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Current and Future Water Demand of the Texas Oil and Gas and Mining Sectors and Potential Impact on Aquifers

Jean-Philippe Nicot

Bureau of Economic Geology, Jackson School of Geosciences,
University of Texas at Austin, University Station, Box X, Austin, Texas 78713, U.S.A.

ABSTRACT

The Texas mining industry, in addition to oil and gas, produces mostly lignite coal and aggregates (sand and gravel and crushed rocks). Operations always involve water, either as an aid in extraction or as a byproduct. A recent study compiled current water use in the various sectors of the mining industry and made projections for the next 50 years. The study concerned the upstream segment of the oil and gas industry (drilling, hydraulic fracturing, waterfloods), the aggregate industry (washing included but no further processing), the coal industry (pit dewatering and aquifer depressurizing), and other substances mined in a fashion similar to that of aggregates (industrial sand, lime, etc.), as well as through solution mining. Overall, in 2008, the industry used ~160 thousand acre-ft (kAF), including 35 kAF for hydraulic fracturing and ~21 kAF for other purposes in the oil and gas industry. The coal and aggregate industries used 20 kAF and 71 kAF, respectively. Mining of industrial sand dominates the remainder. Approximately three-fourths of the water used is consumed, and approximately two-thirds of the water consumed is groundwater. Projection estimates call for a steady increase in water use in coal and aggregate production and a sharp increase, followed by a slow decrease, in the oil and gas industry. Operators favor surface water when it is plentiful, but groundwater is a more drought-proof source. Because the various segments of the energy industry are spread out across the state, they impact many different aquifers. Mining withdrawals represent only ~1% of total withdrawals at the state level but can be much higher locally and compete with other uses, such as municipal usage or irrigation.

INTRODUCTION

Mineral resources in Texas fall into four categories: (1) hydrocarbons (oil and gas), (2) lignite and coal, (3) crushed rock and sand and gravel (collectively known as aggregates), and (4) other substances. Oil and gas make up most of the dollar value and compose a significant fraction in terms of volume with the aggregate category (Table 1). Oil and gas are produced from almost every county in the state (Fig. 1a), whereas lignite mines are located in a narrow band in the middle of the state (Fig. 1c) and parallel to the coast (Kyle, 2008; Kyle and Clift, 2008). Sand and gravel are exploited mostly along rivers (Fig. 1d). Crushed-stone quarries are present mostly in the footprint of the Edwards Limestone. The objective of a recent study performed for the Texas Water Development Board (TWDB) was to determine county-level historical and projected mining water use in Texas, focusing on fresh water (total dissolved solid content [TDS] < 1000 mg/L). Disregarding oil and gas wells and other oil- and gas-related facilities, the U.S. Census Bureau (2005) listed a total of 11 lignite mines, 100+ crushed stone, and ~200 sand and gravel operations, many of them small, as well as ~70 facilities of a different type, neither lignite nor aggregate, in Texas in 2000. More details about mine count, as well as a more detailed account of water use, can be found in Nicot et al. (2011).

Oil and gas resources are generally sorted into conventional and unconventional categories (Figs. 1a and b). The former represents the archetypal reservoir traps in either sandstones or carbonates and is made up of interconnected pores that allow 'easy' communication with the well bore. The latter is generally characterized by the use of advanced technologies and consists of different types of formation and/or extreme environmental conditions (pressure and temperature). Characteristics of unconventional resources of interest relevant to this study include low permeability and a need to stimulate the reservoir through hydraulic

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Table 1. Fuel and nonfuel raw mineral production in Texas (2009 data).

Mined Substance	Quantity
Fuel Minerals	
Oil[a]	344.5 MMbbl
Gas[b]	7.53 Tcf
Coal/lignite[c]	$37{,}099\times10^3$ short tons
Uranium[d]	Withheld
Nonfuel Minerals[e]	
Cement (overwhelmingly portland)	$11{,}682\times10^3$ metric tons
Clays (common clay, bentonite)	2289×10^3 metric tons
Gypsum	1430×10^3 metric tons
Lime	1650×10^3 metric tons
Salt	9570×10^3 metric tons
Sand and gravel:	$99{,}500\times10^3$ metric tons
Industrial sand	1530×10^3 metric tons
Crushed stone:	$136{,}000\times10^3$ metric tons
Dimension stone	31×10^3 metric tons[f]
Other: talc, brucite, other clays, helium, zeolites, sulfur	

Source:
a: http://www.rrc.state.tx.us/data/production/oilwellcounts.php—2009 data;
b: http://www.rrc.state.tx.us/data/production/gaswellcounts.php—2009 data;
d: Information withheld for confidentiality (small number of producers);
e: USGS (2009) —2006 data; and
f: Seems to be a slow year or underreporting.

fracturing (HF). In this study, the unconventional category consists of tight formations, usually 'tight gas,' and resource plays such as gas shales and liquid-rich shales. Resource plays are generally defined as those plays with relatively predictable production rates and costs and with a lower commercial risk, as compared with that of conventional plays. Shale plays with their extensive, continuous resources and 'no dry well' attribute are examples of resource plays. Water needed for drilling wells and for secondary and tertiary recovery of oil (waterfloods and enhanced oil recovery—EOR) falls into the oil and gas category also.

Coal is generally ranked as anthracite, bituminous, subbituminous, or lignite. Low-rank, low-energy lignite is the only coal present in Texas in significant amounts (Fig. 1c) and is produced through open pits. Crushed stone consists mostly of limestone and dolomite, with many facilities located along the Interstate Highway IH35 corridor (San Antonio to the Dallas–Fort Worth metroplex) (Fig. 1d). Additional quarries are dedicated to cement production. However, upstream water use for cement production is not included in this work, consistent with the North American Industry Classification System (NAICS), which classifies cement production as manufacturing. Because of important capital costs, crushed-stone operations tend to be larger than sand and gravel facilities. The latter are concentrated along streams and on the coast. Allied mined substances include industrial sand and dimension stone. Other substances tend to be mined at only a few locations. Note that several mining activities require no fresh water or no water at all.

All studies and surveys agree that, overall, mining-water use in Texas represents only a small fraction of total water use in the state, and historical estimates have varied, given the relatively low priority of this category of water use. Previous estimates from water-demand surveys and projections determined that the demand for water use in mining was ~300 thousand acre-ft (kAF; 1 AF = 325,851 gallons), compared with 18 million AF (1.6%) for total water use in 2010 (TWDB, 2012, their Table 3.3), ~280 kAF and 17 million AF (1.6%) for total water use in 2000 (TWDB, 2007, their Table 4.2), ~250 kAF and ~17 million AF (TWDB, 2002, their Table 5.2), and ~200 kAF and ~16.5 million AF (TWDB, 1997, their Table 3.2), both also for 2000 (Table 2). In addition to efforts at the state level, the U.S. Geological Survey (USGS) publishes every 5 years (with a lag of a few years relative to data collection) information about all types of water use across the nation. The most recent versions were authored by Kenny et al. (2009) for 2005 and by Hutson et al. (2005) for 2000 (Table 3). USGS typically extrapolates from the information obtained from the states and publishes only aggregated data. For Texas, Kenny et al. (2009, their Table 2B) reported a mining-water withdrawal of 102 and 614 kAF/yr, respectively, for water of fresh (defined in the USGS report as TDS < 1000 mg/L) and saline (TDS > 1000 mg/L) quality. Kenny et al. (2009, their p. 35) stated that lignite dewatering operations were included in the water withdrawal total only if the water were put to beneficial use (for example, dust control). USGS figures for 2000 (Hutson et al., 2005, their Table 4) are somewhat different and more closely align with those of the TWDB, with a total fresh-water use of 246 kAF. Whereas 1995 (Solley et al., 1998) figures are consistent with those of 2000, the difference between 2000 and 2005 figures corresponds to a change in accounting. Such a change underlines the difficulty of comparing results from different studies with different assumptions. Nicot et al. (2011) determined that 2008 mining-water use was likely in the vicinity of 160 kAF of fresh water, intermediate between the values suggested by USGS and TWDB. Water use was distributed in a relatively balanced way among its main users (Fig. 2). The oil and gas industry used ~57 kAF (36%), whereas the coal and aggregate industry used ~20 (12%) and ~72 (45%) kAF, respectively. The 'other' category (~11 kAF, 7%) is dominated by industrial sands.

The amount of groundwater used in the mining category is not easy to determine, particularly in the oil and gas and aggregate subcategories. However, a significant fraction of water used in the state is groundwater (59%, TWDB, 2007, p. 176), although this statistic is biased because a sizable fraction comes from the Ogallala Aquifer in the Texas Panhandle that is used for irrigation. In this area of Texas, the groundwater-use fraction is somewhat higher, whereas elsewhere it tends to be smaller. Irrigation is an important category used by TWDB to detail water use in the state and is the largest in terms of volume. Other categories in approximately decreasing volumes are municipal, manufacturing, steam-electric, livestock, mining, and domestic/other.

The body of this paper details the methodology followed to obtain estimates of historical and future water use in the mining category in the state. In later sections, it also addresses the issue of future use and impact of mining water use on aquifers. We also present the important distinction between water use (water withdrawal) vs. water consumption (net water use), which is not always easy to determine.

DATA SOURCE AND METHODOLOGY

Historical Water Use

Historical data were obtained, with various success rates, from (1) databases of state agencies (TWDB; Railroad Commission of Texas—RRC), (2) private vendor databases (IHS Enerdeq

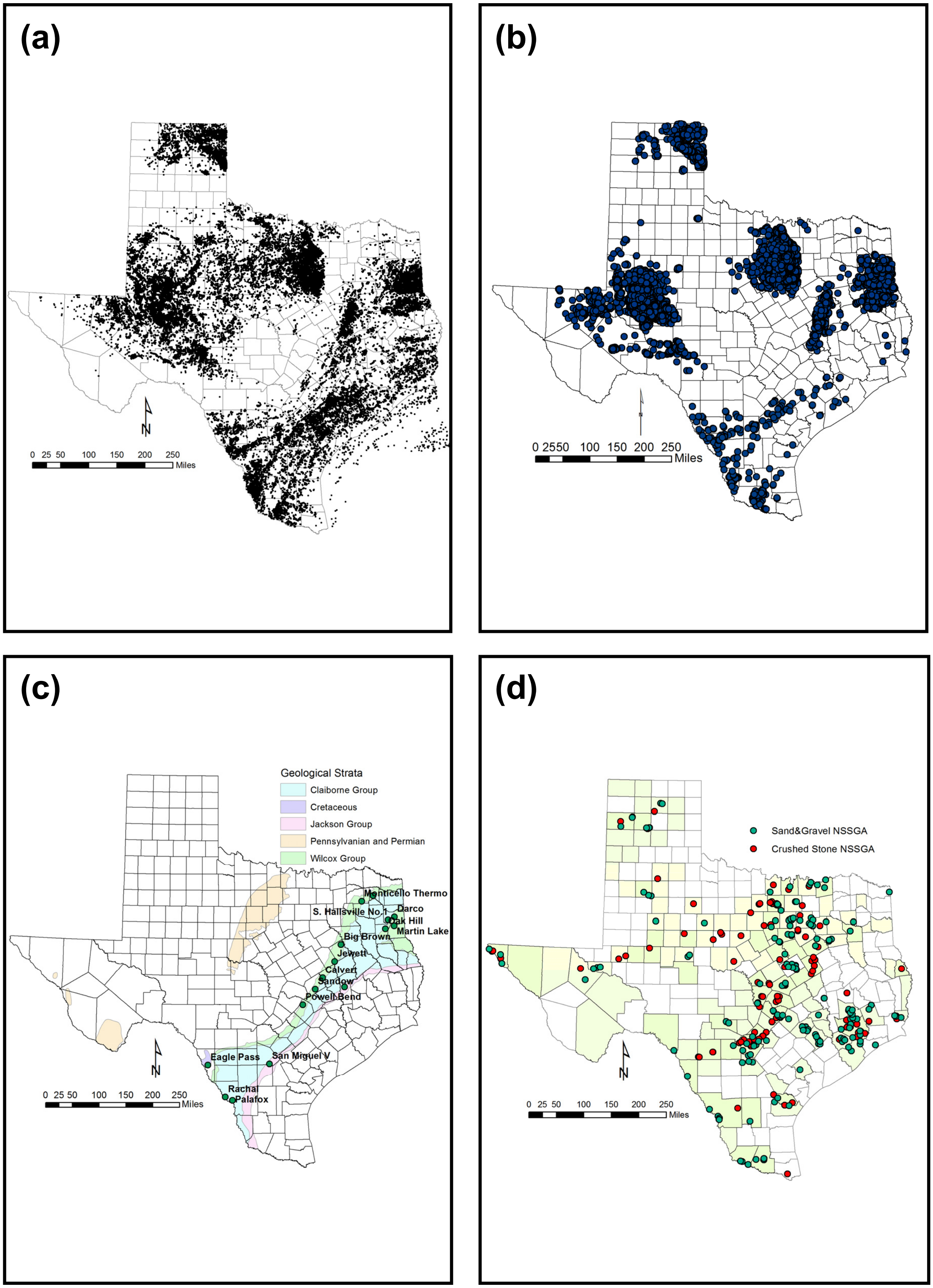


Figure 1. (a) Location map of all wells with a spud date between 1/1/2005 and 12/31/2009 (~75,000 wells); (b) map showing locations of all HF jobs, 2005–2009, in Texas; ~23,500 wells displayed; (c) location map of coal/lignite operations; (d) location map of aggregate operations from NSSGA database (2010) (data points) and MSHA database (2010) (selected counties). Sources: (a and b) IHS Enerdeq database; (c) Ambrose et al. (2010); and (d) NSSGA/USGS (2010) and MSHA databases (2010).

Table 2. Historical projected mining water use (top of cell) and total water use (bottom of cell) for all water uses in Texas by TWDB (kAF). Each row represents actual or projected (depending on the date) water use for a given water plan. It can be observed that projections for mining and total water use increase as the projection timeframe decreases.

Water Plan	1990	2000	2010	2020	2030	2040	2050	2060
1997	149 15,729	205 16,586	187 16,867	182 17,135	191 17,489	194 17,900	188 18,354	
2002	149 15,729	253 16,919	246 17,662	245 18,195	252 18,732	252 19,369	244 20,022	
2007		279 16,977	271 18,312	281 19,011	286 19,567	276 20,105	277 20,759	286 21,617
2012			296 18,011	313 19,039	296 19,821	285 20,518	285 21,191	292 21,952

Source: TWDB (1997, 2002, 2007, 2012).

Table 3. Historical mining water use in Texas by USGS (kAF).

	Fresh	Saline	Total
1995			
Groundwater	143	458	602
Surface water	93	0	93
Total	236	458	694
2000			
Groundwater	144	565	709
Surface water	102	0	102
Total	246	565	811
2005			
Groundwater	30	614	644
Surface water	72	0	72
Total	102	614	716

Source: Kenny et al. (2009), Hutson et al. (2005), and Solley et al. (1998).

database) used for completion-water use in the oil and gas category, and (3) surveys to facilities and/or operators relayed by trade associations (Texas Aggregates and Concrete Association—TACA; Texas Mining and Reclamation Association—TMRA; Texas Oil and Gas Association—TXOGA), which are mostly useful for the aggregate industry. Nicot et al. (2011) provided details. Historical water use was computed using direct data if available (oil and gas production from shales, coal operations), with the potential problem of completeness, in which case extrapolations were performed. In other cases, water-use coefficients were used. The approach consisted of extrapolating water use computed from a relatively small subset of facilities with known production and known water use to the whole segment, for which only production was known (oil and gas drilling and secondary and tertiary recovery, aggregates). The reference year is 2008.

HF is a major water use in the oil and gas segment. We extracted data from the IHS Enerdeq database relative to all HF operations from the origins of the technology (ultimate source of information was W–1 and G–1 forms submitted to RRC by operators) to determine historically and currently active plays with HF jobs. The main shale plays include the Barnett, Eagle Ford, and Haynesville plays, but tight-gas (for example, the Cotton Valley Formation in East Texas; Coleman, 2009) or other tight formations containing oil (for example, the Wolfberry play in the Permian Basin) are also subject to HF and account for a non-negligible fraction of HF water use. We compiled all wells completed in the 2005–2009 period (Fig. 1b) and then selected wells with water use >0.1 Mgal. This threshold is somewhat arbitrary and was used to distinguish high-volume HF jobs from simple well stimulation by traditional HF and acid jobs. Although simple stimulation is applied to many wells (Table 4), overall water-use volume is small (Nicot and Scanlon, 2012).

Nicot (2009) and then Nicot and Scanlon (2012) detailed the approach. A post-audit of the projections made during the 2006 Barnett Shale study (Nicot, 2009) suggests that the approach is valid (Nicot and Scanlon, 2012). The first step of the processing is to check data consistency. The general approach to achieving this goal is to compute proppant loading and water-use intensity for each individual well. Average proppant loading (proppant mass divided by water volume) is expressed in field units of pounds per gallon (ppg or lb/gal). An acceptable value is near 1 (0.5–2, e.g., Curry et al., 2010; Nicot et al., 2011). Water-use intensity is computed by dividing total amount of water used by length of vertical or lateral overall productive interval. Lateral length can be computed from two techniques that generally agree: distance between surface location of the wellhead and bottom-hole location or length of total driller depth minus true depth. HF jobs with missing water use are treated by estimating it from the proppant amount and the median proppant loading for that play and/or from the average water intensity of the play combined with the specifics of the well. If no data are available, the HF job receives the median well water use for the play. Water use at the play level is then computed by summing up all individual well water use numbers. A major assumption is that all water is fresh and not from recycling/reuse. The industry is clearly moving in the direction of using more brackish water, and the numbers presented most likely represent an upper bound. Recycling would also lower net water use, but evidence suggests that it is not widespread in Texas, where deep injection is the preferred method of disposal of flowback water (Nicot et al., 2011).

No information on waterflooding or tertiary recovery processes or on drilling-water use has been systematically compiled since the 1995 RRC study (De Leon, 1996). More recent, but partial, information about waterflooding was obtained by sending survey forms to leading oil-producing companies in West Texas, where waterflooding and EOR operations are concentrated (Galusky, 2010; Nicot et al., 2011). Drilling-water-use information is extremely fragmented and variable and was collected through informal discussions with practicing field engineers, a survey of operators in the Permian Basin (Galusky, 2010), and a borehole-volume approach (Nicot et al., 2011).

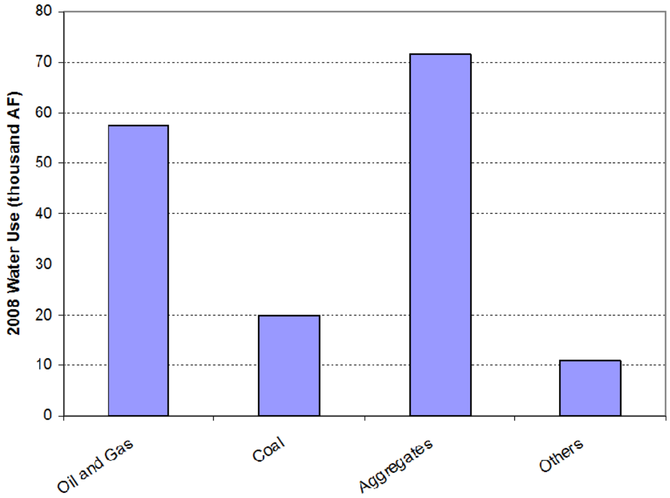


Figure 2. Summary of 2008 water-use estimates in Texas by mining-industry segment (Nicot et al., 2011).

Coal mine operators must report drawdowns and pumping rates for depressurization to the RRC as a requirement for their mine-operating permits. Surveys were sent to operators to access other coal mining-water uses not reported to RRC. Pit-dewatering volumes, originating from rain falling into the pit and being captured by its drainage area, as well as seepage from the overburden and diverted runoff, are typically directed toward retention ponds and used, although they are not counted toward withdrawal/consumption in this study (Nicot et al., 2011). Aquifer depressurization also lacks the clear-cut classification of some other water uses. Although the amount pumped for depressurization represents a net loss to the aquifer and is counted as consumption in this work (Nicot et al., 2011), water taken from the aquifer becomes available for other uses, especially environmental flow when the water is directed to nearby surface water (e.g., streams, rivers).

Aggregate facilities, particularly in the sand and gravel category, are fragmented, and obtaining an accurate water-use count has been historically difficult. The approach used in this study was to use water-use coefficients (water use per unit of production) to access both water-use and production numbers from a few facilities and then extrapolate the findings to statewide production. Generic water-use coefficients are available from various publications (Quan, 1988; Mavis, 2003); however, water use varies considerably as a function of climate, location, production technique, and operator and has been historically improving. Some facilities use little water (only dust suppression) and rely on pit water and rain-fed ponds, whereas others are larger users and could significantly enhance their recycling operations. The Bureau of Economic Geology received completed surveys from ~25 facilities (mostly larger crushed-stone facilities representing ~22% of total production, but only a few percent of total production for sand and gravel facilities), which, combined with information received from Groundwater Conservation Districts (GCD's) and from TWDB water-use surveys, allow for the determination of approximate water-use coefficients. Overall production at the state level is well known (153 million tons crushed stone and 87.7 million tons sand and gravel in 2008, USGS, 2010); however, production of individual facilities is not generally in the public domain. Instead we loosely used MSHA data, documenting the number of employees as an approximate proxy for production of individual facilities.

Water-Use Projections

How much longer will substances currently mined be mined? Do any of the substances mined in the past have a credible chance of being exploited again, both in terms of substance and location? What are the new substances that could be mined in the future? Some of these questions are not easy to answer, but, overall, the main drivers of water use in the mining sector are (1) population growth and (2) economic development, especially concomitant energy demand nationally. Population growth relates to resources consumed within the state (aggregates, coal), whereas economic development impacts all substances, including those mostly exported out of the state, either in their raw form or transformed. Even more uncertain is extrapolating for long periods of time from a short period of time of a few years, such as for shale gas and liquids. Post-audit analyses of long-term projections show that they often deviate from actual figures because of unpredicted events. A case in point is the rapid development of water-intensive gas production from gas shales.

As discussed previously, a large fraction of the mining output is related to energy production (oil, gas, coal). King et al. (2008) discussed future directions of the power sector in Texas as it relates to water use. For example, development of nuclear power would merely transfer water use from the mining category to the power-generation category, as well as move it to different counties and regions, as would a shift from coal to natural gas. Some analysts have also predicted that gas would slowly overtake coal as the major electricity-generating fuel in Texas, whereas others have maintained that, given the nature and age of electricity-generating facilities in Texas, coal share in the state energy mix will remain stable or increase. In light of such uncertainty and conflicting opinions, we elected to simply extrapolate current trends.

The methodology to project completion-water use in the oil and gas category is explained in some detail in Nicot and Scanlon (2012):

(1) Gather historical data in terms of average well water use and average well spacing for plays with mostly vertical wells (e.g., Permian Basin) or in terms of water intensity and spacing between laterals in plays with mostly horizontal wells (shale plays). This subtask is accomplished mostly while historical information is being compiled.

(2) Estimate maximum well density/lateral spacing across the play; different values can be applied to subdomains of the play (counties in this study). Knowing the total number of wells or the total cumulative lateral length, combined with average water use per well or per unit length of lateral, yields a total uncorrected water use, which represents the high end of a range that is unlikely to be met.

(3) Correct uncorrected water use by applying a <1 correction factor, which is a function of several factors, such as geological prospectivity (for example, within play core or not, shale thickness) and cultural features (urban/rural). The correction factor can be close to 1 in core areas, but a more common value is 0.5.

(4) Distribute through time constrained by the assumed number of drilling rigs available and applying an additional factor to account for reuse and recycling. This study assumes no refracking; that is, operators do not frac the same well a second time in most cases. Discussions with operators suggest that little refracking will occur. Sinha and Ramakrishnan (2011) suggested that a maximum of 15–20% of Barnett Shale horizontal wells have some attributes that make them suitable candidates for refracking. We assumed that county-level water use follows a triangular

Table 4. Well statistics and water use for 2010 in major basins (~8000 wells out of ~9500 completed in 2010). Regions are: not fracked (statewide), stimulated but without using high-volume HF (statewide), and different plays in which high-volume HF was used. 'Water Use' column represents fraction of total HF water use for each category. 'Number of Wells' column represents number of wells in each category. Note that non-high-volume HF is applied to ⅓ of the wells but uses little water. 'Vertical Wells' column represents fraction of vertical wells, the remainder being horizontal wells, in each play (for example, only 2% of the wells completed in the Fort Worth Basin in 2010 were vertical, whereas 94.6% were in the Permian Basin).

Category/Region	Water Use (% of Total)	Number of Wells (% of Total)	Vertical Wells (% of Wells for Region)
Not fracked	0.0%	25.6%	
Stimulated	1.7%	34.6%	
Anadarko Basin	3.0%	2.2%	28.1%
East Texas Basin	7.8%	5.0%	44.8%
Fort Worth Basin	57.3%	13.6%	2.0%
Gulf Coast	12.3%	4.8%	33.4%
Permian Basin	17.9%	14.1%	94.1%

shape as a function of time, with a peak 5 to 10 yr after start of major operations in the county, followed by a slow decline for 30 to 40 yr.

(5) Check consistency with future production estimates in terms of estimated ultimate recovery (EUR) for the average well and at the play level using production projections such as those by Mohr and Evans (2010).

Water use for secondary and tertiary oil production is less dependent on number of rigs because most consumption occurs after drilling and during pressure maintenance or enhanced-recovery operations. We assumed that waterflooding activities occur mostly in the Permian Basin, which is also the world center of CO_2 EOR. Estimates in this category are obtained through a combination of historical data, survey results, and knowledge of the industry.

Energy makeup of the state still relies heavily on gas- and coal-fired power plants (some of the coal is imported from out of state), with nuclear energy as a distant third. We assumed a slow growth scenario for the coal industry and projected that the share of coal will stay the same in the energy mix. Current mines, or future mines located nearby in the same county, will simply increase production and water use in pace with increasing electricity demand.

If some mining activities such as oil and gas are independent of the state population because their products are not necessarily consumed in the state, others, such as aggregates and lignite coal, which have high transportation costs, are consumed mostly locally and depend more strongly on the population level in the state, nearby counties, and economic activity. Future aggregate production (and concomitant future water use) is correlated with population growth. Population of the state is predicted to grow by 21 million, from ~25 million in 2010 to ~46 million in 2060 (TWDB, 2012). To estimate future aggregate production we relied on extrapolation from historical data and noted that aggregate production is coupled to absolute population level, but also to its derivative through time (population growth) (Nicot et al., 2011). In 2008, the amount of crushed stone produced per capita was ~153 Mt/24,000,000 people; that is, ~6.5 ton/capita/yr. During the same 1-year period, population growth was ~0.5 million, that is, ~310 ton/capita growth/yr. A similar analysis yields ~4 ton/capita/yr and ~200 ton/capita growth/yr for the sand and gravel category. As a whole, additional people will need houses, highways, and other facilities at a higher rate than people already living in the state, supporting the assumption that population growth has a greater impact on aggregate consumption than the population parameter itself:

$$Aggr.Prod. = 2/3 \times Pop. \times Rate1 + 1/3 \times Pop.Growth \times Rate2$$

The population-growth component (*Rate1*) remains at a stable absolute level because growth rate (*Rate2*) itself remains stable, whereas the population as a whole component keeps increasing in absolute value and as a fraction of the total. Once aggregate production at the state level has been determined, historical water-use coefficients are applied to obtain aggregate-water use at the state level.

CURRENT WATER USE

Oil and Gas

Shale and tight-sand plays in Texas occur in all corners of the state (Fig. 1b). Between 2005 and 2009, the number of HF jobs was >23,500 performed in 100+ formations. Tight-sand plays are more numerous than shale-gas plays and have a longer history, going back to the 1950s and early days of the HF technology. The bulk of the HF jobs are limited to a few formations (Barnett, Cotton Valley of East Texas, Granite Wash in the Anadarko Basin, and Wolfberry in the Permian Basin). Emerging plays such as the Haynesville and Eagle Ford shales already hosted a few HF jobs in 2008 but not to the level seen in 2012.

The Barnett Shale of Mississippian age (Pollastro et al., 2007) is the formation in which the current technology was pioneered, and it has been producing gas since the early 1990s. Figures 3a and b illustrate the transition from smaller, earlier HF jobs in vertical wells and the clear jump in average water use per well in 1998 for both horizontal and vertical wells to ~1.5 Mgal. The amount of water used then has remained more or less constant through time for vertical wells, although with a much larger variance, whereas it keeps increasing for horizontal wells until it reaches a current average of 3–4 Mgal/well. In 2008, water use in the Barnett Shale was ~25.5 kAF. Note that this water-use amount includes some recycling and reuse. Recycling and reuse are likely to be at the most 10% and, more likely, just a few percent; that is, water consumption is similar to water use.

The productive interval of the Haynesville Shale (Hammes, 2009; Spain and Anderson, 2010) of Jurassic age is >10,000 ft deep. The first year with significant HF water use was 2008.

Total water use from 2008 to ~mid-2010 was ~0.5 billion gal or 1.5 kAF, 7% of which (0.1 kAF) was used in 2008, 50% (0.75 kAF) in 2009, and 43% (0.65 kAF) during the first ~8 months of 2010. The Eagle Ford Formation of Late Cretaceous age (Hentz and Ruppel, 2010) covers a large section of South Texas all the way to East Texas. The discovery well was drilled in 2008. The Eagle Ford Shale contains oil updip, gas downdip, and gas and condensates in between. We found total water use to date (~mid-2008 through ~mid-2010) to be 1.43 billion gal, or 4.4 kAF, 3% of which was used in 2008 (0.13 kAF), 37% (1.6 kAF) in 2009, and 60% (2.6 kAF) during the first ~8 months of 2010. Average water-use intensity in shale plays ranges 750–1250 gal/ft. Nicot et al. (2011) and Nicot and Scanlon (2012) provided more details.

The Anadarko Basin (Hentz and Ambrose, 2010) has seen several cycles of activity since the 1950s, as evidenced by its HF history (Fig. 3c). However, the wells were vertical, and the HF water volumes were small (<0.1 Mgal/well). Since 2008, the HF water volume has increased to an average of 0.4 Mgal/well. More recently, horizontal wells have been developed in the basin. Average water intensity is ~450 gal/ft, with a broad mode. The formation described as the Granite Wash has been fracked the most often, followed by the Cleveland Formation. In 2008, 2.2 kAF of water was used for HF purposes.

Cotton Valley is the tight formation currently being fracked primarily in the East Texas Basin (Fig. 3d), followed by the Travis Peak Formation. Several other formations are also being stimulated, such as the Bossier and Pettet formations. Most of the wells are vertical, although the proportion of horizontal wells is growing. HF took off in the 1990s, as it did in other tight formations, with a sharp increase in average water use in recent years—0.9 Mgal and 3 Mgal/well for vertical and horizontal wells, respectively. In 2008, operators in the East Texas Basin used a total of 4.26 kAF of water for HF purposes on tight formations.

Most of the Permian Basin is in the oil window, although significant amounts of gas may exist deeper. The important development of the so-called Wolfberry play in the Midland Basin corresponds to operators fracking similar rocks of stacked Spraberry, Dean, and then Wolfcamp, and possibly Strawn basinal deposits in vertical wells at a depth of >7000 ft. Spraberry/Dean reservoirs have historically had a fairly low recovery (Dutton et al., 2005). Most of the HF has focused on the margins of the basin along the Central Platform and the Eastern Shelf. Overall the Permian Basin has seen 50,000+ HF jobs in the past 50 yr (Fig. 3e), including 18,300+ jobs with water use >0.1 Mgal (Fig. 3f), and ~2,900 HF jobs with water use >0.5 Mgal, mostly in the past few years. The plots show a clear upward trend in all percentiles since 2000, with average water use approaching 1 Mgal/well. This is a relatively modest amount per current standards, but most of the wells are vertical. In 2008, operators in the Permian Basin (Texas section) used a total of 3.25 kAF of water for HF purposes.

The Texas southern Gulf Coast province is well known for its gas-prone hydrocarbon accumulations and includes the Frio Formation, a prolific conventional-gas producer, as well as the Wilcox deltaic reservoirs. Tight-gas formations such as the Vicksburg and Wilcox Lobo tend to occur deeper (Dutton et al., 1993). The Maverick Basin, included in the Gulf Coast area for the purpose of this study, contains the Olmos Formation, another important tight-gas formation. Overall, Gulf Coast tight formations have not seen the increase in average HF water volume, as seen in all other basins, despite a sharp increase in the number of HF jobs (Fig. 3g). Recently active plays include the Vicksburg, Wilcox, and Olmos formations. The amount of water used is low (<0.2 Mgal/well for the most part). In 2008, operators in the Gulf Coast Basin used a total of 0.60 kAF of water for HF purposes.

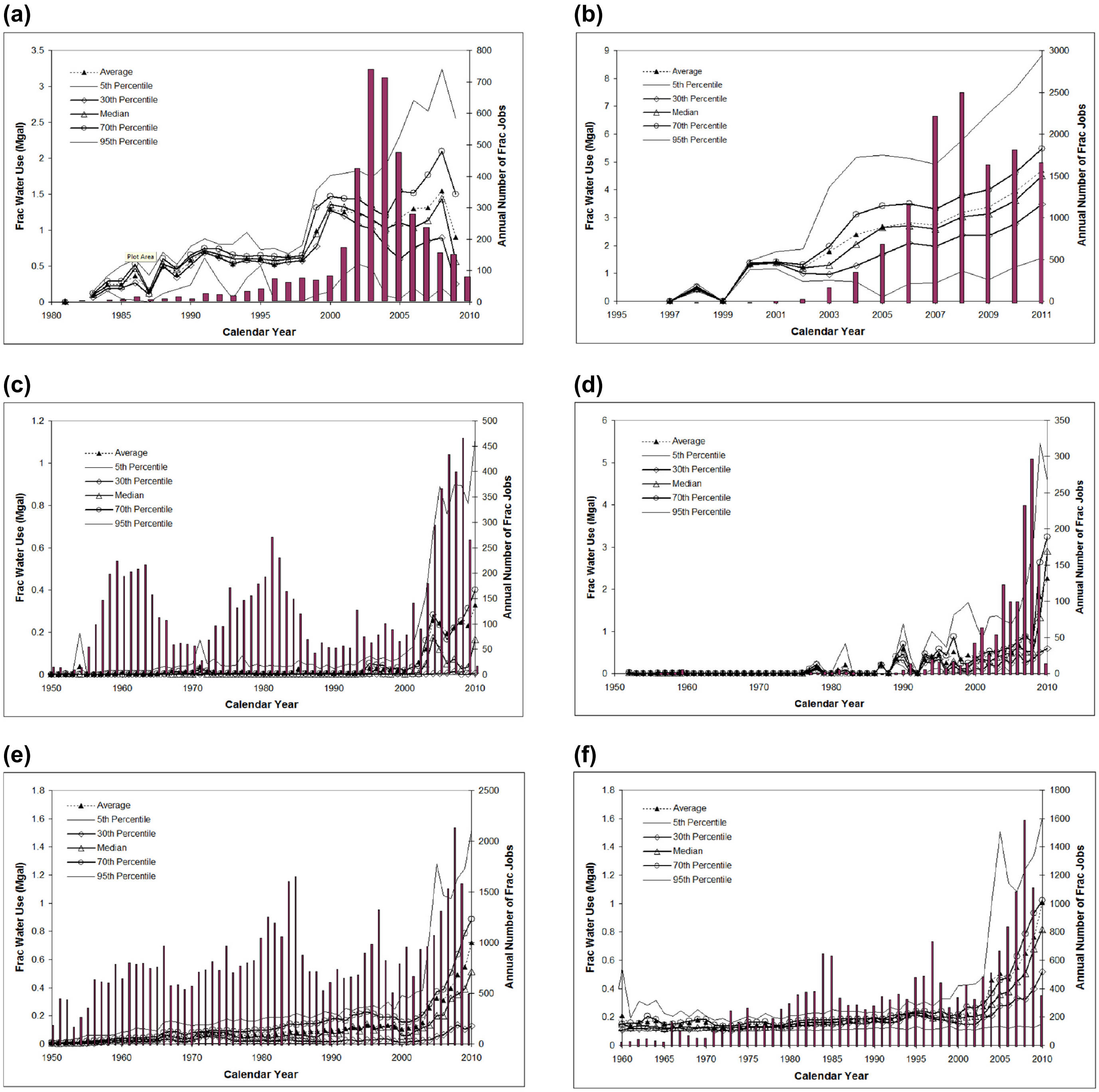
In partial conclusion, completion of water-use shale-gas wells was dominated (99.0%) by the Barnett Shale in 2008 (Fig. 4a), at ~25.5 kAF used, whereas all tight formations across the state amounted to ~10.4 kAF. In 2010 (Fig. 5), ~32 kAF and ~13 kAF of water was used for fracking shale and tight formations, respectively, for a total of 45 kAF

Historical reports suggest that the amount of fresh water used in the oil and gas industry for secondary and tertiary recovery has been decreasing during the past few decades. Guyton (1965, p. 40) estimated that in Texas (mostly the Permian Basin) and southeast New Mexico, the industry used ~50 to 70 kAF/yr of fresh water in the early 1960s for the extraction process. RRC (1982) reported that fresh-water use was at ~80 kAF in 1980 and 1981. The latest comprehensive survey of fresh-water use in the oil and gas industry dates back to the 1990s (De Leon, 1996), and fresh-water use was estimated at ~30 kAF. Definition of fresh water is more lax than for the rest of this work because it includes all water with a TDS < 3000 mg/L. The RRC survey was combined with another survey performed for this study (Galusky, 2010). The state-level estimated 2008 water use for nonprimary recovery processes is ~13.0 and 25.5 kAF for fresh and brackish water, respectively (Fig. 6), mostly in the Permian Basin (Fig. 4b). We are reasonably confident in the total of 38.5 kAF, but less so in the distribution between fresh and brackish categories.

Water used to develop drilling muds for the 10 to 20,000 wells drilled each year in the state could significantly contribute to total fresh-water use. Well drilling requires a fluid carrier to remove the cuttings and dissipate heat created at the drill bit. The fluid also keeps formation-water pressure in check. Broadly, fluid carriers fall into three types: (1) air and air mixtures, (2) water-based muds, and (3) oil-based muds. By far the most common method involves water-based muds, and fresh water is needed to optimize mud performance. For similar subsurface conditions, drilling practices differ from region to region and from operator to operator. Oil-based mud is used typically at greater depths or when sensitive clays, for example, could be a problem (as in the Eagle Ford play). A final figure of 8.0 kAF was eventually retained for drilling fresh water (Nicot et al., 2011).

Coal

In general, coal-mining processes require water during operations for activities such as dust suppression, equipment washing, waste disposal, reclamation and revegetation, coal washing, transportation, and drilling. However, some Texas mines need dewatering and depressurization. Texas currently has 11 active coal mines or groups of mines, with 2 mines coming fully online in the next few years. All coal operations in Texas are currently mine-mouth, meaning the coal is used to power a power plant or other facility close to the mine. All mines with significant production in the past decades are still in operation, except for Sandow Mine, recently closed but replaced by the adjoining, newly operational Three Oaks Mine, and two other mines. In 2009, 37.1 million short tons (st) of lignite was produced in the state, requiring production of ~20 kAF of water and resulting in an average raw-water use of 175 gal/st. However, including only consumption (and not dewatering or depressurization), the same coal production required only 2.6 kAF or 22.8 gal/st (Nicot et al., 2011)



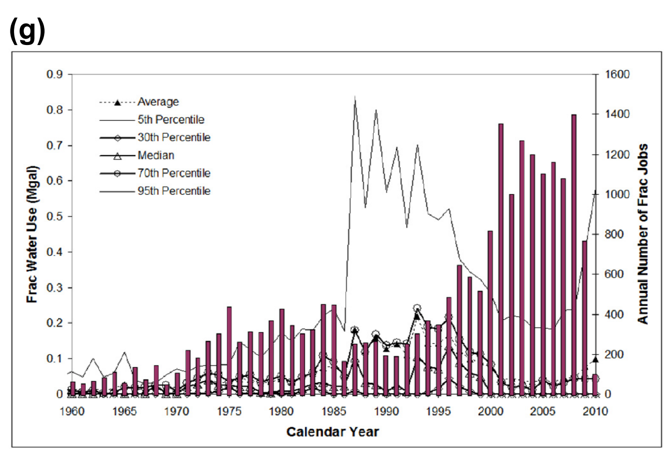


Figure 3. Annual number of HF jobs (columns, right-hand side, vertical axis) superimposed to annual average, median, and other percentiles of individual well frac water use (lines, left-hand-side, vertical axis) for (a) Barnett vertical wells, (b) Barnett horizontal wells, (c) Anadarko Basin, (d) East Texas Basin (mostly Cotton Valley), (e) Permian Basin, (f) Permian Basin (>0.1 Mgal only), and (g) Gulf Coast.

Sandow Mine used to contribute a large fraction of total coal-mining water use, more than half of the ~40 kAF/yr of produced groundwater, until 2008. The current overall amount is <20 kAF/yr. At present, no mine comes close to the threshold of 10 kAF/yr. Luminant mines in East Texas (Monticello Thermo, Monticello Winfield, Oak Hill, Martin Lake, and Big Brown) (1) have a total water use of between 1 and 2.5 kAF/yr, which is due mostly to overburden dewatering; (2) do not need to be depressurized (or very little); and (3) have to pump supplementary (variable across mines) amounts of water to satisfy their operational needs. All of the water is fresh and is used mostly for dust suppression. An additional mine in the same Sabine Uplift area shows only small water use for water supply. Some of these mines do report larger water volume for pit dewatering from surface water and seepage. However, pit dewatering is not included in the data presented in this report. Central Texas mines (including Jewett, Calvert/Twin Oak, and Sandow/Three Oaks) are characterized by some depressurization pumping. Levels of depressurization and dewatering vary considerably across mines. Mines located in the Calvert Bluff Formation above the prolific Simsboro aquifer of Central Texas produce large amounts of water to depressurize and avoid heaving of the mine floor. San Miguel Mine taps the Jackson Group lignite, not the Wilcox lignite, and does produce groundwater, but it is saline and is reinjected into the subsurface. For the purpose of this study, San Miguel Mine has zero water use. Table 5 summarizes the findings: out of a total of 19.9 kAF withdrawn, only 2.6 kAF is consumed. Most is groundwater (18.4 kAF), 1.1 kAF of which is consumed (Nicot et al., 2011).

Aggregates and Others

Overall, crushed stone consists mostly of limestones, particularly along the U.S. Interstate Highway 35 (IH35) corridor, but also sandstones, as well as granitic rocks, in the Llano area and volcanic rocks (‘trap rock’) in the Uvalde area. Having a low value on a mass basis, aggregates tend to concentrate around urban areas because transportation costs can be prohibitive unless they possess an intrinsically higher value, such as industrial sand (used in HF) or igneous crushed stones. Sand and gravel facilities are located mainly along streams and rivers and in the Gulf Coastal Plains and tend to be smaller and sometimes intermittent.

In general, no water is used during extraction except for roadway watering and dust suppression. Initial rock crushing and separation are also performed dry, except for dust suppression. Water is used mostly to wash and sort the different-sized products. Wash water is then directed to settling ponds to remove the fines and be used again. As a result of active water recycling and reuse efforts in place at most crushed-stone quarries, only an average of ~20 to 30%of the water used in the operation is actually consumed and must be replaced. Water loss generally results in four ways: (1) retention of water in the moisture content of the final product shipped to customers; (2) application of water on roadways, conveyor belts, and transfer points to suppress dust; (3) spillage and absorption of water from washing-process equipment and pipes; and (4) evaporation from ponds and open equipment (Walden and Baier, 2010; Nicot et al., 2011). The amount of reported recycling varies widely from none for dry-process, crushed-stone facilities, which consume water only for dust suppression and a few wet-process, crushed-stone facilities, possibly because they have stormwater in excess, to almost 100% in some highly water-conscious facilities. Most facility recycling rates range from 65 to 90%. Survey results show a large spread for all aggregate-water use. However, values cluster from ~0 to 30 gal/t for dust control (roads and machinery) and show a bimodal distribution at <20 gal/t and ~50 gal/t for washing (Nicot et al., 2011). Both distributions have long tails. Washing-water use reportedly ranges from a minimum of 180 for very clean rock (rare) up to 900 gal/t for dirty rock (as sometimes seen in the Edwards Limestone) (Walden and Baier, 2010). The surveyed facilities (18 crushed stone and 8 sand and gravel) show a large range in terms of production (<0.2 to >13 million tons per year), reported gross water use (up to >4 kAF/yr), and reported net water use (up to >2 kAF/yr). Overall, ~53 and ~18.3 kAF (total of 71.6 kAF) was used across the state for crushed rock and sand and gravel production, respectively.

Industrial sand followed a similar approach, but with a larger water-use coefficient of 600 gal/t, resulting in 9.7 kAF of water use across the state (Nicot et al., 2011). Uranium extraction, through in situ recovery, accounts for almost 1 kAF. Water use for mining all other mineral commodities accounts for <2 kAF.

Conclusions

Overall, of the ~160 kAF used by the industry in 2008, ~113 kAF (or ~71%) can be considered consumption (Table 5). Rough estimates of groundwater withdrawal and consumption are ~56% (of total withdrawal) and ~64% (of consumption), respectively.

WATER-USE PROJECTIONS

Most uncertainty about future water use in the mining category comes from unknowns in the rapidly evolving exploration of shales and tight formations, whose gas and oil production is ultimately tied to national economic activity. Aggregates and coal-mining water use are better constrained and directly driven by local conditions, such as population growth, but are also connected to national economic activity. An element strongly impacting future water use is the national energy policy, particularly the impact of any cap and trade or other legislation regulating CO_2 emissions. It will drive the reliance on fossil fuels and the breakdown between fossil fuels.

Oil and Gas

In the short term, operators are likely to focus on plays such as the Wolfberry or the combo play of the Barnett Shale or the Eagle Ford, all producing oil with significantly better economics than gas. Gas is typically a regional commodity and does not travel as well as oil, which is a world commodity. The projections overall assume a sustaining natural gas price. Because of the assumption of no refracking, water use is projected to reach a peak in the next decade and then decrease in a multi-decadal tail (Fig. 7)

Barnett Shale water-use projections will peak in 2017 at ~48 kAF and then decrease to almost nothing in 2040. High-water-use counties are outside the core area because it has already passed its peak of drilling activity. The part of the Haynesville/Bossier shales lying in Texas is estimated at ~35% of each play. Projections suggest that water use will peak at 22 kAF around the 2020s. Eagle Ford Shale water-use projections assume a 2024 peak, with a total water use of ~45 kAF. The Wolfberry Trend in the Permian Basin is assumed continuous and is treated in a way similar to that of gas shales. Projections result in a 2023 peak year, with water use of 11.7 kAF.

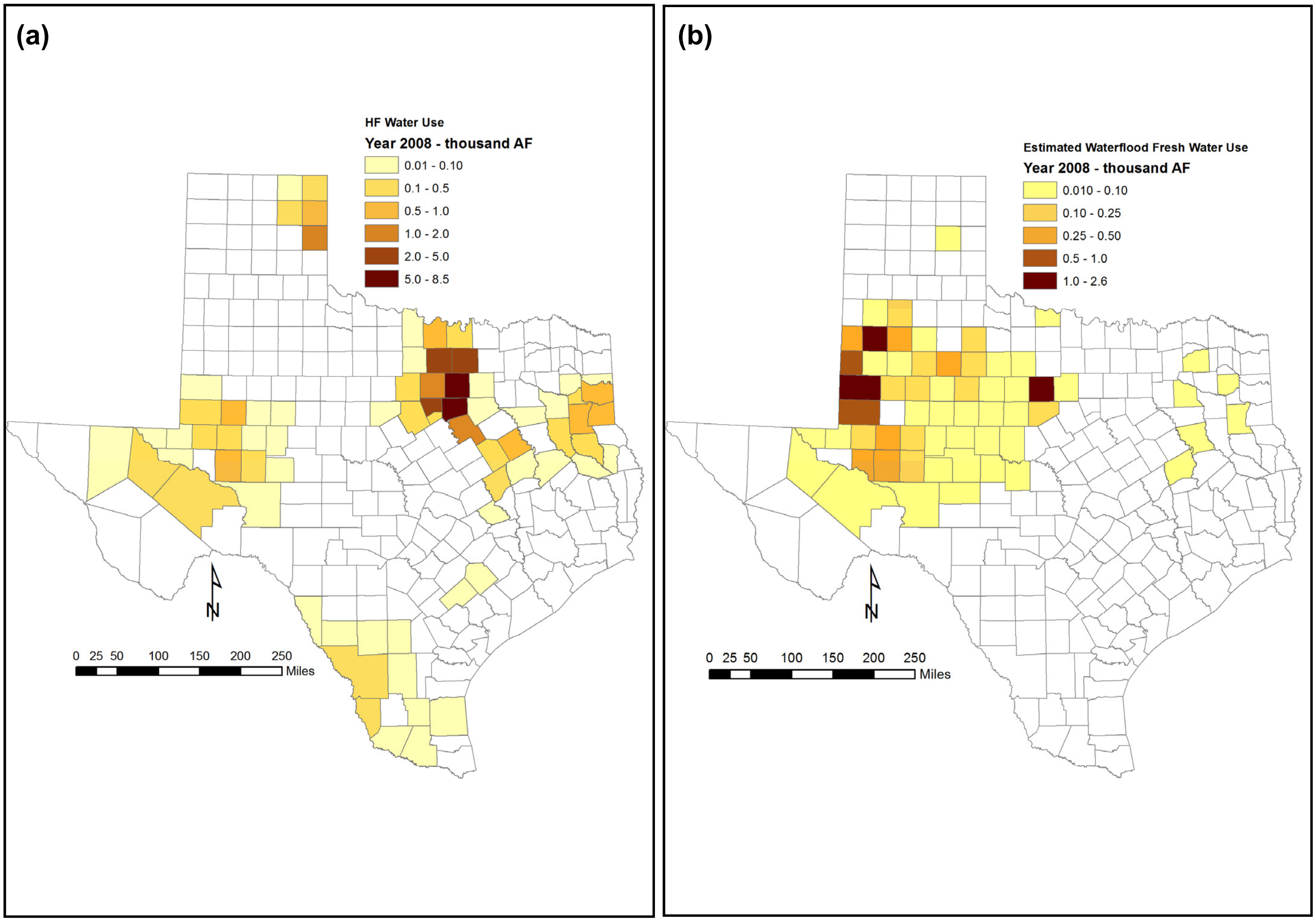
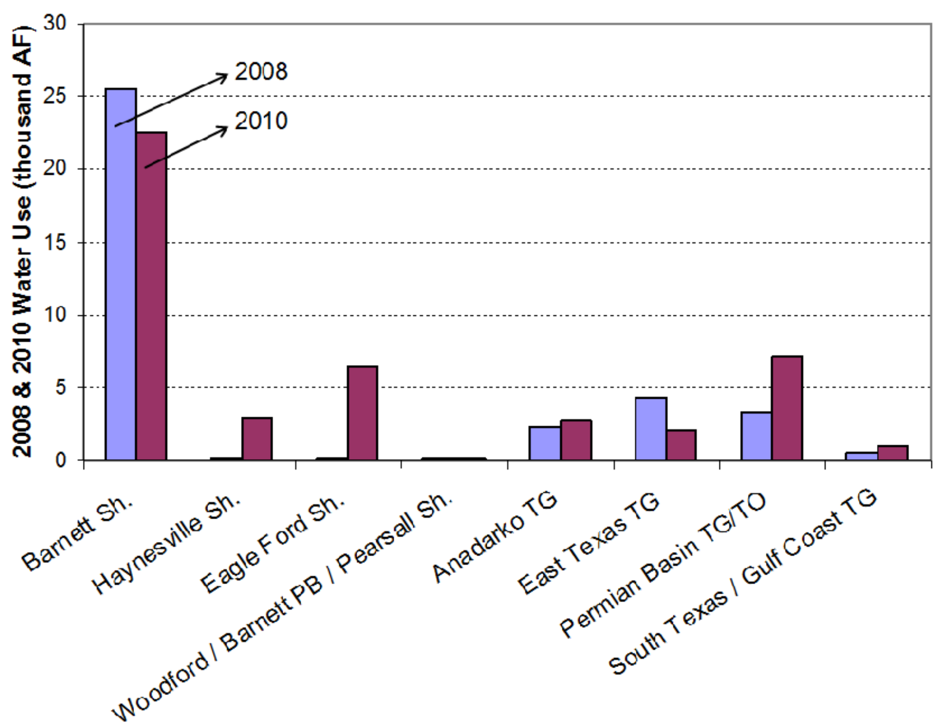


Figure 4. (a) County-level HF water use and (b) waterflood fresh-water use (2008).

Figure 5. Water use for well completion in gas shales and tight formations (2008 and 2010).



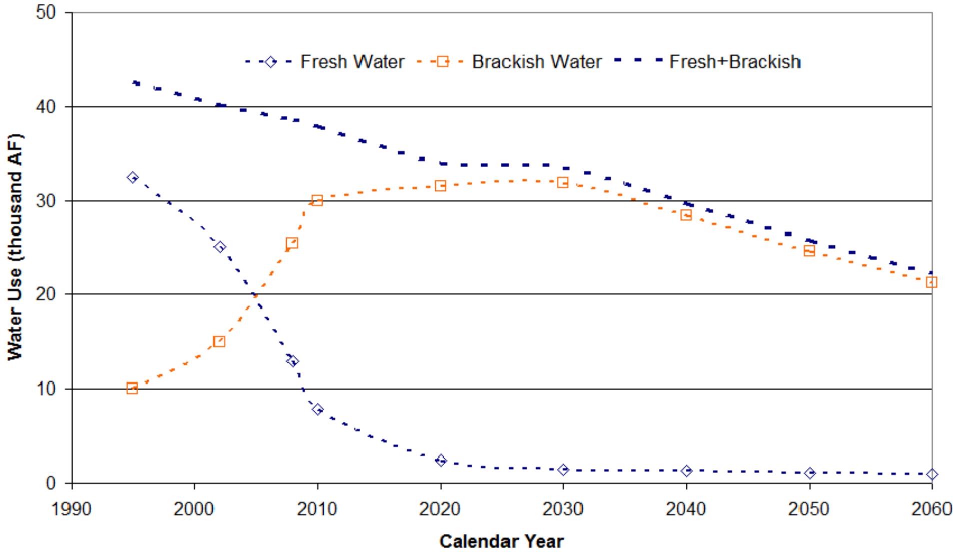


Figure 6. Statewide estimated current and projected fresh- and brackish-water use for pressure maintenance and secondary and tertiary recovery operations. The 1995 data points are from 1995 RRC survey and are fairly accurate; other data points represent interpolation and extrapolation from 1995 survey guided by Galusky (2010) survey.

Tight-gas plays are discontinuous and cannot be approached exactly as the gas shales were. In addition, most of them have been producing both conventional and tight gas for years. Their water use is also smaller for these very reasons: less gas to recover and only a small fraction of a county is of interest. Water use in East Texas Basin tight-gas plays is projected to peak in 2024 at 5.5 kAF. Water-use projections for the Anadarko Basin will peak at 3.1 kAF in 2020. The south Gulf Coast Basin has a small projected water use of 2.4 kAF distributed over many counties at its peak (2027). The Permian Basin, which has a higher potential, shows the highest water use in 2017 at 7.8 kAF, distributed over many counties as well (Nicot et al., 2011).

Overall water use of HF will increase from the current ~37 kAF to a peak of ~120 kAF by 2020–2030 (Fig. 7). However, uncertainty is large. We assumed no major technological breakthrough in HF technology and no more than a small incremental annual increase in efficiency.

Waterflood and EOR projections of overall water use, estimated at ~8 kAF in 2010, is decreasing through time because of the built-in assumption of decreased fresh-water use for the purpose of waterflood and other recovery processes (Figs. 6 and 8). The amount of fresh water used in drilling shale-gas wells is variable and is a function of the play. Including water use from shale-gas activity yields a peak of 13 kAF within the current decade (Fig. 8).

Coal

Coal resources are plentiful in Texas and are unlikely to be exhausted within the next 5 decades at the current average production rate. All mines currently in production, except Jewett Mine, which is slated to end production around 2025, are assumed to keep producing at a rate similar to the current one. Three Oaks Mine came on line recently (2005) after Sandow Mine retired. Two new mines will come on line in the next few years: Kosse Mine in Limestone County and Twin Oaks Mine in Robertson County. Future water-use breakdown for these two mines was estimated from Jewett and Calvert mines, respectively.

Water projections are done in two steps: (1) compiled survey returns are distributed to counties (one or two, if mine is across county lines) and (2) an annual growth rate is applied. Examining current and known future mines (Step 1 only) at the state level reveals that water use is assumed to ramp up from ~20,000 AF/yr to ~35,000 AF/yr, mostly because of Three Oak and Twin Oak Mines. Other mines' water use remains relatively steady (Nicot et al., 2011). Adding an annual growth rate of 0.9% (EIA, 2011) increases projected water use to ~55,000 AF/yr in 2060. EIA projections go only to 2035, and we extrapolated the same trend to 2060. Figure 9 also depicts the claim by EIA, corroborated by discussions with industry experts, that the share of coal and natural gas will stay relatively constant in the energy mix. Overall, most of the water is groundwater, little of which is consumed and most of which is discharged to streams. The focus on conservation of groundwater will probably strengthen, and beneficial use of aquifer water will increase, essentially transferring water use from the coal-mining category to the municipal or manufacturing category.

Aggregates

Projections for future aggregate-water use relate population growth and aggregate production growth (Fig. 10). We assumed that crushed stone and construction sand and gravel will follow a trajectory similar to that of the past 2 decades. The increased gap between crushed-stone and sand and gravel operations (Fig. 10) is consistent with the societal trend of having large operations at one location for a long period of time, rather than having dispersed, generally smaller, sand and gravel operations. However, both categories are expected to grow in the future. The overall growth rate is 1.5%–2% (Nicot et al., 2011). Some analysts have projected a higher annual growth in the industry of 3%–5% (Walden and Baier, 2010). How a 3% annual growth (translating into a production of ~1200 million instead of ~550 million tons in 2060) can be sustained in terms of water use without increasing water recycling or developing dry processes is not, however, clear. Aggregate operations are located mostly close to large cities, and their water needs will eventually conflict with those of expanding cities. The aggregate water-use projections can therefore be construed as either modest annual growth with no change from current practices or higher annual growth with concomitant decrease in water-use intensity. Overall aggregate water use will increase from ~75 kAF/yr in 2010 to ~140 kAF/yr in 2060.

Table 5. Estimates of groundwater–surface water split with estimates of withdrawal vs. consumption (year 2008).

Mining Category	Total Withdrawal	Consumption	Withdrawal Groundwater	Withdrawal Surface Water	Consumption Groundwater	Consumption Surface Water
Barnett Shale	25,446	25,446	10,178	15,268	10,178	15,268
Haynesville and Bossier shales	106	106	74	32	74	32
Eagle Ford Shale	68	68	68	0	68	0
Permian B. and other Sh.	89	89	89	0	89	0
Anadarko B.	2224	2224	1334	890	1334	890
East Texas B.	4258	4258	2555	1703	2555	1703
Permian B. + C.T. Fm.	3253	3253	1952	1301	1952	1301
Gulf Coast B.	604	604	362	242	362	242
Total Fracking	***36,048***	***36,048***	***16,612***	***19,436***	***16,612***	***19,436***
Waterflood	12,951	12,951	10,361	2590	10,361	2590
Drilling	8000	8000	7200	800	7200	800
Total Oil & Gas	**56,999**	**56,999**	**34,173**	**22,826**	**34,173**	**22,826**
Coal*	**19,895**	**2560**	**18,449**	**1452**	**1116**	**1447**
Crushed Rock	53,328	33,034	26,160	6873	26,160	6873
Sand & Gravel	18,293	13,066	5227	7840	5227	7840
Total Aggregate**	**71,621**	**46,100**	**31,387**	**14,713**	**31,387**	**14,713**
Other**	**11,000**	**6814**	**5396**	**1418**	**5396**	**1418**
Total Mining	**159,515**	**112,473**	**89,405**	**40,409**	**72,072**	**40,404**
		70.5% of Total Withdrawal	**56.0% of Total Withdrawal**		**64.1% of Total Consumption**	

Note: * a large fraction of withdrawal is for depressurization; ** difference between withdrawal and consumption is 'storm water' whose ultimate origin is unclear (groundwater seepage, surface drainage of the facility); and B.= basin; Sh. = shale; and C.T. Fm. = Caballos and Tesnus formations.

Other Mineral Resources

Industrial-sand mining is more water intensive than the closely related aggregate category. Industrial-sand production is clearly connected to the increase in well stimulation/ HF through the use of proppants (Fig. 11). Assuming that the water coefficient would linearly improve from the current 620 gal/t to a value of 350 gal/t in 2060 (Nicot et al., 2011), the maximum water use close to 18 kAF is projected to be reached between 2020 and 2030 (Fig. 12, 'Others' category).

Conclusions

Combining all water uses, projections suggest that peak mining-water use will occur between 2020 and 2030 at 300+ kAF, sustained by transient oil and gas activities (Fig. 12). HF represents the most significant fraction of oil and gas mining use (Fig. 8). Percentages of oil and gas water use currently below 50% of total water use would reach its largest fraction above 50% between 2015 and 2025 and slowly decrease (assuming no widespread refracking). HF is dominant in that use. Eventually oil and gas water use will recede and be slowly overtaken by aggregate-water use, which is projected to constitute two-thirds of total mining-water use by 2050.

IMPACT ON AQUIFERS

Mining-water use represents a small fraction of the state's total water use but may be significant at the local scale, although studies besides anecdotal observations to support the statement either way are scarce. Groundwater represents more than half of the withdrawals and almost two-thirds of the consumption (Table 5). Aquifers impacted by aggregate production are the Trinity and the Edwards aquifers. The Carrizo-Wilcox (Fig. 13), particularly the middle Wilcox in Central Texas known as the Simsboro Formation, is impacted by lignite-mine depressurization. The Carrizo aquifer has been used by oil and gas operators in the Eagle Ford footprint and in East Texas. The Ogallala and Edwards-Trinity aquifers have been targeted by oil operators in the Permian Basin. Nicot and Scanlon (2012) noted that these aquifers have all been subjected to regional decline in water levels owing to municipal use or irrigation and that some had started to recover. The unresolved question is whether transient oil and gas use will subside fast enough to allow for municipal-water use increase (which is due to population growth) in areas where they compete (Barnett Shale and Trinity aquifer in the Dallas–Fort Worth metroplex area, Eagle Ford Shale and Carrizo aquifer in the San Antonio area, and several smaller cities). The sharp increase in water use in rural areas where the baseline is low can also lead to local issues (water-level drop), although the aquifer itself would not be in danger.

Bené et al. (2007) incorporated Barnett Shale early development into their analysis of the Trinity aquifer and concluded that municipal use is the driver for water-level decline but is locally exacerbated by HF water use. They also noted the transient nature of HF on aquifer water levels. Dutton et al. (2003) projected water use from the central section of the Carrizo-Wilcox aquifer, and modeling results suggest that depressurization of lignite

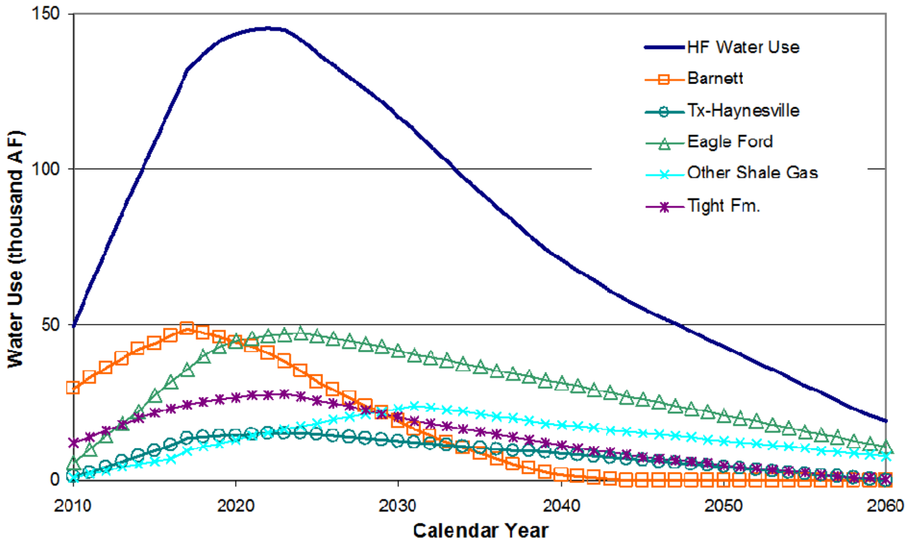


Figure 7. Summary of projected HF water use (2010–2060) showing statewide total, individual shale plays, and statewide tight-formation water use.

mines does not impact municipal well fields tapping the same aquifer. Huang et al. (2012) presented a recent analysis of the Carrizo-Wilcox aquifer, including its southern section in the footprint of the Eagle Ford Shale, demonstrating that recovery from the heavy irrigation of the second half of the 20th century may take 100 yr or more. How HF water use will impact that same section of the aquifer is unclear. Lindgren et al. (2004) modeled the Edwards aquifer and noted that most mining (aggregate) withdrawals were in Comal County. However, the aquifer is dynamic, with water levels responding quickly to temporal and spatial variations in recharge and mostly municipal withdrawals with no long-term decline.

CONCLUSIONS

Throughout 2008, the mining and oil and gas industry as a whole withdrew ~160 kAF of fresh water, most of it consumption. The distinction between withdrawals and consumed amounts is not always straightforward. The coal industry produces large amounts of fresh water that are not counted toward consumption in this paper but that contribute to aquifer depletion. The so-called stormwater from aggregate and similar facilities is not counted toward consumption, although some fraction is undoubtedly groundwater.

The uncertainty associated with the ~160 kAF is relatively high because only figures from the coal industry (20 kAF) are relatively well known. Water usage for HF in the oil and gas industry is also relatively well constrained (35.8 kAF) because it is reported to the RRC with other parameters gathered during well completion. Other water uses in the oil and gas industry such as for drilling and waterfloods and CO_2-EOR (21 kAF) are known by about a factor of 2. Fresh-water use for aggregate and similar commodities (lime, industrial sand, etc.) production are not well known and rely on educated guesses supported by limited survey results. We also estimate that fresh-water use is known by about a factor of 2 for sand and gravel operations and maybe by a factor of 1.5 for generally larger crushed stone and industrial sand operations. Although water use from some large facilities or some small contributors (uranium, metallic substances) is well documented, they make up only a small fraction of the total state water use. Applying these uncertainty factors implies that true water use is within the 125–235 kAF range, although these bounds are much less likely than the value of ~160 kAF derived in this document. Besides the accuracy and representivity of the collected data, higher-level uncertainties exist, particularly for the oil and gas industry. Multiple HF operations on a single well in hopes of periodically improving its production (refracking), although not currently widespread, may become more common in the future. We also limited the analysis to known plays. More plays may eventually be hydraulically fractured, such as in the lower Gulf Coast, which has seen little HF activity, or in the deeper Permian Basin. A renewed interest in residual oil zones (ROZs), which contain large volumes of oil at residual saturation next to conventional reservoirs, could also increase water use for CO_2-EOR (Melzer et al., 2006). These harder-to-predict developments were not included in the analysis.

Projections for 2010–2060 suggest a mining-water-use peak occurring in between 2020 and 2030 at 300+ kAF, decreasing to ~240 kAF by 2060. Many assumptions went into the building of the projections, particularly in relation to activities of the oil and gas industry. Water use for counties in which a large component of mining-water use is from shale-gas HF or counties overlying currently little-known (mostly deep) oil or gas accumulations can deviate dramatically from projections, owing to political/legal and economic factors. The ramp-up to full activity in particular could be steeper than anticipated. To reduce the uncertainty of long-term water sourcing and to limit competition with other users, oil and gas operators have turned their interest to alternative sources of water, such as brackish water.

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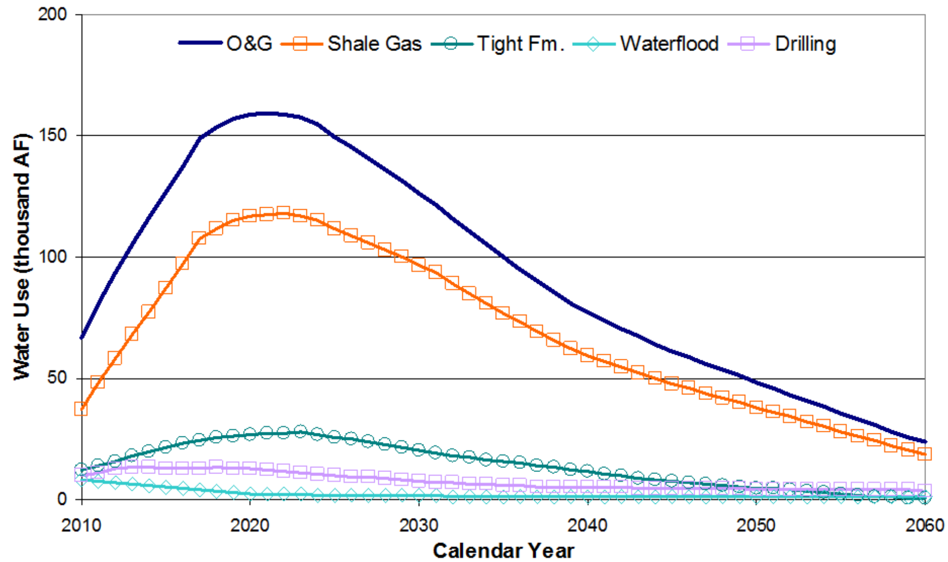

Figure 8. Summary of projected water use in oil and gas segment (2010–2060), including statewide water use for shale and tight-formation plays (whose sum is displayed in Figure 7), waterflood, and drilling.

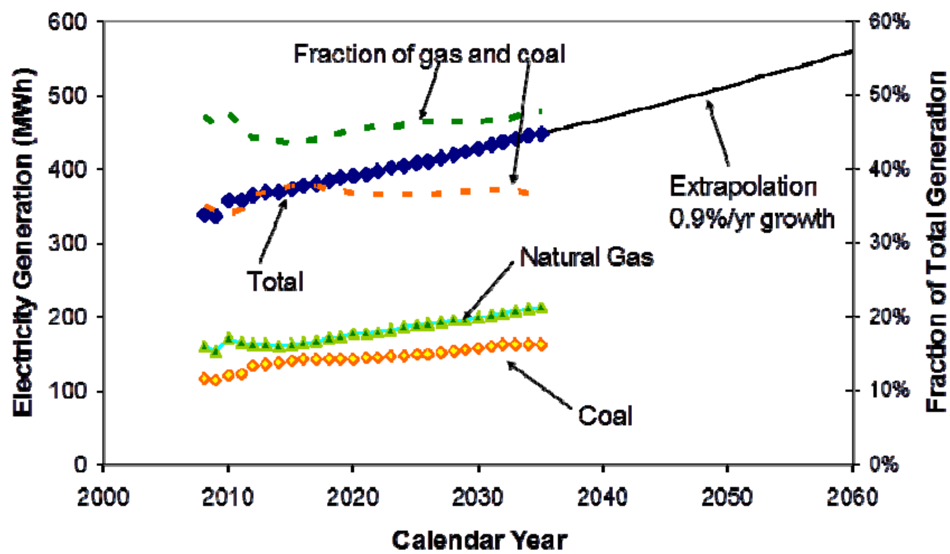

Figure 9. EIA projection of sources of energy for electricity generation to 2035 in Texas (EIA, 2011).

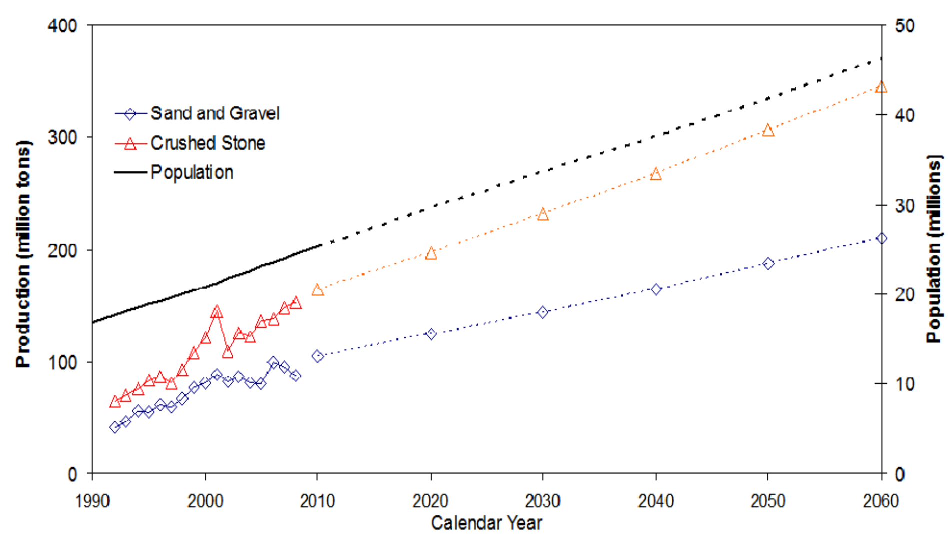

Figure 10. Historical values for Texas population and statewide aggregate production extrapolated to depict projections for future population and aggregate production used for water-use projections.

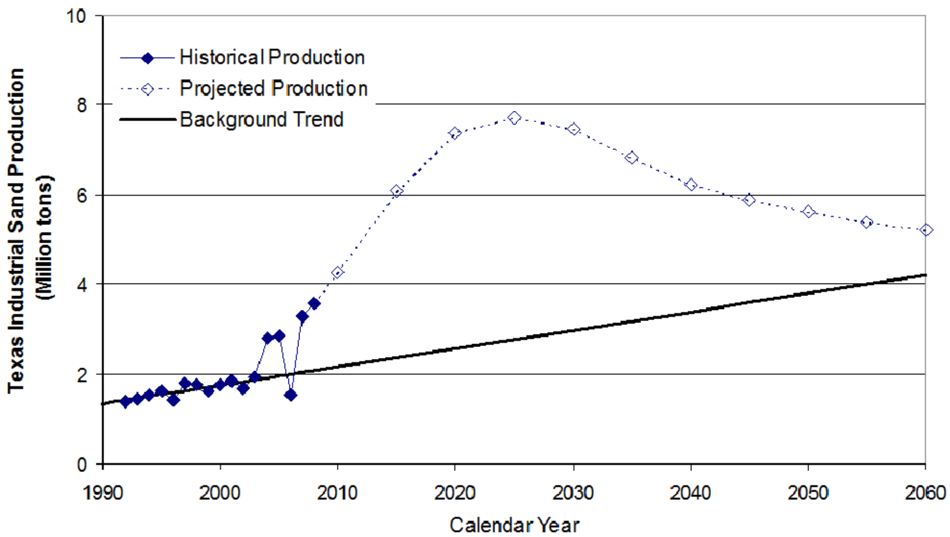

Figure 11. Projection of industrial-sand production. Departure from background trend can be attributed to use by oil and gas industry.

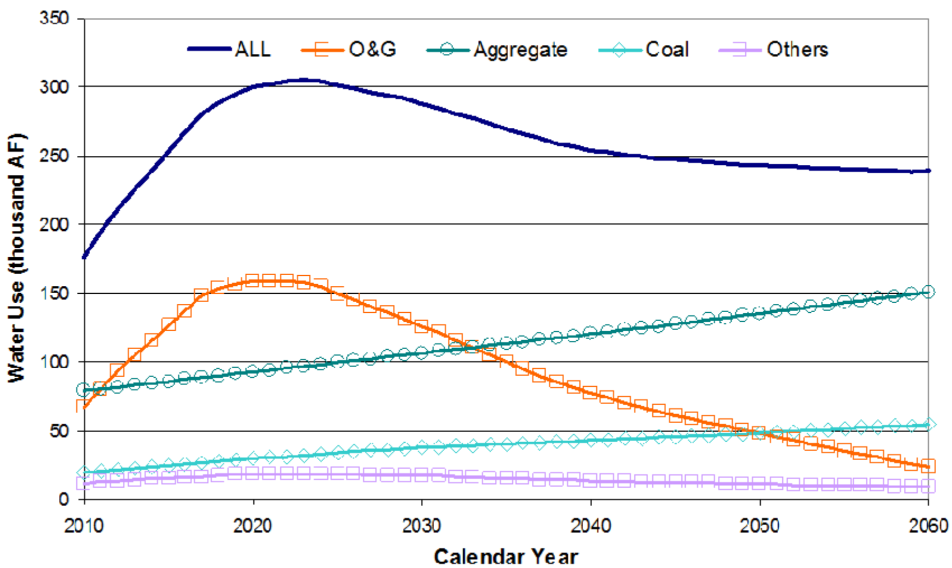

Figure 12. Summary of projected water use by mining-industry segment (2010–2060).

REFERENCES CITED

Ambrose, W. A., C. Breton, S. D. Hovorka, I. J. Duncan, G. Gülen, M. H. Holtz, and V. Núñez-López, 2010, Geologic and infrastructure factors for delineating areas for clean coal: Examples in Texas, USA: Environmental Earth Sciences, doi:10.1007/s12665–010–0720–2.

Bené, P. G., R. Harden, S. W. Griffin, and J.-P., Nicot, 2007, Northern Trinity/Woodbine aquifer groundwater availability model: Assessment of groundwater use in the northern Trinity aquifer due to urban growth and Barnett Shale development: Report prepared by Harden, R. W., and Associates for Texas Water Development Board, 50 p., <http://www.twdb.state.tx.us/groundwater/models/gam/> Last Accessed May 2012.

Chan, M., J. Duda, S. Forbes T. Rodosta, R. Vagnetti, and H. McIlvried, 2006, Emerging issues for fossil energy and water: U.S. Department of Energy, National Energy Technology Laboratory, DOE/NETL–2006/1233, <http://www.netl.doe.gov/technologies/oil-gas/publications/AP/IssuesforFEandWater.pdf> Last Accessed September 19, 2012.

Coleman, J., 2009, Tight-gas sandstone reservoirs: The 200-year path from unconventional to conventional gas resource and beyond: Proceedings of the 29th Annual Gulf Coast Section of the Society of Economic Paleontologists and Mineralogists Foundation Bob F. Perkins Research Conference, Houston, Texas, p. 397–441.

Curry, M., T. Maloney, R. Woodroof, and R. Leonard, 2010, Less sand may not be enough: Society of Petroleum Engineers Paper 131783, Richardson, Texas, 14 p.

De Leon, F., 1996, Results of fresh water injection survey, January 22: Internal memorandum to David E. Schieck, Director of the Oil and Gas Division at the Railroad Commission, 14 p.

Dutton, A. R., R. Harden, J.-P. Nicot, and D. O'Rourke, 2003, Groundwater availability model for the central part of the Carrizo-Wilcox aquifer in Texas: Report prepared by the Texas Bureau of Economic Geology for the Texas Water Development Board, 295 p., <http://www.twdb.state.tx.us/groundwater/models/gam/> Last Accessed May 2012.

Dutton, S. P., S. J. Clift, D. S. Hamilton, H. S. Hamlin, T. F. Hentz, W. E. Howard, M. S. Akhter, and S. E. Laubach, 1993, Major low-permeability-sandstone gas reservoirs in the continental United States: Texas Bureau of Economic Geology Report of

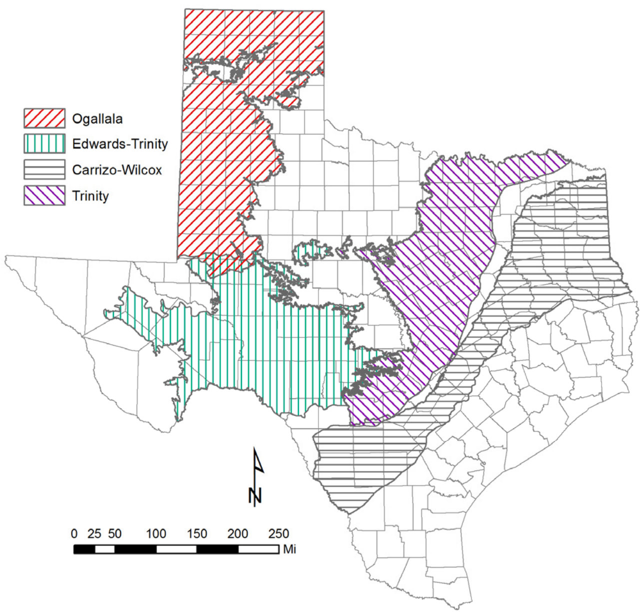

Figure 13. Selected Texas major aquifers.

Investigations 211, Austin, 221 p.

Dutton, S. P., E. M. Kim, R. F. Broadhead, C. L. Breton, W. D. Raatz, S. C. Ruppel, and C., Kerans, 2005, Play analysis and leading-edge oil-reservoir development methods in the Permian basin: Increased recovery through advanced technologies: American Association of Petroleum Geologists Bulletin, v. 89, p. 553–576.

EIA (Energy Information Administration), 2011, 2011 annual energy outlook, data tables, <http://www.eia.gov/forecasts/aeo/data.cfm> Last Accessed March 2012.

Galusky, L. P., Jr., 2010, West Texas water use estimates and forecasts for oil exploration and production activities: Report prepared by Texerra LLC, Midland, Texas, for the Texas Bureau of Economic Geology, Austin, 7 p. and spreadsheets.

Guyton, W. F., 1965, Ground water for the oil industry in Texas and southeast New Mexico, *in* Oil and water-related resource problems of the southwest: A symposium of the Southwestern Federation of Geological Societies and University of Texas at Austin, January 29, p. 40–51

Hammes, U., 2009, Sequence stratigraphy and core facies of the Haynesville mudstone, east Texas: Gulf Coast Association of Geological Societies Transactions, v. 59, p. 321–324.

Hentz, T. F., and W. A. Ambrose, 2010, Cleveland and Marmaton tight-gas reservoirs (Pennsylvanian), northwest Anadarko Basin: Sequence stratigraphy, depositional framework, and production controls on tide-dominated systems: Houston Geological Society Bulletin, v. 52, no. 9, p. 25–29.

Hentz, T. F., and S. C. Ruppel, 2010, Regional lithostratigraphy of the Eagle Ford shale: Maverick basin to east Texas basin: Gulf Coast Association of Geological Societies Transactions, v. 60, p. 325–337.

Huang, Y., B. R. Scanlon, J.-P. Nicot, R. C. Reedy, A. R. Dutton, V. A. Kelley, and N. E. Deeds, 2012, Sources of groundwater pumpage in a layered aquifer system in the upper Gulf Coastal plain, USA: Hydrogeology Journal, doi:10.1007/s10040-012-0846-2.

Hutson, S. S., N. L. Barber, J. F. Kenny, K. S. Linsey, D. S. Lumia, and M. A. Maupin, 2005, Estimated use of water in the United States in 2000: U.S. Geological Survey Circular 1268, 46 p.

IHS Enerdeq, 2010, Private data provider, access to most historical water use for completion in Texas, <http://www.ihs.com/products/oil-gas-information/data-access/enerdeq/browser.aspx> Last Accessed March 2012.

Kenny, J. F., N. L. Barber, S. S. Hutson, K. S. Linsey, J. K. Lovelace, and M. A. Maupin, 2009, Estimated use of water in the United States in 2005: U.S. Geological Survey Circular 1344, 52 p.

King, C. W., I. J. Duncan, and M. E. Webber, 2008, Water demand projections for power generation in Texas: Report prepared by the Texas Bureau of Economic Geology for the Texas Water Development Board, Austin, 90 p., <http://www.twdb.state.tx.us/RWPG/rpgm_rpts/0704830756ThermoelectricWaterProjection.pdf> Last Accessed March 2012.

Kyle, J. R., 2008, Industrial minerals of Texas: Texas Bureau of Economic Geology, Austin, scale ca. 1:6,336,000.

Kyle, J. R., and S. Clift, 2008, Geology of Texas industrial minerals, *in* Proceedings of 44th Forum on the Geology of Industrial Minerals Annual Meeting, Oklahoma Geological Survey, May 11–16.

Lindgren, R. J., A. R. Dutton, S. D. Hovorka, S. R. H. Worthington, and S. Painter, 2004, Conceptualization and simulation of the Edwards aquifer, San Antonio region, Texas: U.S. Geological Survey Scientific Investigations Report 2004–5277, 143 p.

Mavis, J., 2003, Water use in industries of the future: Mining industry: Report prepared by CH2M Hill, Seattle, Washington, for the U.S. Department of Energy, Washington DC, 7 p.

Melzer, L. S., G. J. Koperna, and V. A. Kuuskraa, 2006, The origin and resource potential of residual oil zones: Society of Petroleum Engineers Paper 102964, Richardson, Texas, 14 p..

MSHA (Mine Safety and Health Administration), 2010, Raw data for Texas not in the public domain.

Mohr, S. H., and G. M. Evans, 2010, Shale gas changes N. American gas production projections: Oil and Gas Journal, July 26, p. 60–64.

Nicot, J.-P., 2009, Assessment of industry water use in the Barnett shale gas play (Fort Worth basin): Gulf Coast Association of Geological Societies Transactions, v. 59, p. 539–552.

Nicot, J.-P., and B. R. Scanlon, 2012, Water use for shale-gas production in Texas, U.S.: Environmental Science and Technology, v. 46, p. 3580–3586, <http://dx.doi.org/10.1021/es204602t> Last Accessed September 19, 2012.

Nicot, J.-P., A. K. Hebel, S. M. Ritter, S. Walden, R. Baier, P. Galusky, J. A. Beach, R. Kyle, L. Symank, and C. Breton, 2011, Current and projected water use in the Texas mining and oil and gas industry: Report prepared by the Texas Bureau of Economic Geology for the Texas Water Development Board, Austin, 357 p., <http://www.twdb.state.tx.us/RWPG/rpgm_rpts/0904830939_MiningWaterUse.pdf> Last Accessed March 2012.

Pollastro, R. M., D. M. Jarvie, R. J. Hill, and C. W. Adams, 2007, Geologic framework of the Mississippian Barnett shale, Barnett-Paleozoic total petroleum system, Bend Arch–Fort Worth Basin, Texas: American Association of Petroleum Geologists Bulletin, v. 91, p. 405–436.

Quan, C. K, 1988, Water use in the domestic non-fuel minerals industry: U.S. Bureau of Mines Information Circular 9196, 61 p.

NSSGA (National Stone, Sand, and Gravel Association), 2010, Aggregates industry atlas of the U.S., in collaboration with the U.S. Geological Survey, CD-ROM publication.

RRC (Railroad Commission of Texas), 1982, A Survey of secondary and enhanced recovery operations in Texas to 1982: Railroad Commission of Texas, Oil and Gas Division, Underground Injection Control, Austin, and Texas Petroleum Research Committee, College Station, 608 p.

Sinha, S., and H. Ramakrishnan, 2011, A novel screening method for selection of horizontal refracturing candidates in shale gas reservoirs: Society of Petroleum Engineers Paper 144032, 10 p.

Solley, W. B., R. R. Pierce, and H. A. Perlman, 1998, Estimated use of water in the United States in 1995: U.S. Geological Survey Circular 1200, 71 p.

Spain, D. R., and G. A. Anderson, 2010, Controls on reservoir quality and productivity in the Haynesville shale, northwestern Gulf of Mexico basin: Gulf Coast Association of Geological Societies Transactions, v. 60, p. 657–668.

TWDB (Texas Water Development Board), 1997, Water for Texas, vol. II: Document GP–6–2, Austin, variously paginated.

TWDB (Texas Water Development Board), 2002, Water for Texas, vol. I: Document GP–7–1, Austin, 156 p.

TWDB (Texas Water Development Board), 2007, Water for Texas, vol. II: Document GP–8–1, Austin, 392 p.

TWDB (Texas Water Development Board), 2012, Water for Texas: Document GP–9–1, Austin, 299 p.

U.S. Census Bureau, 2005, Texas 2002: Economic census, mining, geographic areas series, variously paginated: Report EC02–21A–TX, <http://www.census.gov/prod/ec02/ec0221atx.pdf> Last Accessed June 2010.

USGS (U.S. Geological Survey), 2009, 2006 Minerals yearbook: Texas, <http://minerals.usgs.gov/minerals/pubs/state/tx.html> Last Accessed June 2010.

USGS (U.S. Geological Survey), 2010, 2008 Minerals yearbook, <http://minerals.usgs.gov/minerals/pubs/commodity/m&q/myb1-2008-mquar.pdf> Last Accessed March 2012.

Walden, S., and R. Baier, 2010, Water use in the Texas industrial mineral mining industry: Report prepared by Steve Walden Consulting for the Texas Bureau of Economic Geology, Austin, 39 p. and appendices.