change continues it is apparent that its possible effects in the region need to be considered. According to an article in the Dallas Morning News, temperatures in Dallas will be consistently warmer than the average in the area between 1860 and 2005 by 2063 (NYT, 2013). As discussed, increased temperatures increase evaporation which would have an effect on DWU's surface water supplies. The EPA website also lists more frequent droughts in the Great Plains region, which includes most of North Texas, as a likely result of climate change (EPA, 2013). As with the current drought these droughts would reduce the recharge rate for reservoirs and would negatively affect the available water supply.

Increased precipitation would perhaps be enough to offset the predicted increased evaporation, while decreased precipitation would certainly exacerbate the problem and further stress the water supply. All models evaluated by Kim et al (2013) project a decrease in precipitation over North Texas due to climate change, however the reference data provided by Climatic Research Unit surface analysis indicates an increase in East Texas that would offset this decrease with DWU's reservoirs located to the East. The models results were all variable and slightly different from each other, Kim et al (2013) found that each had some sort of bias in predicting changes in precipitation. Until models improve it is difficult to truly evaluate the extent of the effects climate change will have on the region. Due to these results and their uncertainty this thesis focuses on the more

immediate and well studied impacts such as the current drought, population changes, and invasive species.

In addition, climate change is tied to increased greenhouse gases, particularly carbon dioxide, in the atmosphere (Metz, 2007). Just as natural gas requires less water than coal to produce the same amount of electricity, it also releases less carbon dioxide (EPA (2), 2013). Producing more natural gas to provide electricity in our region could then reduce the carbon footprint and perhaps impact the speed of climate change.

Population

Dallas is considered a part of North Texas, which is expected to continue to grow and put greater strain on available water supplies. As the country has suffered from a slowing economy the economy in North Texas has remained strong, encouraging people not only to stay but also to move to the area. While the economy continues to do well this migration is likely to continue.

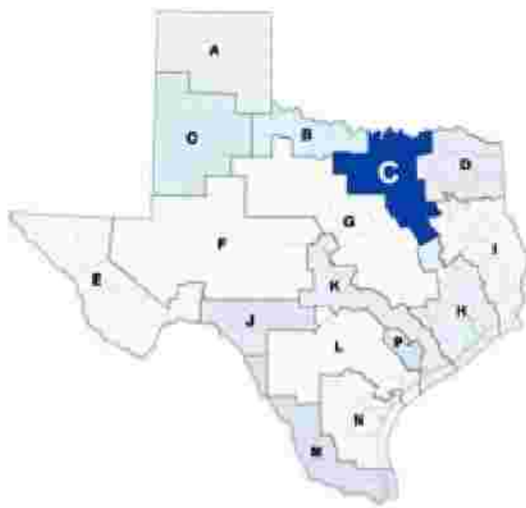

Figure 6 – Region C Planning Area (TWDB 2, 2013)

According to the Texas Water Development Board (TWDB, 2011), “[t]he population in Texas is expected to increase 82 percent between the years 2010 and 2060, growing from 25.4 to 46.3 million people.” The Texas Water Development Board (TWDB) has divided the state of Texas into sixteen regional water planning areas, each with their own water planning group of about twenty members (TWDB, 2013). DWU and Dallas County are included in Region C (Figures 6, 7), along with Collin, Cooke, Denton, Ellis, Freestone, Fannin, Grayson, Jack, Kaufman, Navarro, Parker, Rockwall,

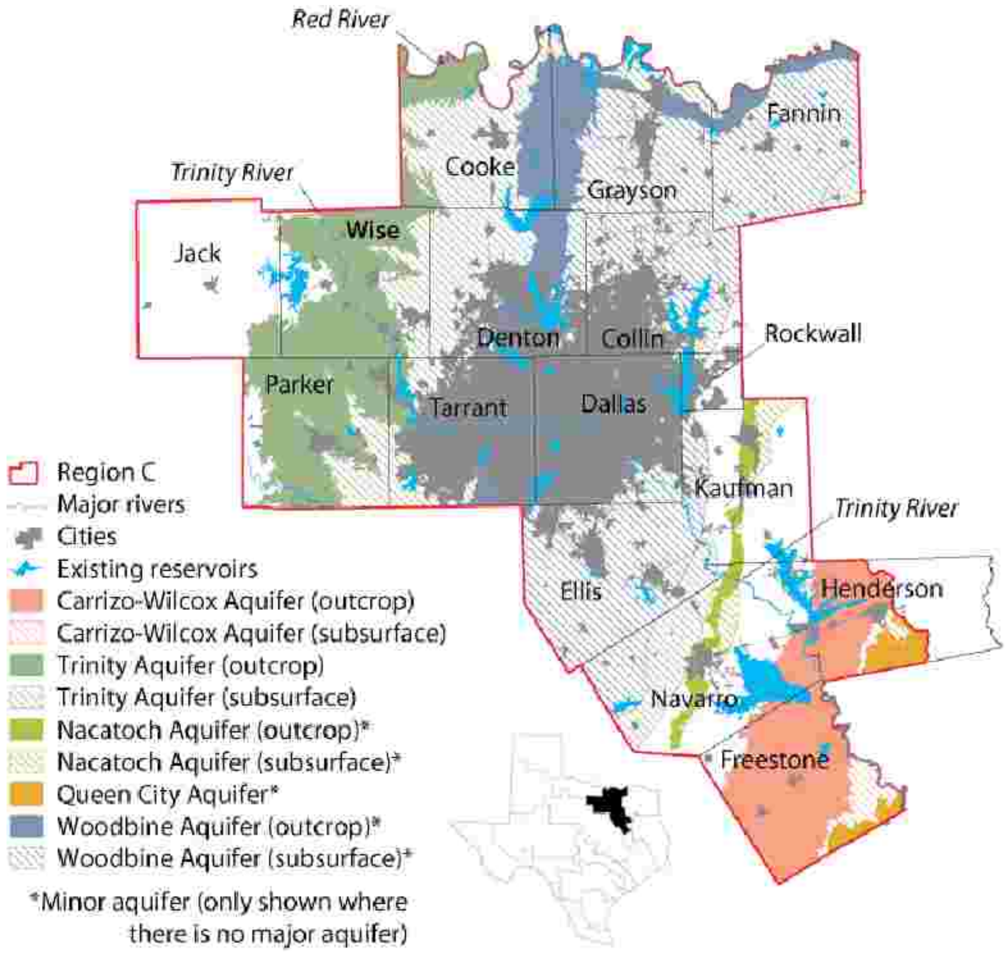

Figure 7 – TWDB Region C Counties (Combs 2, 2013)

Tarrant, and Wise Counties and the Trinity River Basin portion of Henderson County (Combs 2, 2013).

The expected population increase of Region C is 96% (TWDB, 2011). Only Planning Regions K (100%) and M (142%) exceed Region C in growth expectations (TWDB, 2011). The TWDB projects water demand for municipal, manufacturing, mining, steam-electric, livestock, and irrigation use; all projections are developed from water use during “dry years” (TWDB, 2011).

Overall municipal use is expected to increase as the population increases, though per capita use should decrease "due to the installation of water-efficient plumbing fixtures (shower heads, toilets, and faucets) as required in the Texas Water Saving Performance Standards for Plumbing Fixtures Act of 1991. These fixtures are assumed to be installed as older ones require replacement." (TWDB, 2011).

According to Table 5 per capita use (including all categories of use) is expected to increase for all 6 of the largest 40 cities in Texas that are included in Dallas Water Utilities' Service Area (TWDB, 2011).

Table 5 – Per Capita Water Use of Large Cities in North Texas (gallons per capita per day) (Adapted from TWDB, 2011 Table 3.4)

City	2008 Per Capita Use	2008 Residential Per Capita Use	2020 Per Capita Use	2040 Per Capita Use	2060 Per Capita Use
Dallas	213	95	252	247	246
Irving	193	104	249	246	246
Carrollton	162	102	188	184	183
Grand Prairie	152	89	152	148	148
Denton	150	60	179	176	176
Lewisville	143	75	173	171	170

Just over 96% of Dallas' water use in 2011 was for municipal use, decreasing only slightly to 95% in 2012 (Dallas Water Use, 2013). In 2011 municipal use was 149,206,298,674 gallons of water, and in 2012 the amount decreased to 145,838,645,827 gallons (Dallas Water Use, 2013). The 2010 population of the city of Dallas was 1,197,833 people and the estimated population in 2012 is 1,241,162 people (USCB, 2013). Even as population increased, municipal use slightly decreased possibly due to

conservation measures, but compared to expected population increases this population increase is minor.

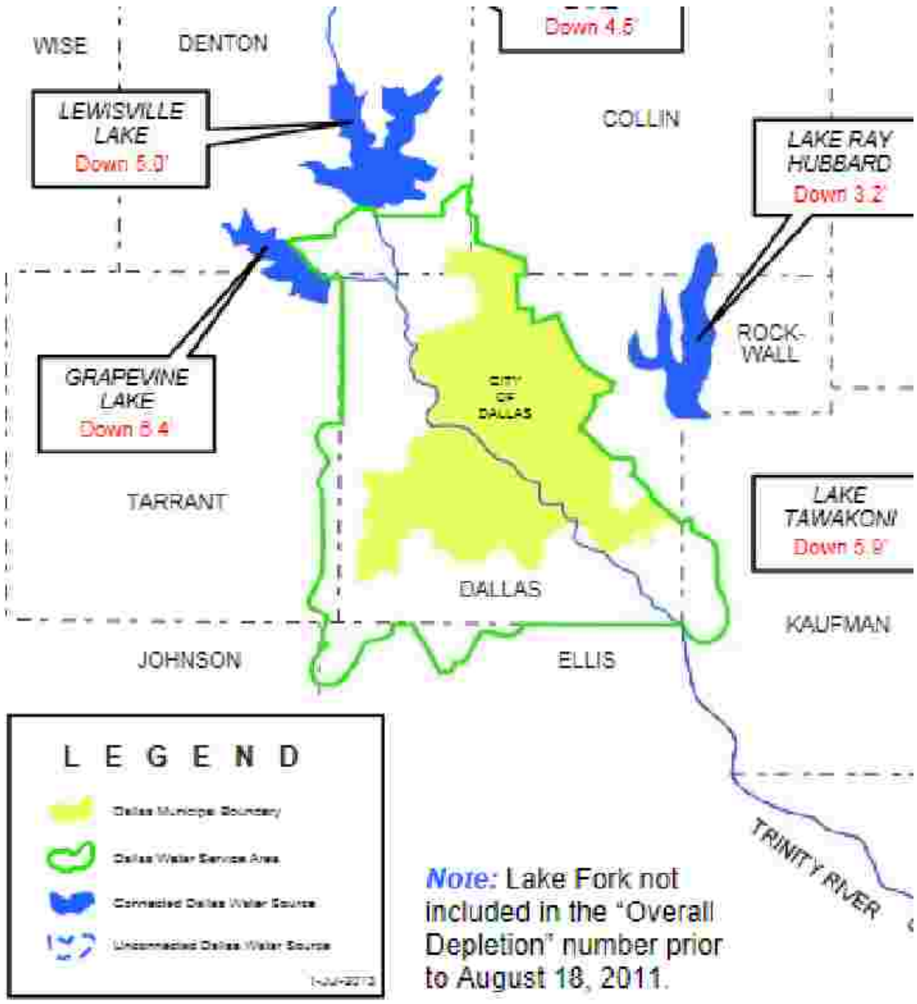

Figure 8 - Current DWU Service area (indicated by green line) (Dallas, 2013)

Population increase is not expected to be greatest within city limits; however, most growth is expected to occur in suburban or unincorporated areas (VNT, 2013) that may be served by Dallas Water Utilities. According to the City of Dallas Population and Water Demand Forecasts the population of the city itself should increase from about 1,200,000 to nearly 2,000,000 people by 2060 (City of Dallas, 2013). The population

served by Dallas Water Utilities is expected to double from about 2,800,000 currently to nearly 5,200,000 by 2060 (City of Dallas, 2013).

The Texas State Data Center (TSDC) provides population projections by county (TSDC, 2012). Dallas Water Utilities covers most of Dallas County and a bit of area just outside (see Figure 8). The TSDC calculated their projections using a cohort-component projection technique (TSDC, 2012). “The basic characteristics of this technique are the use of separate cohorts – persons with one or more common characteristic – and the separate projections of each of the major components of population change – fertility, mortality, and migration – for each of the cohorts.” (TSDC, 2012). TSDC projected using four groups: Non-Hispanic White (Anglo), Non-Hispanic Black, Hispanic (of all races), and a Non-Hispanic Other population group which also includes anyone listing two or more races (TSDC, 2012). They provide three migration scenarios: Zero Migration, One-Half 2000-2010 Migration, and the 2000-2010 Migration scenarios. Zero migration is calculated as though net migration is zero, One-Half 2000-2010 Migration is essentially an average of the Zero Migration and 2000-2010 Migration scenarios, and the 2000-2010 Migration assumes that net migration rates from 2000-2010 remain constant (TSDC, 2012). For long term planning the One-Half Migration scenario is likely the most accurate scenario (TSDC, 2012). According to these calculations, the Zero migration scenario projects a population of 3,257,805 residents by 2050 while the 2000-2010 Migration scenario projects a population of 3,522,190 residents with an average of 3,438,782 residents for the One-Half Migration scenario (Dallas County, 2013). All of these projections are an increase from the 2010 Dallas County population of 2,368,139 residents (Dallas County, 2013). Through these projections, an increase of between

889,666 residents (Zero Migration) to 1,154,051 residents (2000-2010 Migration) can be expected in the county by 2050.

Figure 9 - Dallas' Strategic Planning Area for Water Supply Planning (City of Dallas, 2006)

DWU's planning area also includes most of Denton County (see Figure 9). The TSDC carried out population projections for Denton County using the same strategies as for Dallas County, and also included Zero, One-Half, and 2000-2010 Migration scenarios. In 2010, Denton County had a population of 662,614 residents (Denton County, 2013). The Zero Migration projection scenario is 807,644 residents while the 2000-2010 Migration scenario projection is 3,167,198 residents by 2050 (Denton County, 2013). The difference in these numbers indicates the incredibly rapid population increase

in Denton County due to immigration between 2000 and 2010. The more reasonable One-Half Migration scenario projects a population of 1,535,959 residents in 2050 (Denton County, 2013). The potential increases in Denton County range from 145,030 residents to 2,504,584 residents. Even the more reasonable One-Half Migration scenario predicts that the population in Denton County will more than double by 2050. As DWU includes so much of Denton County in their planning strategies, this is a potential increase of 1,697,310 residents with Zero Migration in either Dallas or Denton Counties to 4,321,249 residents with a 2000-2010 Migration scenario. According to these numbers, DWU should plan for their service population to potentially double or triple from the current Dallas County population of 2,368,139 residents.

Table 6 – Projected Population and Increases for Dallas County, Denton County, and the Approximate DWU Planning Area comprised of Dallas and Denton Counties (Dallas County, 2013; Denton County, 2013)

			Total Population Projection by 2050	**Projected Increase by 2050**
Dallas County	2010 Population: 2,368,139	Zero Migration	3,257,805	889,666
		One-Half Migration	3,438,782	1,070,643
		2000-2010 Migration	3,522,190	1,154,051
Denton County	2010 Population: 662,614	Zero Migration	807,644	145,030
		One-Half Migration	1,535,959	873,345
		2000-2010 Migration	3,167,198	2,504,584
Approximate DWU Planning Area	2010 Population: 3,030,753	Zero Migration	4,065,449	1,034,696
		One-Half Migration	4,974,741	1,943,988
		2000-2010 Migration	6,689,388	3,658,635

DWU faces a growing population in the coming decades and must plan water supplies accordingly to be able to keep up with all water uses, particularly municipal. The largest change will occur if more cities and towns in Denton County become DWU wholesale customers, with Denton County projected to exhibit such incredible growth.

Zebra Mussels

Zebra Mussels (*Dreissena polymorphia)* are an invasive species originally from Russia that were first found in the United States in Lake St. Clair of Michigan in 1988 (LCRA, 2013; Texas Invasives, 2013). They were first found in Texas in 2009 in Lake Texoma and have since been found in the Trinity River Basin (specifically Sister Grove Creek) and recently, 2012, in Lake Ray Roberts (LCRA, 2013; Texas Invasives, 2013). Since they were found in Lake Ray Roberts biologists from the University of North Texas are concerned that they will continue to migrate downstream in the Trinity River (Scott, 2013). As of June 21, 2013 a juvenile Zebra Mussel was found in Lake Lewisville, though there is still not evidence of an established population (Young, 2013). Researchers are trying to determine whether this is the result of a veliger moving downstream or the result of an early breeding population (Young, 2013).

A large amount of Zebra Mussel's energy is devoted to reproduction (Wang, 1995). Spawning most frequently occurs during the warmer months (Wang, 1995) which may mean an increased time available for spawning in the warm Texas weather. A single female can produce up to 1 million eggs per year and roughly 2% survive to adulthood (DWU, 2012). They begin life as a veliger, which is microscopic and can survive floating freely in the water column for one month (Hosler, 2010; Wang, 1995). Due to their miniscule size, these veligers can move easily throughout a water system and quickly spread. After their month as a veliger, they mature to the juvenile stage and begin to attach (DWU, 2012). The mussels attach to any available hard surface via proteinaceous byssal threads (Wang, 1995). Zebra mussels can also be introduced as boaters visit

different lakes: if a boat has not been cleaned and drained thoroughly hitchhikers may be introduced to previously unaffected lakes (USGS, 2012).

Zebra Mussels foul water intake pipes as they attach to the solid surface and do not move. They often begin to layer upon themselves and can significantly reduce the amount of water that can be moved through a system. Water treatment facilities have reported Zebra Mussel infestations essentially shrinking the diameter of their intake pipes by two-thirds (Cataldo, 2001). The mussels frequently populate these intake pipes "because of the enormous number of potential colonists entrained in the intake current, constant replenishment of food resources and removal of mussel wastes, and the absence of predators." (MacIsaac, 1996). The presence of mussels in intake pipes can also increase corrosion (Hosler, 2010).

Due to water quality changes caused by the mussels, water clarity increases allowing sunlight to penetrate further and more attached algae to grow (Cataldo, 2001). These algae can detach and then become caught in and clog filtration systems, which becomes more of a problem in lakes than rivers (Cataldo, 2001). DWU relies solely on lakes.

On August 14, 2012 DWU provided an update on Zebra Mussels in North Texas, specifically the DWU water supply system. The presence of Zebra Mussels in the DWU water system will require additional cleaning to remove the mussels from water intake screens, pumps, pipes, monitoring equipment, etc. (DWU, 2012). Initially the presence of the mussels in Lake Texoma required that North Texas Municipal Water District (NTMWD) stop pumping from Lake Texoma in order to avoid violating the Lacey act (DWU, 2012). The Lacey Act was first passed in 1900 and makes it illegal to transport

invasive species across state lines (Lacey Act, 2008). They have since been able to switch to a closed conveyance system and resume pumping. All of DWU's water supplies are currently within the state of Texas so the Lacey Act should not interrupt pumping.

Tarrant Regional Water District (TRWD) is working on an Integrated Pipeline Design with DWU and in March 2012 began a *Control of Invasive Species Study* to examine what effects zebra mussels will have on the pipeline and water supply (DWU, 2012). The pipeline will be 150 miles long traveling through Navarro, Ellis, Johnson and Tarrant counties (IPL, 2013). It will pump from Lake Palestine to Lake Benbrook, as well as have connections to Cedar Creek and Richland-Chambers Reservoirs (IPL, 2013). Construction should begin in 2014 with expected completion of the pipeline is in 2021; it should deliver an additional 350 million gallons per day (MGD) to TRWD and DWU (IPL, 2013).

DWU has examined multiple control strategies including chemical (oxidizing: chlorine, bromine, ozone, chloramines, chlorine dioxide, potassium permanganate, and hydrogen peroxide; nonoxidizing: organic molluscicides, potassium salts, copper-ion generation, pH depression, oxygen scavengers), physical (velocity, removal [pipeline pigging, manual cleaning/scraping], coatings/materials, and filtration/screening), biological (desiccation, thermal, and bacterial), design/operation (redundant piping, facility shutdown), and experimental (ultraviolet radiation, acoustics, electric fields, and air bubbling) (DWU, 2012). Zebra mussels are most commonly removed through physical measures (DWU, 2012). A study performed in 1994 performed by Claudi and Mackie (1994) found that if the flow velocity of the intake is greater than 1.5 $m \cdot sec^{-1}$ the likelihood of a mussel settlement forming is reduced.

If Zebra Mussels migrate down the Elm Fork water system (including Lakes Ray Roberts, Lewisville, and Grapevine) "Dallas' water treatment plant intakes and raw water lines" as well as the "intakes and piping of Dallas' Untreated Water Contract customers in Lewisville and the Elm Fork" may become infested. (DWU, 2012)

In August 2011 a study began to develop the North Texas Zebra Mussel Guidance Manual which is due to be finalized by the U.S. Army Corps of Engineers by December 2012. The study was unable to be found and accessed for this thesis.

The United States Geological Survey (USGS) has also prepared a Zebra Mussel Monitoring Program for North Texas which monitored Lakes Ray Hubbard, Lewisville, Grapevine, Ray Roberts, Fork Reservoir, Tawakoni, and Palestine as of August 2012. "The program is designed to assess zebra mussel occurrence, distribution, and densities in north Texas waters by using four approaches: (1) SCUBA diving, (2) water-sample collection with plankton tow nets (followed by laboratory analyses), (3) artificial substrates, and (4) water quality sampling." (USGS, 2012) SCUBA diving is performed on an annual basis, though more dives may be performed if the situation warrants. Water samples are used to identify zebra mussel veligers, the microscopic larvae of zebra mussels. Artificial substrates are placed near areas vulnerable to zebra mussel infestation and checked periodically for the presence of the mussels. If mussels are detected their density can be measured. Water-quality sampling is used to measure the suitability of the water to support a zebra mussel population (USGS, 2012).

Future Water Plans

According to the Texas Water Development Board's (TWDB) Region C 2011 Water Plan, "In 2006, the three largest wholesale water providers in Region C (Dallas Water Utilities, Tarrant Regional Water District, and North Texas Municipal Water District) provided 85 percent of the water used in the region" (TWDB, 2010). The population in Region C is expected to continue to grow, and as one of the largest water providers DWU needs to be prepared to meet that demand. In Region C municipal use accounts for the largest portion of water use, so increasing population will increase the demand on these water supplies (TWDB, 2010).

In 2006, DWU provided 70,662.84 million gallons of water to wholesale customers, 1,002.32 million gallons of water for manufacturing, 92,621.31 million gallons for municipal retail, 875.24 million gallons for other uses, a total of 165,161.71 million gallons of water provided (TWDB, 2010). This amount made DWU the highest volume water provider in Region C in 2006, with Tarrant Regional Water District following second with 128,497.56 million gallons of water provided (TWDB, 2010). According to the 2011 Region C Water Plan "DWU has the capacity to treat up to 900 million gallons of water per day (mgd) with another 100 mgd of treatment capacity under construction" (TWDB, 2010).

Table 7 – Amount of water provided by DWU to various users in 2006 (Adapted from TWDB, 2010)

Users	Amount (in millions of gallons)
Wholesale Customers	70,662.84
Manufacturing	1,002.32
Municipal Retail	92,621.31
Other Uses	875.24
Total	165,161.71

In 2060 the projected water demand for DWU is 323,951.06 million gallons (TWDB, 2010). The 2011 Water Plan expects that 178,755.58 million gallons will be provided by current sources, with new supplies doubling the available amount by adding 182,412.28 million gallons for a total of 361,159.39 million gallons in 2060, surpassing the estimated demand (TWDB, 2010). The strategies to provide these supplies include conservation and reuse, which is estimated to account for 22.1% of 2060 water supplies (TWDB, 2010). All strategies together are expected to cost $3,836,000,000.00 for DWU (TWDB, 2010).

Table 8 –Projected supply and demand for 2060 (Adapted from TWDB, 2010)

2060 Projected Demand	323,951.06 millions of gallons
Current Sources	178,755.58
New Supplies	182,412.28
Projected Total Available	361,159.39

In March of 2013 the City of Dallas provided an update on the progress of their current Long Term Water Supply Plan (Long, 2013). In this update they provided their current plan for sources and how much water each would provide (see Table 9). Currently, Lake Palestine is not connected to the DWU system although DWU has already obtained the water rights (City of Dallas, 2006). The goal is to construct a pipeline and have the lake connected by 2015 (City of Dallas, 2006). DWU and the Tarrant Regional Water District (TRWD) are working together on the Integrated Pipeline Project to connect Lake Palestine to their systems (TWDB, 2010). Construction of the pipeline should begin in December of 2013 (Long 2013).

Table 9 – Existing Estimates for Dallas' Water Supply Sources (Long, 2013)

Current	**Underway**	**Likely**	**At Some Risk**	**Total Need (MGD)**
• Ray Roberts/Lewisville • Grapevine • Ray Hubbard • Tawakoni • Elm Fork of Trinity • Lake Fork	• Lake Palestine – 2015 (100.00 MGD) • Conservation – various dates (47.4 MGD) • Direct Reuse – various dates (18.25 MGD)	• Contract for return flows – various dates (71.02 MGD) • Ray Hubbard Indirect Reuse – permitted 2012 (60.00 MGD) • Lewisville Indirect Reuse – permitted – 2022 (60.00 MGD)	• Wright Patman Flood Pool – 2035 (100.00 MGD) • Lake Fastrill – 2045 (100.00 MGD)*	
483.90	165.65	191.02	200.00	1,040.57

*A recent Supreme Court Ruling has removed Lake Fastrill from the plan. According to Dallas' long term supply plan (2013)"Alternative strategies are being considered that include but are not limited to additional water conservation, Lake Texoma, Toledo Bend Reservoir, Lake 'O the Pines, Lake Livingston, groundwater, Marvin Nichols Reservoir, Lake Columbia, George Parkhouse Reservoir (North), George Parkhouse (South), Oklahoma water and Neches River Run-of-the-River."

Future water supply plans are located to the east of Dallas because rainfall tends to increase towards East Texas (City of Dallas, 2006; TWDB, 2010). Reservoir evaporation also decreases to the east (TWDB, 2010). The Region C Water Plan notes that "[t]he rate of evaporation from a reservoir surface exceeds rainfall throughout Region C, but the margin is much greater in the western part of the region than in the east" (TWDB, 2010). Placing reservoirs further to the east is the best method of reducing water loss through evaporation as DWU utilizes only surface water sources. Currently Dallas County is not included in a groundwater conservation district (TWDB, 2010)

because so little groundwater lies beneath the county (Figures 10, 11). Dallas may however consider groundwater as an alternative to the construction of Lake Fastrill (Long, 2013).

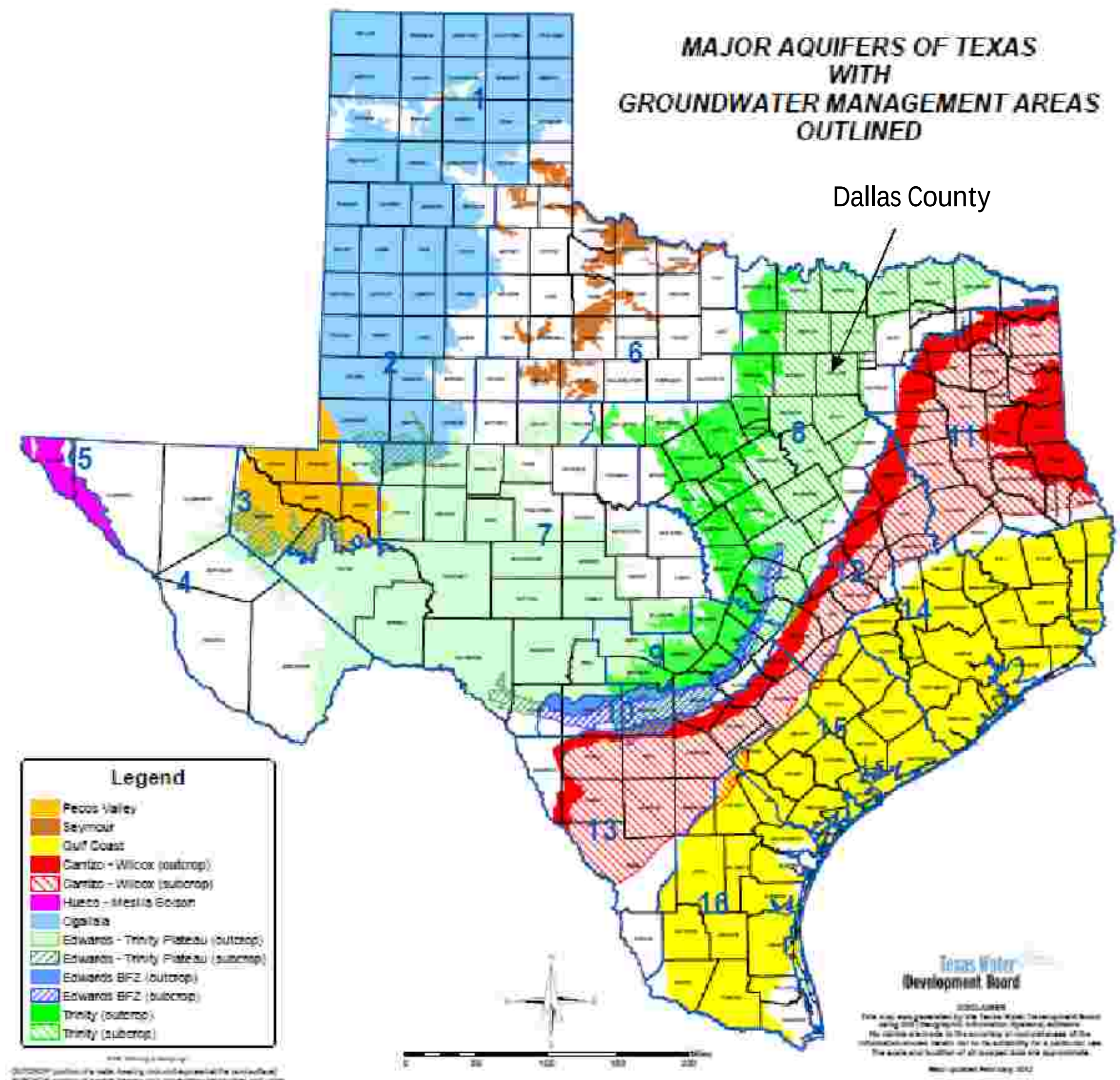

Figure 10 – Major Texas Aquifers (Adapted from TWDB 3, 2013)

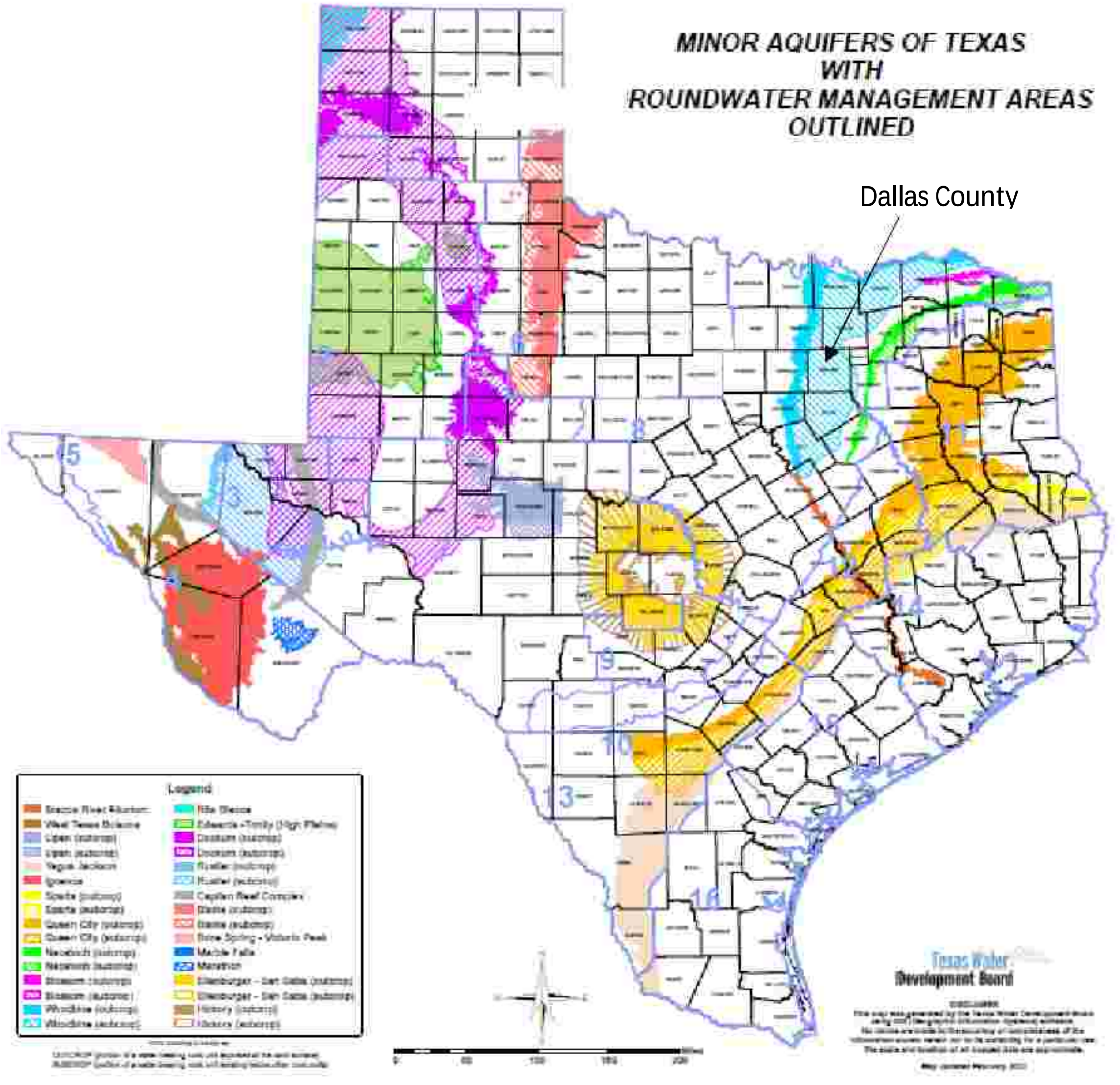

Figure 11 – Minor Texas Aquifers (Adapted from TWDB 4, 2013)

In the city's new Long Range Water Supply Plan they plan to review the possibility of supplies from: "conservation, reuse, existing reservoirs, groundwater, off channel reservoirs, interstate water, the Sulphur River Basin, the Neches River Basin, the Sabine River Basin, the Cypress River Basin, [and] the Red River Basin" (Long, 2013).

The construction of additional reservoirs requires permitting administered by the Texas Commission on Environmental Quality (TCEQ) (TWDB, 2010). However, "TCEQ

has increased its scrutiny of the environmental impacts of water supply projects, and permitting has become more difficult and complex." (TWDB, 2010). Texas Senate Bill One of the 75th regular session, which created regional planning efforts, also requires permitting for interbasin transfers of water supplies (TWDB, 2010). Region C has considered a lot of interbasin transfer to fulfill future demand (TWDB, 2010).

Dallas plans to participate in the Sulphur River Basin Wide Study, an authorized U.S. Army Corps of Engineers (USACE) study (Long, 2013). If Dallas participates DWU "would receive: preferred options and permitting strategies for water availability from the Sulphur River Basin; approximately 23.36% of any water available from project(s) in the Sulphur River Basin; access to all detailed study data, including data developed prior to Dallas' participation in the Study; and water management strategies within the Sulphur River Basin for incorporation in the LRWSP [Long Range Water Supply Plan]" (Long, 2013). The area covered in this study includes Wright-Patman Lake (Long, 2013).

Lake Fastrill was to be located in the Neches River Basin and in 2005 Dallas was authorized to enter a contract with the Upper Neches River Municipal Water Authority (UNRMWA) to evaluate the feasibility of the Lake Fastrill project (Long, 2013). However, in 2006 the Neches River National Wildlife Refuge was established by the United States Fish and Wildlife Service (USFWS) on the proposed Lake Fastrill site (Long, 2013). Dallas and the TWDB promptly "filed actions in two US District Courts against USFWS and the US Dept. of Interior. In 2008 the District Court affirmed USFWS and Dallas the TWDB filed appeals" (Long, 2013). The Fifth Circuit affirmed the District Court's decision in 2009 and "in 2010 the U.S. Supreme Court declined to hear the

Fastrill case, cementing the Wildlife refuge" (Long, 2013). It was unclear if the city was still participating in a study with UNRMWA of other potential sites or strategies.

Table 10 – DWU Reservoir Supply Availability (Values in Millions of gallons per Year) (TWDB, 2010 Table 3.2)

Reservoir	**2010**	**2020**	**2030**	**2040**	**2050**	**2060**
Lewisville/Ray Roberts	60,217.67	59,869.66	59,521.65	59,173.64	58,825.63	58,476.97
Grapevine	2,470.93	2,400.55	2,329.84	2,259.13	2,188.74	2,118.03
Lake Ray Hubbard	18,712.67	18,284.50	17,856.66	17,428.82	17,000.65	16,572.80
Tawakoni	59,832.51	59,386.75	58,940.66	58,495.22	58,049.13	57,603.04
Fork	39,102.17	39,083.60	38,807.28	38,531.28	38,254.96	37,978.31
Palestine	36,782.44	36,422.37	36,061.98	35,701.26	35,340.22	34,979.17

The TWDB uses the Texas Commission on Environmental Quality (TCEQ) approved Water Availability Models (WAMS) to calculate the potential supply available from each reservoir (TWDB, 2010). Based on these models, the 2010 availability of Lakes Elm Fork, Lewisville, and Ray Roberts combined was calculated to be 60,217.67 million gallons per year which is estimated to decrease to 58,476.97 million gallons per year by 2060 (TWDB, 2010 Table 3.2). Lake Grapevine's availability for 2010 was calculated to be 2,470.93 million gallons per year and it is also expected to decrease, to 2,118.03 million gallons per year (TWDB, 2010 Table 3.2). Lake Ray Hubbard's 2010 availability was calculated to be 18,712.67 million gallons per year in 2010 and goes down to 16,572.80 million gallons per year in 2060 (TWDB, 2010 Table 3.2). The 2010 availability for Lake Tawakoni was given as 59,832.51 million gallons per year and it is also predicted to decrease to 57,603.04 million gallons per year by 2060 (TWDB, 2010 Table 3.2). Lake Fork was calculated to have 39,102.17 million gallons per year available in 2010 and only 37,978.31 million gallons per year available in 2060 (TWDB, 2010

Table 3.2). Lastly, Lake Palestine was calculated to have 36,782.44 34,979.17 million gallons per year available in 2060 (TWDB, 2010 Table 3.2).

Current Supplies

Currently, DWU's available water supplies do not entirely match the availabilities calculated by the WAM models. According to TWDB (2010) Table 3.8, DWU only had 13,223.38 million gallons per year from Lake Fork in 2010. This is expected to increase to 15,452.85 million gallons per year by 2060. DWU also had temporary rights to an additional 16,227.40 per year from Lake Ray Hubbard in 2010 but these rights expire by 2020 (TWDB, 2010 Table 3.8). Direct reuse through Cedar Crest Golf Course are expected to remain at 182.80 million gallons per year through 2060, while available water supply from indirect reuse is expected to increase from 9,762.83 million gallons per year in 2010 to 27,697.37 million gallons per year by 2060 (TWDB, 2010 Table 3.8). White Rock Lake, located in Dallas, is used by DWU for irrigation only but available supplies are expected to decrease from 1,140.48 million gallons per year in 2010 to 651.07 million gallons per year by 2060 (TWDB, 2010 Table 3.8). Lake Palestine is not included here because it is not currently connected to DWU's system and Table 11 examines only currently connected supplies. Overall, examining only DWU's currently available supplies, that total available is expected to decrease from 181,770.68 million gallons per year in 2010 to 178,755.58 million gallons per year in 2060 (TWDB, 2010 Table 3.8). This demonstrates the necessity of pursuing other water supply options, such as Lake Palestine. Even with indirect reuse nearly tripling if no changes are made and additional water supplies found, DWU will not be able to support the water needs of Dallas and its wholesale customers. Already DWU is estimated to be in need of

Table 11 – Supplies currently available to DWU (Values in Millions of gallons per year) (TWDB, 2010 Table 3.8)

Source	**2010**	**2020**	**2030**	**2040**	**2050**	**2060**
Lake Ray Roberts/Lake Lewisville System	60,217.67	59,869.66	59,521.65	59,173.64	58,825.63	58,476.97
Lake Grapevine	2,470.93	2,400.55	2,329.84	2,259.13	2,188.74	2,118.03
Lake Ray Hubbard	18,712.67	18,284.50	17,856.66	17,428.82	17,000.65	16,572.80
Lake Ray Hubbard Temporary	16,227.40	0	0	0	0	0
Lake Tawakoni	59,832.51	59,386.75	58,940.66	58,495.22	58,049.13	57,603.04
Lake Fork	13,223.38	13,669.14	14,115.23	14,560.67	15,006.76	15,452.85
Direct Reuse (Cedar Crest Golf Course)	182.80	182.80	182.80	182.80	182.80	182.80
Indirect Reuse	9,762.83	13,700.75	17,318.03	19,761.59	22,764.31	27,697.37
White Rock Lake (Irrigation Only)	1,140.48	1,042.72	944.97	847.21	749.46	651.70
Total	181,770.68	168,536.88	171,209.84	172,709.08	174,767.48	178,755.58

15,900.57 million gallons per year for current customers, a number expected to increase to 145,261.31 million gallons per year by 2060 (TWDB, 2010 Table 4A.4).

Reuse

DWU is also expected to increase available water supplies through reuse (City of Dallas, 2006; TWDB, 2010). According to the TWDB (2010): "Categories of reuse include (1) currently permitted and operating indirect reuse projects, in which water is reused after being returned to the stream; (2) existing reuse projects for industrial purposes (including recycled water for mining use); and (3) authorized direct reuse projects for which facilities are already developed." The recycled water for mining use refers to flowback or produced water from hydraulically fracturing wells that can potentially be recycled and reused to drill or hydraulically fracture other wells.

TWDB (2010) defines indirect reuse as "when reclaimed water is discharged to a stream or reservoir and is diverted downstream or out of the reservoir for reuse. The discharged water mixes with ambient water in the stream or reservoir as it travels to the point of diversion." The projected increase in indirect reuse (Table 11) can be accounted for by an agreement between DWU and the North Texas Municipal Water District (NTMWD) between Lake Ray Hubbard and the EFWSP wetlands, with the addition of water from Lake Fork to come as well.

DWU and NTMWD have contracted to give Dallas the right to divert and use the return flow from NTMWD's wastewater treatment plants which discharge into Lake Ray Hubbard (TWDB, 2010). In return, Dallas will pump an equal amount of its return flows, currently discharged into the Trinity River, to the NTMWD East Form Water Supply Project (EFWSP) wetland (TWDB, 2010). To this purpose, DWU is constructing a pump

station at the Main Stem of the Trinity River to deliver the water to NTMWD's wetlands (TWDB, 2010). NTMWD is also working to obtain the rights for Elm Fork return flows and then help DWU obtain the necessary rights to use the water (TWDB, 2010). Once DWU has these rights, they will also pump this additional amount to the EFWSP wetland (TWDB, 2010). However, overall Dallas County's permitted and available reuse supplies are not expected to increase from their 2010 value of 2,877.59 million gallons per year (TWDB, 2010).

Direct reuse, such as that by Cedar Crest Golf Course, "occurs when reclaimed water is delivered from a wastewater treatment plant to a water user, with no intervening discharge to waters of the state. Direct reuse requires a notification to the TCEQ" (TWDB, 2010). These projections do not indicate any plans for DWU to increase direct reuse; however this is an option that should be pursued further. Direct reuse may be a possibility for drilling and hydraulically fracturing wells, which would reduce their load on the water supply (Grottenthaler, 2011; Hunter, 2012; Jenkins, 2012; Kidder et al., 2011). Table 4B.2 in the TWDB (2010) Region C 2011 Water Plan shows an increase in direct reuse by DWU from 0 gallons per year in 2010 to 6,666.27 million gallons per year by 2020, which the table shows as constant through 2060.

Water reuse is highly recommended by the TWDB as "water reuse provides a reliable source that remains available in a drought; water reuse quantities increase as population increases; water demands that can be met by reuse are often near reuse sources; and water reuse is a viable way to defer and avoid construction of new surface water impoundments." Construction of new reservoirs requires time (planning,

permitting, land acquisition, construction, etc.) and is expensive, while reuse is comparatively quick and cheap (Dallas, 2011; TWDB, 2010).

Conservation

TWDB also recommends that DWU increase available water through conservation. According to the Texas Water Code §11.002(8) "'Conservation' means: (A) the development of water resources; and (B) those practices, techniques, and technologies that will reduce the consumption of water, reduce the loss or waste of water, improve the efficiency in the use of water, or increase the recycling and reuse of water so that a water supply is made available for future or alternative uses." The Code §11.002(9) defines "conserved water" as the "amount of water saved by a holder of an existing permit, certified filing, or certificate of adjudication through practices, techniques, and technologies that would otherwise be irretrievably lost to all consumptive beneficial uses arising from storage, transportation, distribution, or application."

TWDB (2010) differentiates between drought or emergency management measures, "temporary measures that are implemented when certain criteria are met and are terminated when these criteria are no longer met," with conservation measures which "are designed to provide permanent or long-term water savings." (See "Drought Contingency Plan" under "Drought" for specific conservation measures). One simple method, that began as a drought management measure and is now a local ordinance in many regional cities, is restriction of the time of day when users may water their lawns (Dallas' 2, 2011; TWDB, 2010). By limiting watering during the hottest part of the day, evaporation is reduced so that less water is needed to adequately irrigate the lawn and plants. Other examples of conservation are "water wise landscaping (Xeriscape), low

flow showerheads, repairing leaky faucets, and [overall reduction of] the frequency of watering lawns" (DWU Drought Update, 2011). Examples of drought management measures for the city of Dallas include "restricting lawn watering, prohibiting permitting or filling of swimming pools, prohibiting operation of ornamental fountains, [and] prohibiting recreational water use" (DWU Drought Update, 2011).

The 2011 Region C Water Plan projects that DWU conservation will reach 31,835.68 million gallons per year by 2060, "not including savings from low-flow plumbing fixtures (which are built into the demand projections) and not including reuse."

Dallas has also begun public information campaigns to encourage conservation efforts (City of Dallas, 2006; TWDB, 2010). During the drought of 2011 the city introduced the "Lawn Whisperer" media campaign to encourage less frequent lawn watering (DWU Drought Update, 2011). DWU also has a website, "Save Dallas Water," that includes methods to save water, possible rebates and incentives, links to Dallas' drought and conservation plans, as well as updates on how well the city is conserving water and other effects this conservation is having (Save Dallas Water, 2013).

<u>Recommended Future Projects</u>

The 2011 Region C Water Plan recommends that DWU increase the ability to transfer water from Lake Fork so that the full available supply of 39,102.17 million gallons per year is actually available to Dallas (TWDB, 2010 Table 4C.1). The Plan also recommends the construction of Lake Fastrill and raising the Wright-Patman Lake – Flood Pool for an additional 36,527.95 million gallons per year each (TWDB, 2010 Table 4C.1). However, a recent Supreme Court Ruling, supporting the creation of the Neches River National Wildlife Refuge (NRNWR), has removed the possibility of building Lake

Fastrill from the plan (Dallas, 2011; TWDB, 2010). The connection of Lake Palestine is expected to increase available water supply by 36,319.40 million gallons per year (TWDB, 2010 Table 4C.1). Return Flows above DWU Lakes, in conjunction with the Upper Trinity Regional Water District, would provide an estimated additional 25,939.40 million gallons per year (TWDB, 2010 Table 4C.1). Reuse of Lake Ray Hubbard as well as Lewisville Lake is projected to supply an additional 21,914.49 million gallons per year each as well (TWDB, 2010 Table 4C.1).

A part of the plan to increase available water supplies includes increasing the available supply from Lake Fork (Dallas, 2011; TWDB 2010). Currently a pipeline connects Lake Fork to Lake Tawakoni and 84” and 72” pipelines connect Lake Tawakoni to Dallas (TWDB, 2010). Dallas plans to replace the pipeline currently running from Tawakoni to Dallas with 144” pipeline (TWDB, 2010). The construction of this additional pipeline will enable DWU to maximize the use of their water rights for these sources (TWDB, 2010).

Other potential projects DWU may help sponsor include the Toldeo Bend Reservoir (potentially 195,510.86 million gallons per year), Gulf of Mexico desalination (unlimited supply), Lake Texoma blend (potentially 71,687.31 million gallons per year) or desalinization, Lake Livingston (potentially 71,687.31 million gallons per year), raising the flood pool of Wright Patman Lake (potentially 58,653.26 million gallons per year), the Wright Patman Lake System (potentially 127,082.06 million gallons per year) importing Oklahoma water (53,765.49 million gallons per year or more), Carrizo-Wilcox groundwater, and DWU Cypress River Basin supplies (Lake O’ the Pines) (potentially 29,196.29 million gallons per year) (TWDB, 2010 Tables 4C.2, 4C.5). DWU may also

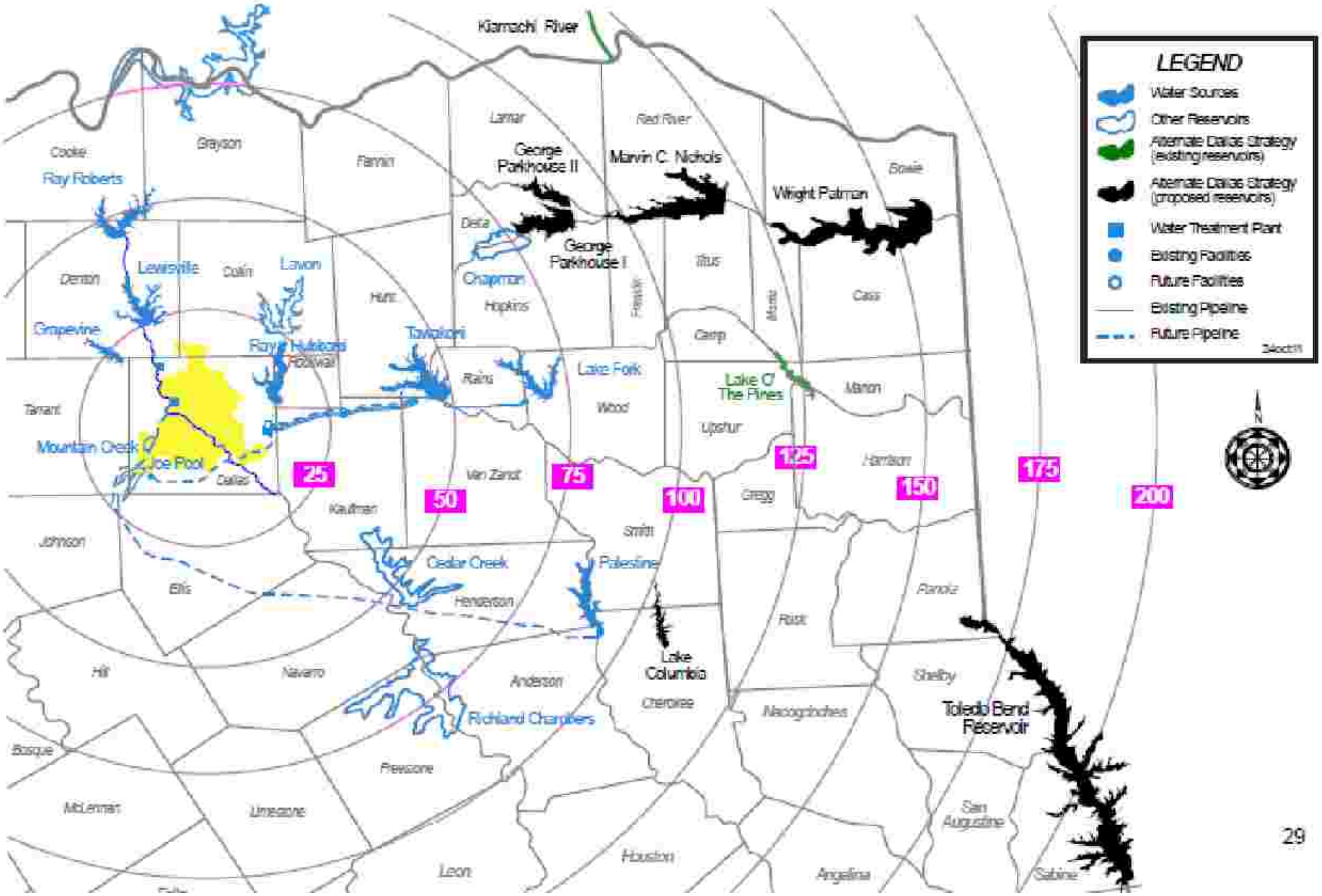

Figure 12 – Dallas' Existing and Potential Water Supply Sources and Strategies (Dallas, 2011)

potentially consider Neches River Run of River rights (potentially 36,527.95 million gallons per year), Wright Patman Lake – Texarkana (potentially 32,585.14 million gallons per year), and the Main Stem Trinity River Pump Station (potentially 21,673.03 million gallons per year) (TWDB, 2010 Table 4C.5).

Potential new reservoirs include the Marvin Nichols Reservoir, George Parkhouse Lake (South and North), and Lake Columbia (TWDB, 2010 Table 4C.3). The Marvin Nichols Reservoir would potentially be sponsored by DWU as well as the North Texas Municipal Water District (NTMWD), the Tarrant Regional Water District (TRWD), and the Upper Trinity Regional Water District (UTRWD), and Irving for up to an additional 159,615.06 million gallons per year (TWDB, 2010 Table 4C.3). George Parkhouse Lake potential sponsors include DWU, NTMWD, UTRWD, and Irving (TWDB, 2010 Table 4C.3). The Southern portion would possibly provide up to 44,185.45 additional million gallons per year, and the Northern portion could provide up to 38,763.29 million gallons per year (TWDB, 2010 Table 4C.3). DWU is the sole potential sponsor of Lake Columbia which could provide up to 11,665.48 million gallons per year (TWDB, 2010 Table 4C.3).

Most of these plans would require permits for interbasin transfers (TWDB, 2010). According to the Region C 2011 Water Plan (TWDB, 2010), "[o]verall water supplies in the Trinity and Brazos River Basins are mostly or completely allocated, while the Red, Sulphur, Cypress Creek, Sabine, and Neches Basins may have supplies in excess of their projected demands." (See Figure 13)

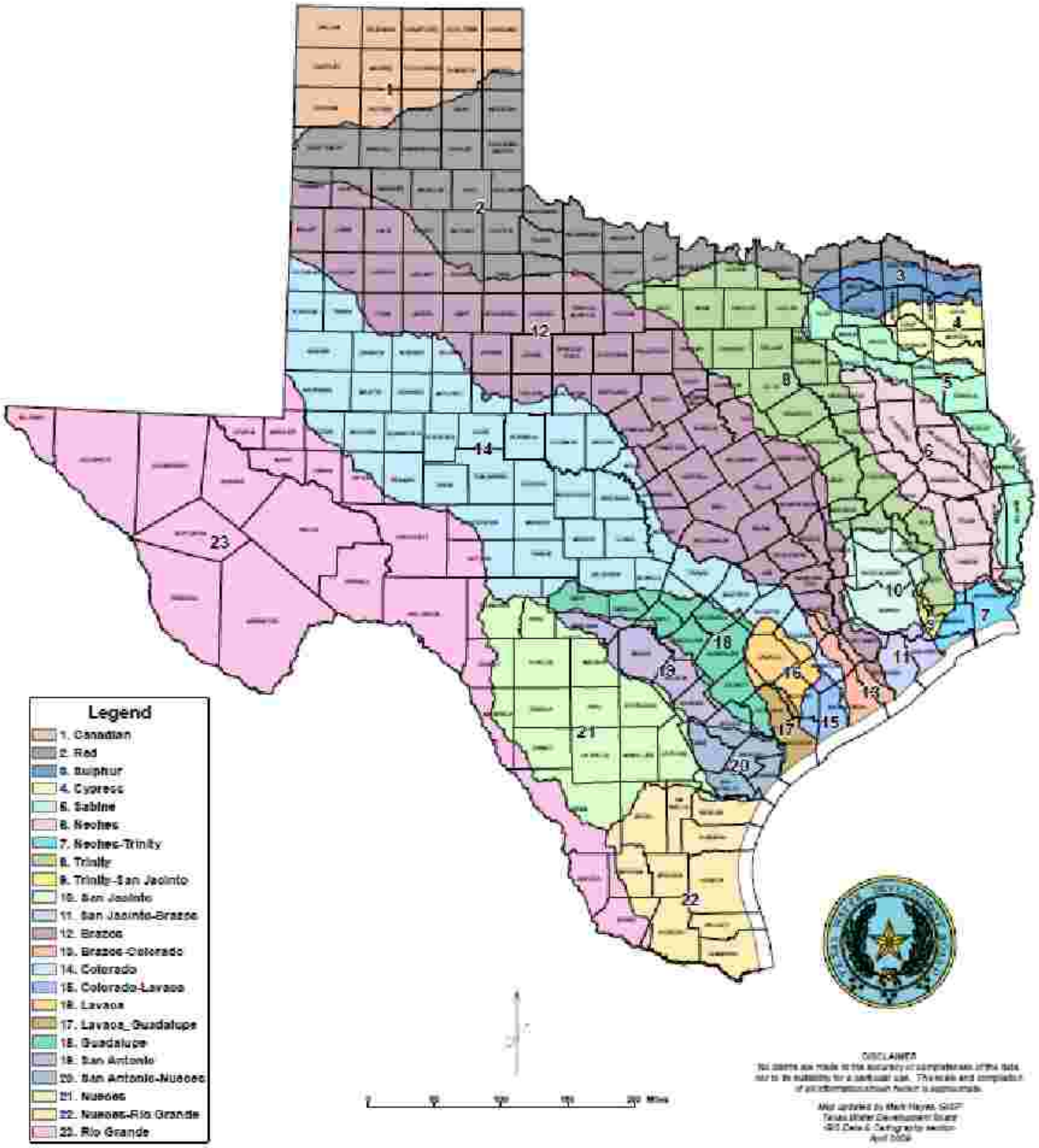

Figure 13 – Texas River Basins (TWDB 6, 2013)

Whichever of these strategies DWU chooses to increase water availability to meet projected demands new water treatment plants will need to be constructed (TWDB, 2010). Current treatment plants will be unable to process all of the water necessary, so the TWDB plan recommends both building new plants as well as expanding current plants (TWDB, 2010).

Table 12 – Potentially feasible water management strategies supplying 25,000 acre-feet per year or more (TWDB, 2010 Table 4C.5)

Strategy	Potential Sponsor(s)	Maximum Supply Available to Region C in Millions of gallons per Year
Toledo Bend Reservoir	SRA[a], NTMWD[b], TRWD[c], DWU, and UTRWD[d]	195,510.86
Gulf of Mexico with Desalination	DWU, NTMWD, and TRWD	Unlimited
Marvin Nichols Reservoir	DWU, NTMWD, TRWD, UTRWD, and Irving	159,615.06
Wright Patman Lake - System	DWU, NTMWD, and TRWD	127,082.06
Lake Texoma - Blend	DWU, NTMWD, TRWD, or UTRWD	71,687.31
Lake Livingston	DWU, NTMWD, or TRWD	65,170.29
Ogallala Groundwater (Roberts County)	DWU, NTMWD, or TRWD	65,170.29
Wright Patman Lake – Raise Flood Pool	DWU, NTMWD, or TRWD	58,653.26
Oklahoma Water	DWU, NTMWD, TRWD, UTRWD, Irving, and Denton	53,765.49 or more
George Parkhouse Lake (North)	DWU, NTMWD, UTRWD, or Irving	38,763.29
Lake Palestine (Integrated pipelines with TRWD)	DWU	36,782.44
Neches River Run of River	DWU	36,527.95
George Parkhouse Lake (South)	DWU, NTMWD, UTRWD, or Irving	35,348.36
Wright Patman Lake - Texarkana	DWU, NTMWD, TRWD, or UTRWD	32,585.14
Carrizo-Wilcox Groundwater (Brazos County)	TRWD, DWU, or NTMWD	32,585.14
DWU Cypress River Basin Supplies (Lake O' the Pines)	DWU, NTMWD, or TRWD	29,196.29
Lake Tawakoni Pipeline	DWU	25,414.46
DWU Southside (Lake Ray Hubbard) Reuse	DWU	21,914.49
DWU Lewisville Lake Reuse	DWU	21,914.49

Table 12 Continued - Potentially feasible water management strategies supplying 25,000 acre-feet per year or more (TWDB, 2010 Table 4C.5)

Strategy	Potential Sponsor(s)	Maximum Supply Available to Region C in Millions of gallons per Year
Main Stem Trinity River Pump Station	DWU and NTMWD	21,673.03
Lake Columbia	DWU	11,665.48
Neches River Run-of-River Supplies	DWU	36,527.95

[a]Sabine River Authority
[b]North Texas Municipal Water District
[c]Tarrant Regional Water District
[d]Upper Trinity Regional Water District

The Region C 2011 Water Plan (TWDB, 2010) summarizes the plight of DWU:

> The water demands on DWU are projected to increase from 607,000 acre-feet [198 billion gallons] per year in 2010 to 994,000 acre-feet [324 billion gallons] per year by 2060. The supply currently available to DWU is slightly less than 560,000 acre-feet [182 billion gallons] per year, which includes 49,800 acre-feet [16 billion gallons] per year from a temporary right for additional water from Lake Ray Hubbard that [expired December 31, 2011]. DWU's current supply is anticipated to decrease to slightly over 543,000 acre-feet [177 billion gallons] per year by 2060. As a result, DWU will need to develop…451,000 acre-feet [147 billion gallons] per year of additional water supplies by 2060…The recommended water management strategies for DWU are as follows: Conservation; additional dry year supply for operational efficiency from Lake Ray Hubbard (2011); Main Stem Trinity River Pump Station (Lake Ray Hubbard reuse – 2013); Direct Non-Potable Reuse (2015); Additional pipeline from Lake Tawakoni (2015); Connect Lake Palestine (Integrated pipeline with TRWD – 2018); Wright Patman Lake – Flood Pool Reallocation (2035); Lake Fastrill Replacement (2055); Southwest treated water pipeline; and water treatment plant expansions.

If DWU is able to successfully implement the strategies listed by the TWDB 2011 Region C Plan then supply is projected to not only meet but exceed demand (TWDB,

2010 Table 4E.1). Table 13 lists all recommended strategies as well as existing resources and their projected supplies.

Table 13 – Summary of recommended water management strategies for DWU (TWDB, 2010 Table 4E.1)

Planned Supplies (Millions of gallons per Year)	**2010**	**2020**	**2030**	**2040**	**2050**	**2060**
Projected Demands	**197,583.27**	**224,411.60**	**238,779.37**	**256,416.07**	**281,248.56**	**323,951.06**
Existing Supplies						
Elm Fork System	60,217.67	59,869.66	59,521.65	59,173.64	58,825.63	56,847.71
Grapevine Lake	2,470.93	2,400.55	2,329.84	2,259.13	2,188.74	2,118.03
Lake Ray Hubbard	18,712.67	18,284.50	17,856.66	17,428.82	17,000.65	16,572.80
Lake Ray Hubbard Temporary	16,227.40	0	0	0	0	0
Lake Tawakoni	59,832.51	59,386.75	58,940.66	58,495.22	58,049.13	57,603.04
Lake Fork	13,223.38	13,669.14	14,115.23	14,560.67	15,006.76	15,452.85
Direct Reuse (Golf courses)	182.80	182.80	182.80	182.80	182.80	182.80
White Rock Lake (Irrigation Only)	1,140.48	1,042.72	944.97	847.21	749.46	651.70
Return Flow*	9,762.83	13,700.75	17,318.03	19,761.59	22,764.31	27,697.37
Total Available Supplies	**181,770.68**	**168,536.88**	**171,209.84**	**172,709.40**	**174,767.48**	**178,755.58**
Need (Demand-Supply)	**15,900.57**	**55,874.722**	**67,480.25**	**83,707.00**	**106,481.08**	**145,195.49**
Water Management Strategies						
Conservation (DWU)	6,006.09	8,642.23	9,174.02	11,112.61	13,531.96	17,265.89
Conservation (Wholesale Customers)	2,349.71	5,224.05	8,387.09	10,180.25	12,042.17	14,541.77
Additional Dry Year Supply	8,146.29	0	0	0	0	0

Table 13 continued – Summary of Recommended Water Management Strategies for DWU (TWDB 2010, Table 4E.1)

Planned Supplies (Millions of gallons per Year)	**2010**	**2020**	**2030**	**2040**	**2050**	**2060**
Projected Demands	**197,583.27**	**224,411.60**	**238,779.37**	**256,416.07**	**281,248.56**	**323,951.06**
Total Available Supplies	**181,770.68**	**168,536.88**	**171,209.84**	**172,709.40**	**174,767.48**	**178,755.58**
Need (Demand-Supply)	**15,900.57**	**55,874.722**	**67,480.25**	**83,707.00**	**106,481.08**	**145,195.49**
Water Management Strategies						
Lake Ray Hubbard Operational Efficiency Supply**	0	49,916.20	50,344.05	50,771.89	51,200.06	51,627.90
Main Stem Trinity Pump Station (Lake Ray Hubbard Indirect Reuse)	0	10,300.82	11,688.94	12,857.77	13,113.56	13,369.36
Additional Direct Reuse	0	6,666.27	6,666.27	6,666.27	6,666.27	6,666.27
Additional Pipeline from Lake Tawakoni (More Lake Fork Supply)		25,414.46	24,692.04	23,970.61	23,248.20	22,525.46
Connect Lake Palestine (Integrated Pipeline with TRWD)		36,422.37	36,061.98	35,701.26	35,340.22	34,979.17

Table 13 continued – Summary of Recommended Water Management Strategies for DWU (TWDB 2010, Table 4E.1)

Planned Supplies (Ac-Ft per Yr)	**2010**	**2020**	**2030**	**2040**	**2050**	**2060**
Projected Demands	**197,583.27**	**224,411.60**	**238,779.37**	**256,416.07**	**281,248.56**	**323,951.06**
Need (Demand-Supply)	**15,900.57**	**55,874.722**	**67,480.25**	**83,707.00**	**106,481.08**	**145,195.49**
Water Management Strategies						
Wright Patman Lake				36,527.95	36,527.95	36,527.95
Fastrill Replacement Strategy						36,527.95
Southwest Treated Water Pipe		0	0	0	0	0
WTP Expansions			0	0	0	0
Total Supplies from Strategies	**16,502.09**	**92,670.19**	**96,670.34**	**137,026.72**	**140,470.31**	**182,403.81**
Total Supplies	**198,272.77**	**261,207.07**	**267,880.18**	**309,735.80**	**315,237.80**	**361,159.39**
Reserve	**601.52**	**36,795.47**	**29,190.10**	**53,319.72**	**33,989.24**	**37,185.51**

Discussion

Will fracking negatively affect Dallas' water supply and that of DWU's wholesale customers? When first looking only at the millions of gallons of water required to frack each individual well, it appears to be a huge amount of water. The average well drilled in Dallas County during 2011 or 2012 used 4,179,414 gallons of water. Forty wells were drilled in Dallas County during this time, for a total of 167,176,564 million gallons of water. This seems to be a lot of water, especially when one stops to consider the drought, growing population, and presence of Zebra Mussels in DWU's water system.

According to an article recently in *The Dallas Morning News*, fracking is using up valuable water supplies in the Barnett Shale and leaving some customers without water when they turn on the tap (Osborne, 2013). In Tarrant County, 3% of overall water use is attributed to fracking but that percentage rises to 55% for Wise County, also located above the Barnett Shale (Osborne, 2013). Due to the high amounts of water used to frack each well, and the increasing number of wells, water is being pumped from aquifers in the area more quickly than the aquifers can recharge (Osborne, 2013). The recharge is particularly slow right now due to the drought conditions covering most of Texas (Nielson-Gammon, 2011). However this situation is unlikely to occur for Dallas Water Utilities' because these problems involve users of aquifer water, and aquifers do not currently account for any of DWU's available supply or any projects for future supplies (Long, 2013).

The drought has however put stress on DWU's water supplies, all surface water. Due to the drought reservoirs are not fully replenished, and the increased heat from the drought also causes increased evaporation. The Region C Water Plan notes that "[t]he

rate of evaporation from a reservoir surface exceeds rainfall throughout Region C, but the margin is much greater in the western part of the region than in the east" (TWDB, 2010). Placing reservoirs further to the east is the best method of reducing water loss through evaporation as DWU relies solely on surface water. Dallas does have plans to increase available water supply, but all of the plans being most aggressively pursued and considered also rely on surface water which will continue to be subject to evaporation, so evaporation must be taken into effect when planning for future water supply. Many of these plans focus on reservoirs in East Texas

The growing population also affects the water supply as more residents demand more water. Even as DWU obtains more water rights and builds more reservoirs, increasing supply, the population will grow and increase the demand. Current projections through the year 2060 show supply increasing to meet demand as it grows with some excess (TWDB, 2010).

Additionally, Zebra mussels have entered DWU's water system and they are here to stay. Once the mussels are present it is impossible to permanently remove them, instead the best hope is to control them. The mussels clog intake pipes and reduce the flow of water as well as increasing corrosion (Cataldo, 2001; Hosler, 2010). Zebra mussels also alter water quality and increase water clarity, allowing sunlight to penetrate more deeply and increase the growth of attached algae (Cataldo, 2001). These algae can detach and clog filtration systems, which becomes more of a problem in lakes than rivers (Cataldo, 2001). DWU relies on water from reservoirs where this could become a problem.

As population grows and increases demand, zebra mussels may reduce the amount of water that is available at a given time by reducing pumping capacity. Methods to control the mussels are also costly and may eat into the budget therefore lengthening the timetable to add more reservoirs and sources to the system, or perhaps cancelling projects altogether as the city struggles to efficiently pump water from sources already online.

Increased heat from the drought and an increased population will also increase demand for electricity as more people power their homes and people struggle to cool their homes with electric air conditioning. This increased electricity use in turn increases water use as water is required to cool the plants, though water used for cooling can be returned to the water system once it has been used. However, more water is used in producing electricity than just that measured at the plant. The majority of water used in producing electricity is used in extracting and preparing the fuel for electricity (Grubert et al., 2012).

Many power plants in Texas use coal to produce electricity. Surprisingly, more water is required to extract the amount of coal to produce 1 kWh^{-1} of electricity than is required for the amount of natural gas necessary to produce 1 kWh^{-1} of electricity. While coal requires 0.071 gallons of water, natural gas requires only 0.022, from extraction to actual electricity production (Grubert et al., 2012). Natural gas requires roughly 30% of the amount of water as coal to produce the same amount of electricity. When considering the increased electricity use, natural gas plants make more sense in an arid region.

Another major concern with water use in hydraulic fracturing is that the water used to fracture a well is permanently removed from DWU’s system. The water either

remains underground, filling in the voids left by the gas, or returns to the surface as produced water or flowback (Jenkins, 2012). This flowback contains chemicals including additives used in the fracking process and any chemicals or additives the water mixes with underground (Chesapeake, 2013; Jenkins, 2012). Currently in the Barnett Shale, most of this water is disposed of via underground injection using saltwater disposal wells (Chesapeake 2, 2013). This water is then permanently lost to the system, just as the water that remains in the formation.

In light of the negative stigma surrounding water use in fracking, companies are pursuing methods of reuse for the flowback. Some flowback is able to be used to fracture future wells, so reducing the amount of freshwater required. However only a portion of the millions of gallons of water used in each well returns as flowback; some amount of freshwater will always be required. Companies are searching for methods to treat the water.

In order to recycle produced water, in 2006 Chesapeake founded their Aqua Renew® program (Chesapeake 3, 2013). According to their website, the program was "founded under the concept of water recovery and reuse…utilizing state-of-the-art technology in an effort to recycle produced water" (Chesapeake 3, 2013). Chesapeake is seeking to expand the use of their AquaRenew® program within the Barnett Shale (Chesapeake 3, 2013). If this endeavor is successful it would reduce the amount of water permanently lost to the water cycle to Chesapeake wells in Dallas. Trinity East could not be contacted for their reuse plans.

Table 14 – Summary of projected water demand and supply for DWU through 2060 (Adapted from TWDB, 2010 Table 4E.1)

Planned Supplies (Millions of gallons per Yr)	**2010**	**2020**	**2030**	**2040**	**2050**	**2060**
Projected Demands	197,583.27	224,411.60	238,779.37	256,416.70	281,248.56	323,951.06
Total Available from Existing Supplies	181,770.68	168,536.88	171,209.84	172,709.40	174,767.48	178,755.58
Need (Demand-Supply)	15,900.57	55,874.72	67,480.25	83,707.00	106,481.08	145,195.49
Total Projected Additional Supplies	16,502.09	92,670.19	96,670.34	137,026.72	140,470.31	182,403.81
Total Supplies	**198,272.77**	**261,207.07**	**267,880.18**	**309,735.79**	**315,237.80**	**361,159.39**
Reserve	*601.52*	*36,795.47*	*29,190.10*	*53,319.72*	*33,989.24*	*37,185.51*

Another possibility is that of direct reuse of some municipal water which would save DWU treatment costs. However, this still removes water from the water cycle as treatment would no longer be a possibility after the water was used in a fracking operation.

In 2011 and 2012, DWU's total water expenditures (for both the city of Dallas and customer cities) was 409,543,152,804 gallons of water. Hydraulic fracturing used 167,176,564 gallons of water in Dallas County during 2011 and 2012, 0.0408% of DWU's overall water use. In comparison, municipal use (for the city of Dallas alone) accounted for 72.7750% of DWU's overall water use in 2011 and 2012.

As Dallas pursues strategies (such as additional reservoirs, increased pumping from current reservoirs, direct reuse, and conservation) to increase future water supplies the Texas Water Development Board actually projects a slight excess each year (See Table 14). The projected demands include all water uses, even current projections for fracking. The projected reserve each year indicates that fracking should not have significant impacts on DWU's water supply in the future, even if it exceeds current projections. This is pictured perhaps more clearly in Figure 14 (see below).

Tarrant County runs alongside Dallas County to the west and is home to an estimated 900 natural gas wells that have been or are being hydraulically fractured (FracFocus, 2013). As Tarrant County is such a close neighbor with so much fracking, it makes sense to see how it has affected their water supply. Other than the report of aquifer water use causing some water users to lose access to water, reports of water shortages due

to fracking were not found. The effects on groundwater are not relevant to this study evaluating DWU's water supplies as groundwater is not a current source of supply nor is it projected to be a future source for DWU.

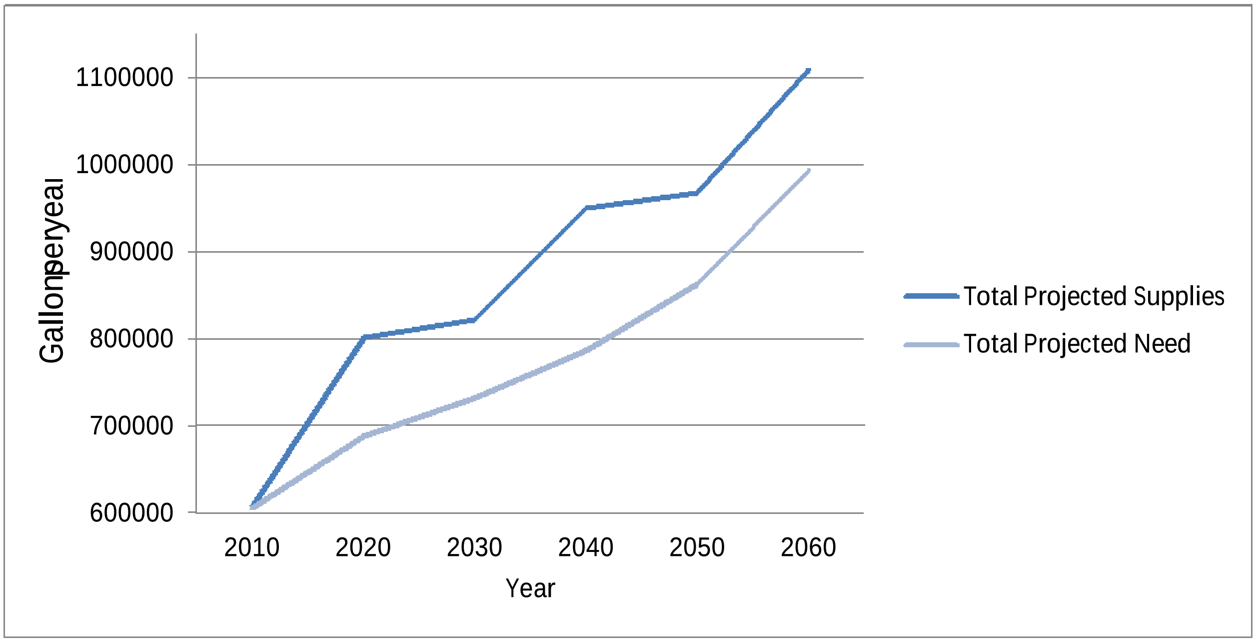

Figure 14 – Projected Demand and Available Supplies in DWU through 2060 (Adapted from TWDB, 2010 Table 4E.1)

A very interesting analysis performed by Rusty Todd, a professor at the University of Texas, compared water use in fracking to water use in irrigation in Tarrant County (Blackmon, 2013):

> In Tarrant County, Texas, Ceres found that fracking consumed 2.8 billion gallons [of water] in 2011, and that was only "about 10% of the water used in all of Texas for hydraulic fracturing."
>
> That's an impressive and disturbing statistic – until you compare it with, say, the amount of water Texans dump onto their lawns. Folks in Fort Worth, Tarrant County's biggest city with a population of more than 750,000, used an average 6.8 billion gallons a year outside their residences from 2004 through 2011, according to the Texas Water Development Board, with 80% to 90% going onto lawns.

> Nationwide, the EPA estimates that landscape irrigation consumes about nine billion gallons of water a day. That’s more than three trillion gallons a year, or more than 20 times its highest estimate for the amount of water used annually in fracking.

This reveals that where water supply is a concern, reducing hydraulic fracturing in the area will not have nearly the same effect on conserving water as reducing irrigation and lawn maintenance. Hydraulic fracturing is still relatively new, and the amount of water consumed by each well seems so vast in comparison to most people’s monthly water usage. Concerned consumers should take into account the size of the population and that each household is likely using a similar amount of water, in order to realize the full effect of their own water use in comparison to fracking. This study indicates why so many of TWDB’s future water plans involve municipal water use conservation and conservation campaigns rather than limiting activities such as fracking (TWDB, 2010).

Conclusion

Based on this analysis, hydraulic fracturing in Dallas, Texas and within Dallas Water Utilities' wholesale customers should not significantly affect Dallas' water supply in the near term. While the region is facing a growing population, a period of extreme drought, invasive species impacts of zebra mussels, as well as uncertain climate change impacts in the future, hydraulic fracturing is placing little strain on water supplies. Water used in hydraulic fracturing may be permanently lost to the water cycle but comprises a small portion of water use in the area and the effects should not be significant. Other water uses, such as lawn irrigation, use far more water than fracking and conservation measures involving these uses would be more beneficial to the area than restricting hydraulic fracturing. In addition, hydraulic fracturing in Dallas would positively impact the economy through job creation and could provide a cleaner source of energy than coal.

References

1. U.S. Energy Information Administration (EIA): Energy in Brief: *What is shale gas and why is it important*? http://www.eia.gov/energy_in_brief/article/about_shale_gas.cfm (accessed July 29, 2013).

2. U.S. Energy Information Administration (EIA2): Energy in Brief: *What are the major sources and users of energy in the United States?* http://www.eia.gov/energy_in_brief/article/major_energy_sources_and_users.cfm (accessed July 29, 2013).

3. Jenkins, S. Frac Water Reuse. *Chemical Engineering*, Feb 2012, p14-16.

4. Mantell, ME. *Deep Shale Natural Gas and Water Use, Part Two: Abundant, Affordable, and Still Water Efficient*. Proceedings of the Water/Energy Sustainability Symposium, Pittsburgh, PA, USA, Sept 26-29, 2010.

5. Chesapeake Energy: Barnett Home: Drilling and Production: Hydraulic Fracturing and Completion. http://www.askchesapeake.com/Barnett-Shale/Drilling-and-Production/Pages/Hydraulic-Fracturing-and-Completion.aspx (accessed July 22, 2013).

6. Railroad Commission of Texas (RRC): Barnett Shale Information. http://www.rrc.state.tx.us/barnettshale/index.php (accessed July 29, 2013).

7. Rahm, D. *Regulating hydraulic fracturing in shale gas plays: The case of Texas*. Energy Policy **2011**, 39:2974-2981. DOI10.1016/j.enpol.2011.03.009.

8. Frac Focus: Find a Well. http://www.fracfocusdata.org/DisclosureSearch/MapSearch.aspx. Data for well names acquired through information requests filed with DWU member cities. Accessed June 2013, July 2013, and Aug 2013.

9. Nicot, JP; Scanlon, BR. Water Use for Shale-Gas Production in Texas, U.S. *Environmental Science and Technology*. 46: 3580-3586. March 2, 2012.

10. Texas Water Development Board (TWDB) Region C 2011 Water Plan. Texas Water Development Board; Austin, TX; Oct 2010.

11. *City of Dallas Population and water Demand Forecasts*; Public Meeting May 16, 2013; City of Dallas: Dallas, TX 2013.

12. Young, ME. How dry we are. *The Dallas Morning News*, July 29, 2013, pp 1A, 7A.

13. Nielson-Gammon, J.W. *The 2011 Texas Drought: A Briefing Packet for the Texas Legislature*. OSC Report: The 2011 Texas Drought. The Texas Legislature: Austin, TX, 2011.

14. Scott, Brian. Zebra Mussels Found in Trinity River. *NBCDFW.com Local News* [Online]. April 2, 2013. http://www.nbcdfw.com/news/local/Zebra-Mussels-Found-in-Trinity-River-201142481.html

15. Cataldo, R. "Musseling" in on the ninth district economy. *Fedgazette*, Jan 2001, pp 15-17.

16. *Drought Contingency Plan*. City of Dallas: Dallas Water Utilities: Dallas, TX. June 9, 2010.

17. USCB. Texas County Selection Map: State and County Quick Facts: United States Census Bureau. http://quickfacts.census.gov/qfd/maps/texas_map.html (accessed July 9, 2013).

18. North Central Texas Council of Governments (NCTCOG) Region Map. http://www.nctcog.org/regional_map.asp (accessed July 10, 2013).

19. Vision North Texas (VNT): *North Texas Now*. Vision North Texas; North Central Texas Council of Governments. http://www.visionnorthtexas.org/regionalchoices/RegChoices_NorthTexasNow_1.pdf (accessed July 10, 2013).
This map titled "Exhibit 3.17: North Texas Communities, by Community Type" was produced by Vision North Texas. It is intended only to illustrate the various types of communities as described in the Regional Choices Report.

20. *Dallas Water Utilities Memorandum of Agreement with Wholesale Treated Water Customers*, City of Dallas: Dallas, TX. May 10, 2010.

21. *City of Dallas Planning and Water Supply Strategies*, City of Dallas: Dallas, TX. Dec 6, 2006.

22. Texas Commission on Environmental Quality (TCEQ) *Rights to Surface Water in Texas*. GI-228 (Rev. 3/09). Texas Commission on Environmental Quality: Austin, TX. March 2009.

23. U.S. Army Corps of Engineers, Fort Worth District: Lake Information: History of Grapevine Lake. http://www.swf-wc.usace.army.mil/grapevine/Information/History.asp (accessed July 14, 2013).

24. Sabine River Authority Comprehensive Sabine Watershed Management Plan Final Report. Section 3.0 Existing Surface Water Supplies. December 1999.

http://www.sratx.org/srwmp/comprehensive_plan/final_report/pdf/SECT3.pdf (accessed July 14, 2013).

25. Barnett Shale: Natural Gas: Barnett Shale 101. http://www.askchesapeake.com/Barnett-Shale/Natural-Gas/Pages/Barnett-Shale-101.aspx (accessed July 9, 2013).

26. Texas Commission on Environmental Quality (TCEQ): Air Quality: Barnett Shale Geological Area: Barnett Shale Maps and Charts: Barnett Shale Counties. http://www.tceq.texas.gov/airquality/barnettshale/bshale-maps Accessed July 9, 2013.

27. Helms, Lynn. Horizontal Drilling. North Dakota Department of Mineral Resources (DMR) Newsletter [Online], 35 *1*. https://www.dmr.nd.gov/ndgs/newsletter/NL0308/pdfs/Horizontal.pdf (accessed July 9, 2013).

28. U.S. Department of Energy (DOE). Office of Fossil Energy: Science & Innovation: Oil & Gas: Shale Gas: Hydraulic Fracturing Technology. http://energy.gov/fe/hydraulic-fracturing-technology (accessed July 9, 2013).

29. Chesapeake Energy: *Water Use in Barnett Deep Shale Gas Exploration*: Fact Sheet. May 2012.

30. Chesapeake Energy (2): *Water Use in Deep Shale Gas Exploration*: Fact Sheet. May 2012.

31. City of Dallas Water Use 2011 and 2012: Information received via public information request, 2013.

32. DWU Wholesale Customer Water Usage 2011 and 2012. Information Received via Public Information Request, 2013.

33. Nicot, JP; Reedy, RC; Costley, RA; Huang, Y. *Oil & Gas Water Use in Texas: Update to the 2011 Mining Water Use Report*. Bureau of Economic Geology: Jackson School of Geosciences: The University of Texas at Austin; Austin, TX. 2012

34. *Water for Texas 2012 State Water Plan*; Chapter 3: *Population and Water Demand Projections*. Texas Water Development Board (TWDB): 1700 North Congress Avenue, Austin, TX; 2011.

35. Texas Water Code. Title 2: Water Administration. Subtitle E: Groundwater Management. Chapter 36: Groundwater Conservation Districts. Subchapter A: General Provisions. Sec. 36.002 Ownership of Groundwater. Amended by Acts 2011, 82nd Leg., R.S., CH. 1207, Sec. 1, eff. Sept 1, 2011.

36. Texas Water Development Board (TWDB): Draft Mining Projections for the 2017 State Water Plan. http://www.twdb.state.tx.us/waterplanning/data/projections/2017/doc/draft/Demand/

DraftNonMunicipalDemands/2017DraftProjections-Mining.pdf (accessed Aug 31, 2013).

37. Chesapeake Energy (2): Barnett Home: Water Use: Produced Water. http://www.askchesapeake.com/Barnett-Shale/Water-Use/Pages/Produced-Water.aspx (accessed July 22, 2013).

38. FracFocus (2): Fracturing Fluid Management. http://fracfocus.org/hydraulic-fracturing-how-it-works/drilling-risks-safeguards (accessed July 29, 2013).

39. Kargbo, DM; Wilhelm, RG; Campbell, DJ. Natural Gas Plays in the Marcellus Shale: Challenges and Potential Opportunities. *Environ. Sci. Technol.* **2010**, *44*, 5679-5684.

40. Halliburton: CleanWave® Frac Flowback and Produced Water Treatment. http://www.halliburton.com/en-US/ps/stimulation/water-solutions/cleanwave.page (accessed July 22, 2013).

41. Els, P; Cuba, JR. Frack Water Treatment Challenge. *Pollution Engineering*, May 2013, p41-44.

42. Siemens: Water Technologies: Oil and Gas Industry: Upstream: Hydrofracturing Water Treatment. http://www.water.siemens.com/en/oil-gas/upstream/fractreat/Pages/default.aspx (accessed July 22, 2013).

43. Ecosphere: Solutions: Produced Water. http://www.ecospheretech.com/water-treatment-services/on-site-produced-water-solutions (accessed July 22, 2013).

44. GIW: Global Industrial Water. http://www.gi-w.com/ (accessed July 22, 2013).

45. Altela: Altela Rain & Reg System. http://www.altelainc.com/applications/detail/altelarain-system/ (accessed July 22, 2013).

46. Boschee, P. Handling Produced Water from Hydraulic Fracturing. *Oil and Gas Facilities*, Feb 2012, pp22-26.

47. Chesapeake Energy (3): Barnett Shale: Water Use: Water Recycling. http://www.askchesapeake.com/Barnett-Shale/Water-Use/Pages/Water-Recycling.aspx (accessed Aug 30, 2013).

48. Grubert, EA; Beach, FC; Webber, ME. *Can switching fuels save water? A life cycle quantification of freshwater consumption for Texas coal- and natural gas-fired electricity*. Environ. Res. Lett. 7 **2012** DOI: 10.1088/1748-9326/7/4/045801.

49. Union of Concerned Scientists (UCS): Clean Energy: Our Energy Choices: Energy and Water Use: *How it Works: Water for Power Plant Cooling*. http://www.ucsusa.org/clean_energy/our-energy-choices/energy-and-water-use/water-energy-electricity-cooling-power-plant.html (accessed July 29, 2013).

50. Union of Concerned Scientists (UCS 2): Clean Energy: Our Energy Choices: Energy and Water Use: *How it Works: Water for Natural Gas*. http://www.ucsusa.org/clean_energy/our-energy-choices/energy-and-water-use/water-energy-electricity-natural-gas.html (accessed July 29, 2013).

51. Combs, Susan. Texas Comptroller of Public Accounts. Window on State Government: Non-Renewable Fuels: Chapter 7: Coal: Costs and Benefits. http://www.window.state.tx.us/specialrpt/energy/nonrenewable/coal.php (accessed Aug 2, 2013).

52. National Weather Service (NWS) Weather Forecast Office: Dallas/Fort Worth, TX. Updated August 4, 2013. http://forecast.weather.gov/product.php?site=FWD&issuedby=FWD&product=DGT (accessed Aug 31, 2013).

53. National Weather Service (NWS) Weather Forecast Office: Dallas/Fort Worth, TX. Updated June 5, 2013. http://forecast.weather.gov/product.php?site=FWD&issuedby=FWD&product=DGT (accessed June 5, 2013).

54. Answers to La Niña Frequently Asked Questions; *NOAA: National Oceanic and Atmospheric Administration*. http://www.elnino.noaa.gov/lanina_new_faq.html (accessed June 28, 2013).

55. *El Niño/Southern Oscillation (ENSO) Diagnostic Discussion* June 6, 2013; Climate Prediction Center; National Centers for Environmental Prediction; NOAA/National Weather Service: College Park, MD 2013.

56. Mantua, N. The Pacific Decadal Oscillation and Climate Forecasting for North America. *Premiere issue of "Climate Risk Solutions" newsletter*. [Online] **1999**. http://www.atmos.washington.edu/~mantua/REPORTS/PDO/PDO_cs.htm

57. Frequently Asked Questions about the Atlantic Multidecadal Oscillation (AMO); *NOAA: National Oceanic Atmospheric Administration*. http://www.aoml.noaa.gov/phod/amo_faq.php (accessed June 28, 2013).

58. U.S. Drought Monitor (USDM) archives. http://droughtmonitor.unl.edu/archive.html (accessed June 20, 2013).

59. *The New York Times (NYT), The Washington Post*. Hot Enough For You? Wait till 2063 Dallas. *The Dallas Morning News*, Oct 10, 2013, p 10A.

60. EPA Home: Climate Change: Impacts and Adaptation: Great Plains Impacts. http://www.epa.gov/climatechange/impacts-adaptation/greatplains.html#water-resources (accessed Oct 10, 2013).

61. EPA (2): Clean Energy: Natural Gas. http://www.epa.gov/cleanenergy/energy-and-you/affect/natural-gas.html (accessed Oct 10, 2013).

62. Kim, J; Waliser DE; Mattmann CA; Meanrs LO; Goodale, CE; Hart AF; Crichton DJ; McGinnis S; Lee H; Lokith, PC; Boustani M. Evaluation of the Surface Climatology over the Conterminous United States in the North American Regional Climate Change Assessment Program Hindcast Experiment Using a Regional Climate Model Evaluation System. *Journal of Climate*. **2013**, 26, 5698-5715.

63. Metz B; Davidson OR; Bosch PR; Dave R; Meyer LA. *Climate Change 2007: Mitigation of Climate Change*. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, United Kingdom and New York, NY, USA 2007.

64. *Water for Texas 2012 State Water Plan*; Chapter 3: *Population and Water Demand Projections*. Texas Water Development Board (TWDB): 1700 North Congress Avenue, Austin, TX; 2011.

65. Texas Water Development Board (TWDB 2): Region C Planning Group. https://www.twdb.state.tx.us/waterplanning/rwp/regions/c/ (accessed July 9, 2013).

66. Combs, Susan (2); Liquid Assets: The State of Texas' Water Resources: *Region C*. Window on State Government: Susan Combs: Texas Comptroller of Public Accounts. http://www.window.state.tx.us/specialrpt/water/regionC.php (accessed July 10, 2013).

67. Dallas Water Use; Information Received via Public Information Request, 2013.

68. Dallas, Texas QuickFacts; *State & County QuickFacts*; United States Census Bureau (USCB). http://quickfacts.census.gov/qfd/states/48/4819000.html (accessed June 28, 2013).

69. *Projections of the Population of Texas and Counties in Texas by Age, Sex, and Race/Ethnicity for 2010-2050*; Texas State Data Center (TSDC) and the Office of the State Demographer: Austin, TX Nov 2012.

70. Dallas Water Reservoirs Overall Depletion; http://66.97.146.6/lakelevels/ (accessed July 1, 2013).

71. Dallas County Projected Population Growth; Texas State Data Center. http://txsdc.utsa.edu/Data/Files.aspx?cmd=Bh4iUm2n75LX0Zy9zmVCmnFcMEVw4iALjjBakybEAzVi74EtX3JW3g (downloaded June 21, 2013).

72. Denton County Projection Population Growth; Texas State Data Center. http://txsdc.utsa.edu/Data/Files.aspx?cmd=Bh4iUm2n75LX0Zy9zmVCmnFcMEVw4iALjjBakybEAzVi74EtX3JW3g (downloaded July 1, 2013).

73. Lower Colorado River Authority (LCRA): Zebra Mussels; http://www.lcra.org/water/quality/invasive/zebra_mussels.html (accessed June 17, 2013).

74. Texas Invasives: Zebra Mussels; http://www.texasinvasives.org/action/report_detail.php?alert_id=2 (accessed June 17, 2013).

75. Wang, S.Y.; Denson, D.R. A historical study of the reproductive pattern of Zebra Mussels. Technical Report EL-95-20; US Army Corps of Engineers: Washington, DC, June 1995.

76. DWU, *Dallas Water Utilities' Update on Zebra Mussels*; Dallas Water Utilities (DWU), Dallas, TX, Aug 14, 2012.

77. Hosler, D.M. Early detection of dreissenid species: Zebra/Quagga mussels in water systems. *Aquatic Invasions*. **2011**, 6 (2): 217-222. DOI 10.3391/ai.2011.6.2.10.

78. *USGS Zebra Mussel Monitoring Program for North Texas*. Fact Sheet 2012-3077; U.S. Department of the Interior; U.S. Geological Survey, Washington, DC, Aug 2012.

79. MacIsaac, H.J. Potential abiotic and biotic impacts of Zebra Mussels on the inland waters of North America. *Amer. Zool.***1996**, 36, pp 287-299.

80. Lacey Act of 2008. 18 USC 42-43; 16 USC 3371-3378. U.S. Fish and Wildlife Service; Office of Law Enforcement.

81. IPL. *Integrated Pipeline: Regional Partnership for Water Supply* Website; http://www.iplproject.com/ (accessed June 24, 2013).

82. Claudi, R.; Mackie, G.L. Practical manual for zebra mussel monitoring and control. 1994. CRC Press, Boca Raton, Florida.

83. *Long Range Water Supply Plan Progress*, Dallas Water Utilities, City of Dallas: Dallas, TX. March 25, 2013.

84. Texas Water Development Board (TWDB 3): TWDB Maps: GMA's with Major Aquifers. http://www.twdb.state.tx.us/mapping/doc/maps/aqu_maj_gma_24x24.pdf (accessed July 15, 2013).

85. Texas Water Development Board (TWDB 4): TWDB Maps: GMA's with Minor Aquifers.

http://www.twdb.state.tx.us/mapping/doc/maps/aqu_min_gma_24x24.pdf (accessed July 15, 2013).

86. Grottenthaler, David. Recycling Water for Hydraulic Fracturing. *Mechanical Engineering*, Dec 2011, pp21-23.

87. Kidder, Mark; Palmgren, Tor; Ovalle, Adriana; Kapha, Mukesh. Treatment options for reuse of frac flowback and produced water from shale. *World Oil* **July 2011**, *232*, 7, pp95-99.

88. Hunter, Pam. Water and Fracking: Changing the Game. *Engineering News*, Oct 8, 2012, *269*, 10, pp22-26.

89. *Dallas' Long Range Water Supply Plan*. Dallas Water Utilities; Dallas, TX. Nov 2, 2011.

90. Texas Water Code. Title 2: Water Administration. Subtitle B: Water Rights. Chapter 11: Water Rights. Subchapter A: General Provisions. Sec. 11.002: Definitions. Amended by Acts 1977, 65th Leg., p. 2207, ch. 870, Sec. 1, eff. Sept 1, 1977.

91. *Dallas' Approach to Water Conservation Briefing*. Dallas Water Utilities; Dallas, TX. Nov 16, 2011. (Dallas 2)

92. *DWU's Drought Update and Impact Briefing*. Dallas Water Utilities; Dallas, TX. Nov 11, 2011.

93. Save Dallas Water. http://savedallaswater.com (accessed July 15, 2013).

94. Texas Water Development Board (TWDB 5): Surface Water: River Basins and Reservoirs: Texas Lakes & Reservoirs. http://www.twdb.state.tx.us/surfacewater/rivers/reservoirs/index.asp (accessed July 13, 2013).

95. Osting, Tim; Mathews, Ray; Austin, Barney. *Analysis of Instream Flows for the Sulphur River: Hydrology, Hydraulics, & Fish Habitat Utilization*. Texas Water Development Board for US Army Corps of Engineers fulfillment of Obligation No. W45XMA11296580 and TWDB Contract No. 2001-REC-015. July 2004.

96. *Reservoir Site Protection Study Draft: George Parkhouse II Lake*. TWDB-0604830615. December 2006. Texas Water Development Board. http://www.twdb.state.tx.us/publications/reports/contracted_reports/doc/ReservoirSiteAcquisitionDraft/08Section%203%20-%20Part%203%20_formatted_.pdf (Accessed July 13, 2013).

97. Gelwick, Frances P; Burgess, Christine C. *Aquatic Studies at the Proposed George Parkhouse I Reservoir Site on the South Sulphur River in Northeast Texas*. Technical Report 244 for Texas Water Development Board: Austin, TX, Dec 2002.

98. Texas Water Development Board (TWDB 6): TWDB Maps: Major River Basin. http://www.twdb.state.tx.us/mapping/doc/maps/mrb_8X11.pdf (accessed July 14, 2013).

99. Osborne, James. Fracking drains water supplies: Drilling, drought stretch aquifers' ability to meet demand. *The Dallas Morning News*, Aug 29, 2013, p 1D.

100. Blackmon, David. Water for Fracking, In Context. *Forbes Energy Blog* [Online], July 1, 2013. http://www.forbes.com/sites/davidblackmon/2013/07/01/water-for-fracking-in-context/ (accessed Aug 29, 2013).

Vita

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