Environmental Science & Technology

Article

pubs.acs.org/est

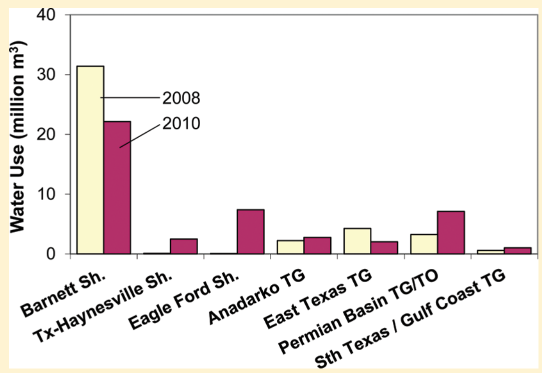
Water Use for Shale-Gas Production in Texas, U.S.

Jean-Philippe Nicot* and Bridget R. Scanlon

Bureau of Economic Geology, Jackson School of Geosciences, The University of Texas at Austin, 10100 Burnet Road, Building 130, Austin, Texas 78758, United States

Supporting Information

ABSTRACT: Shale-gas production using hydraulic fracturing of mostly horizontal wells has led to considerable controversy over water-resource and environmental impacts. The study objective was to quantify net water use for shale-gas production using data from Texas, which is the dominant producer of shale gas in the U.S. with a focus on three major plays: the Barnett Shale (~15 000 wells, mid-2011), Texas-Haynesville Shale (390 wells), and Eagle Ford Shale (1040 wells). Past water use was estimated from well-completion data, and future water use was extrapolated from past water use constrained by shale-gas resources. Cumulative water use in the Barnett totaled 145 Mm^3 (2000−mid-2011). Annual water use represents ~9% of water use in Dallas (population 1.3 million). Water use in younger (2008−mid-2011) plays, although less (6.5 Mm^3 Texas-Haynesville, 18 Mm^3 Eagle Ford), is increasing rapidly. Water use for shale gas is <1% of statewide water withdrawals; however, local impacts vary with water availability and competing demands. Projections of cumulative net water use during the next 50 years in all shale plays total ~4350 Mm^3, peaking at 145 Mm^3 in the mid-2020s and decreasing to 23 Mm^3 in 2060. Current freshwater use may shift to brackish water to reduce competition with other users.



INTRODUCTION

Natural gas has spurred intense interest in reducing greenhouse gases and enhancing energy security. Natural gas produces emissions that are much lower than those from oil and coal: 30%−40% lower for CO_2, 80% for NO, and ~100% for SO_2, particulates, and mercury.[1] Natural gas is used widely for industrial (31%), electric power (27%), residential (22%), commercial (14%), and other purposes (mean 2000−2010).[2] Production of natural gas from hydrocarbon-rich shales is referred to as shale gas. Shales contain gas in micropores, fractures, and adsorbed onto organic matter. Conventional gas has been produced from permeable geologic formations for decades; however, within the past decade, advances in directional drilling, combined with breakthroughs in fracking in Texas, have allowed large-scale expansion of gas production from low-permeability shale formations at depths of >1 km. Shale-gas reservoirs differ from typical oil and gas reservoirs in that the shale serves as the source rock, reservoir, and seal. Although older wells in older plays, such as the Barnett, and exploratory wells in newer plays are vertical (Supporting Information, A), most wells are currently drilled vertically almost to the depth of the shale formation, then deviated to the horizontal and drilled horizontally within the shale. Fracking involves injection of water containing chemical additives and proppant (e.g., sand) under high pressure to fracture the shales.[3] Early expansion of shale-gas production was restricted primarily to the Barnett Shale in Texas, which was the main producer in the 2000s, accounting for 66% of shale-gas production in the U.S. in 2007−2009;[2] however, shale gas is currently produced in 22 of the 50 states, and production increased by an annual average rate of ~50% between 2006 and 2010.[4] Shale-gas production is projected to increase from 23% of U.S. natural gas production in 2009 to 47% by 2035.

Energy and water production are interdependent. In the shale-gas context, there is a strong correlation between water injected and gas production (Supporting Information, B). Most studies of water-resource impacts from shale-gas exploration and production have focused on effects of fracking on water quality;[5] however, some studies also emphasize impacts on water quantity.[6−10] Few published studies quantify water use for shale-gas production and their environmental impact.[11−13] Water use for hydraulically fracturing wells varies with the shale-gas play, the operator, well depth, number of fracking stages, and length of laterals. To date, generally fresh water (total dissolved solids <1000 mg/L) has been used for fracking, sourced from surface water or groundwater, depending on local availability. The commonly used polyacrylamide additives (friction reducers) function best in fresh water.[14]

Impacts of water production for shale-gas development depend on water availability in the region and competing demands for water from other users. Limited water availability in semiarid regions may restrict shale-gas production. Impacts range from declining water levels at the regional[10−12] or local[6]

Received: December 21, 2011
Revised: February 22, 2012
Accepted: March 1, 2012
Published: March 2, 2012

scales and related decreases in base flow to streams. Although shale-gas production is currently mostly limited to North America, large reserves have been estimated in other regions globally, and water availability may be more problematic in some of these regions, such as northwest China and South Africa, where water scarcity is already a problem.[15,16]

The objective of this study was to quantify net water use (water consumption) for shale-gas production using the major shale-gas plays in Texas as examples (Barnett, Haynesville, and Eagle Ford shales) (Figure 1) and focusing on the single best-estimate scenario. Overall fracking activities in Texas show little difference between water use and net water use. Texas has the longest history of shale-gas production, and impacts on water quantity should serve as a guide for production in younger plays in the U.S. and globally. Experience from Texas shale-gas plays provides insights into water-quantity requirements and water-use.

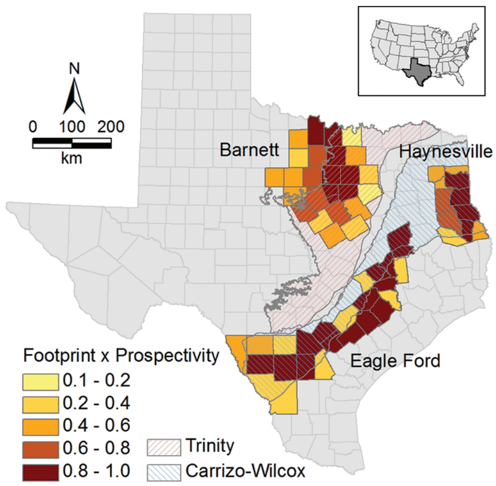


Figure 1. Location of major shale-gas plays in Texas. Colors represent the product of fraction of county area within play footprint (number >0 and ≤1) and prospectivity (number >0 and ≤1). Core counties in the Barnett include Denton, Johnson, Tarrant, and Wise. Core counties in the Haynesville include Harrison, Panola, Shelby, and San Augustine. Counties of interest in the Eagle Ford are Dimmit, De Witt, Karnes, La Salle, Live Oak, and Webb. Outlines of the Trinity and Carrizo Wilcox aquifers are also shown.

■ MATERIALS AND METHODS

Shale-Gas Plays in Texas. The Barnett Shale has been producing gas since the early 1990s and is the formation in which horizontal drilling and fracking were pioneered (Figure 1). Productive Mississippian Barnett Shale is found at depths of 2.0−2.6 km near the Dallas−Fort Worth metroplex, with shale thickness varying from 30 to 180 m. The play, which includes a core area of four counties (7800 km^2 area), extends to all or parts of 26 counties (∼30 000 km^2). The Haynesville Shale extends from Louisiana into Texas, with ∼35% of the play in Texas (Tx-Haynesville). Production in the Upper Jurassic Haynesville Shale began in 2008. Haynesville Shale thickness ranges 60−90 m at 3−4 km depth. The play area is ∼11 500 km^2 in Texas (10 counties), with a core area of 7500 km^2 (four counties). The discovery well for the Eagle Ford Shale was drilled in 2008. The average shale thickness is 75 m, and it is found at depths of 1.2−3.4 km. The play area extends over ∼24 counties (∼50 000 km^2). Some shale plays contain only gas (e.g., the Haynesville), whereas others contain both oil and gas, either at the same location in a so-called combo play (e.g., north section of Barnett) or in spatially distinct zones with oil at shallower depths (e.g., Eagle Ford).

Estimation of Past Water Use for Shale-Gas Production. Water use for shale-gas production in Texas can be readily estimated because operators are required to report water used for completion, including fracking, to the Railroad Commission (RRC) of Texas (forms G-1 and W-2). Unfortunately, because information on source or quality of water is also not required, water use estimates may include a small proportion of slightly brackish water (total dissolved solids <5000 mg/L). Surface water in Texas is owned and managed by the State and requires a water-right permit for diversions. Groundwater is owned mostly by landowners but is generally managed by legislatively authorized groundwater conservation districts (GCDs); nevertheless, groundwater withdrawal for oil and gas exploratory activities, including fracking, is exempt from GCD regulations under the State water code.[10]

Information on water use for fracking for shale-gas production was obtained indirectly from the RRC through a vendor (IHS) database. Water use was either provided in the database or estimated from proppant loading (proppant mass divided by water volume), when available, or from water-use intensity (water use divided by length of vertical or lateral productive interval) for each well. The reliability of water use estimates was evaluated by comparing estimates from different approaches. If discrepancies among various water-use estimates could not be resolved for a particular well, water use was assigned a mean water use in the play (Supporting Information, C). Additional information, such as surface water or groundwater source, was obtained directly from facilities/operators responsible for water use. Wells with water use ≤380 m^3 (0.1 million gallons, Mgal) were omitted from analysis to distinguish simple well stimulation by traditional fracking and acid jobs from the now common high-volume fracking jobs (Supporting Information, C). Data on water use for drilling, rather than fracking, are much more difficult to obtain because operators are not required to report this water use.

Estimation of Future Water Use for Shale-Gas Production. Future water use for shale-gas production was estimated for 2010−2060 based on extrapolation of current trends and performed at the county level (500−8800 km^2 areas) by (1) estimating spatial area of the shale-gas play and most likely spacing between laterals, (2) estimating water-use intensity from historical data, and (3) computing total water use. Estimating spatial well coverage density is an important step. Horizontal well laterals are mostly parallel and oriented approximately perpendicular to minimum local horizontal stress. Distance between laterals ranges approximately from 250 m for oil wells to 300 m for all other wells according to field evidence and discussion with operators. The next steps consisted of (4) adjusting water use for spatial distribution within a county and (5) distributing water use through time. Spatial distribution is controlled by a county-level prospectivity factor (0.3−1.0), which includes assessment of shale depth, thickness, maturity (amount and type of organic matter in shale, thermal maturity, burial history, microporosity, and fracture spacing and orientation), and location relative to core area (Supporting Information, F). The role of the prospectivity factor is to include these variables to the best of our knowledge in the projections. Consequently, this county-level assignment

dx.doi.org/10.1021/es204602t | Environ. Sci. Technol. 2012, 46, 3580−3586

was done on the basis of educated estimates relative to industry projections resulting from discussions with expert geologists.

Temporal distribution of total water use at the county-level was based on assumptions about individual gas-well performance, projections on rig availability, prospectivity, and progress in recycling and reuse. Individual gas-well performance is characterized by initial production (IP), decline curve (how rapidly wells decline from the IP), and cumulative potential (estimated ultimate recovery, EUR). A limiting factor that controls the number of wells drilled each year is the number of available drilling rigs. A lower prospectivity translates into a delayed start date relative to more prospective counties. Recycling and reuse are a strong function of amount of injected water returning to the surface, which is always a relatively small fraction of amount injected.[13] Projections assume a slow annual increase in recycling and reuse up to 20% of total water use in 2060 for the Barnett and Eagle Ford shales (only 3% for Haynesville Shale) to yield the net water use[13] (Supporting Information, E). Refracking can also impact water-use projections. This study assumes that all possible restimulations have already been done and that newer wells will not be restimulated (Supporting Information, H). Earlier projections, following a procedure similar to that presented in this section, but restricted to the Barnett Shale, still hold, increasing confidence in the approach (Figure 2).[12] They also

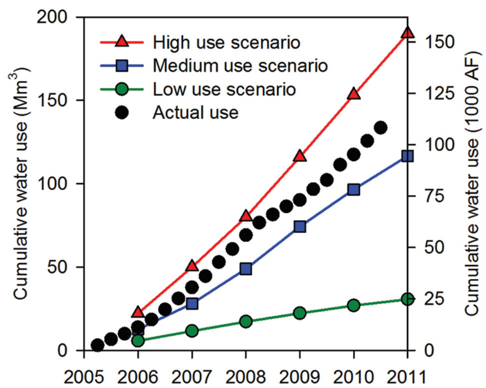


Figure 2. Postaudit analysis of water-use projections (solid lines) made in 2006[12] relative to actual water use (dots) through mid-2011 for the Barnett Shale (cumulative as of June 2011) (tick marks = completed year, so 2011 is 12/31/2011). This figure gives an estimate of the uncertainty associated with the analysis, which provides cumulative water use projections within less than a factor of 2 in the next 5–10 years. The assumption that current trends will still be valid beyond the 10-year horizon becomes weaker with increased uncertainty in the projections. Postaudits of long-term projections show that they often deviate from estimates because of unpredicted events, with unprecedented water-intensive shale-gas production being an example.

suggest that projections of cumulative water use at the play level are valid within a factor of less than 2 at a 5–10-year horizon with increased uncertainty beyond the decade or when the area of interest decreases from shale play to county.

RESULTS AND DISCUSSION

Past Water Use for Shale-Gas Production. Shale-gas production in the U.S. was dominated by production in the Barnett Shale during the past decade, which increased from 0.3 Gm^3 (2000) to 52 Gm^3 (2010) (10–1840 billion cubic feet).[17] Past water use for fracking totaled 145 Mm^3 (117 thousand acre-feet, kAF; 1 AF = 325 851 gal) to June 2011 (Table 1) to

Table 1. Statistics for Major Shale-Gas Plays in Texas[a]

formation	area (km^2)	use (Mm^3)	wells	WUW (m^3)	WUI (m^3/m)	proj (Mm^3)
Barnett	48 000	145	14 900	10 600	12.5	1050
TX-Haynesville	19 000	6.5	390	21 500	14.0	525
Eagle Ford	53 000	18	1040	16 100	9.5	1870
other shales						889
tight formations						895

[a]Area: total area. Use: cumulative water use to 6/2011. Wells: number of wells to 6/2011. WUW: median water use per horizontal well during the 2009–6/2011 period; WUI: median water-use intensity for horizontal wells during the 2009–6/2011 period; Proj: projected additional total net water use by 2060. "Other shales" are mostly located in West Texas, whereas tight formations occur across the state. Note: The same table is reproduced in English units in the Supporting Information.

stimulate ~15 000 wells. Fracking water use in the Barnett in 2010 represented ~9% of the 308 Mm^3 (250 kAF or ~80 000 Mgal) used by the City of Dallas,[18] the ninth-largest city in the U.S. (population 1.3 million 2010). Wells were predominantly vertical until 2005 (~450–600 wells/yr in 2000–2005) when the number of horizontal wells drilled exceeded the number of vertical wells and reached a maximum of ~2500 in 2008 (Figure 3). Water use for horizontal wells in 2010 ranged

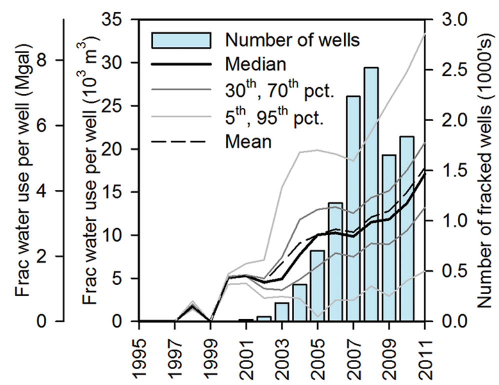


Figure 3. Time evolution of Barnett Shale well count and water use per well percentiles.

2900–20 700 m^3/well (5th–95th percentiles; 0.75–5.5 Mgal), with a median of 10 600 m^3/well (2.8 Mgal) (Supporting Information, D). Water-use percentiles systematically increased during the past decade, as lateral lengths and number of fracking stages increased (Figure 3). Variations in water use among wells result from differences in length of laterals and in water-use intensity (median for horizontal wells of 12.5 m^3/m–1000 gal/ft). Median water use for vertical wells is 4500 m^3 (1.2 Mgal). Water use is reported for most (97% in 2009–2010) Barnett Shale wells. Gas production and water use are concentrated in the core counties, accounting for ~80% of the 31.4 Mm^3 (25.5 kAF) of total water consumed in 2008 (Table 2).

Approximately 1820 wells had been drilled in the entire Haynesville shale-gas play extending into Louisiana by mid-2011, with a total water use of 36 Mm^3 (29.5 kAF), including 390 wells and 6.5 Mm^3 (5.3 kAF) in Texas (Table 1). Currently, most wells are horizontal. Median water use for horizontal wells in the entire Haynesville play in 2010 was 21

Table 2. County-Level 2008 Total and Fracking Water Use in Core Counties[a]

county			2008 net water use				projected net water use		
name	population	area (km^2)	total (Mm^3)[d]	GW (%)	SG (Mm^3)	SG (%)	max (Mm^3)[d]	max (%)	max year
Barnett									
Denton[b]	637 400	2460	120	13	3.4	2.8	2.1	1.7	2010
Johnson	155 200	1880	35	45	10.4	29	4.1	11	2010
Parker	111 600	2390	21	49	2.2	10	4.9	23	2010
Tarrant[b]	174 100	2320	453	5	6.3	1.4	3.9	0.9	2010
Wise	58 500	2400	14	42	2.7	19	5.7	40	2010
Eagle Ford									
De Witt	20 200	2350	8	86			2.8	35	2023
Dimmit	10 000	3460	12	88	0.0	0.1	6.7	55	2015
Karnes	15 300	1970	6	91			2.5	39	2018
La Salle	6000	3840	8	95	0.0	0.1	7.1	89	2019
Live Oak	12 100	2780	8	66			1.0	12	2024
Webb[c]	238 300	8790	56	3	0.0	0.0	2.9	5.2	2013
TX-Haynesville									
Harrison	64 200	2370	45	11	0.1	0.2	3.3	7.4	2017
Panola	23 300	2120	10	37	0.0	0.5	3.0	30	2017
San Augustine	9000	1530	3	30			4.1	136	2017
Shelby	26 200	2160	11	27			5.8	55	2017

[a]Name: county name. Population: estimated 2008 population. Area: county area. Total: total net water use. GW: estimated net groundwater use as a percentage of total net water use. SG: 2008 shale-gas net water use and percentage of 2008 total net water use. Max: projected maximum shale-gas annual net water use and percentage of 2008 total net water use. Max Year: calendar year of projected maximum. http://www.twdb.state.tx.us/wrpi/wus/2009est/2009County.xls. Note: The same table is reproduced in English units in the Supporting Information. [b]Includes City of Fort Worth and other communities relying primarily on imported surface water. [c]Includes City of Laredo. [d]Assumes that the water originates from the county in which it is used.

500 m^3 (5.7 Mgal), ranging from 2700 to 28 100 m^3 (5th and 95th percentiles; 0.7–7.4 Mgal). Water-use intensity is not as clearly defined as it was in the Barnett Shale because of the smaller sample size, but it is slightly higher (14 m^3/m; 1120 gal/ft) than that of the Barnett Shale.

Fracking for shale-gas production in the Eagle Ford Shale began in 2008. Wells drilled in the Eagle Ford Shale totaled 1040 with cumulative water use of 18 Mm^3 (14.6 kAF) by mid-2011 (Table 1). Water use per well ranged from 4600 to 33 900 m^3 (5th and 95th percentiles; 1.2–8.9 Mgal), with a median of 16 100 m^3/well (4.3 Mgal)). Water-use intensity ranged from 3.4 to 22.9 m^3/m (5th–95th percentile; 270–1850 gal/ft), with a median of 9.5 m^3/m (770 gal/ft), currently less than that for the other two plays. This median value quickly decreased from the earlier 15.5 m^3/m (1250 gal/ft) used in the projection section, and that included only 155 wells.[13] Counties with the largest water use are Dimmit, Webb, and La Salle (>50% of total), with six surrounding counties making up the balance, in particular, De Witt, Karnes, and Live Oak, where activity increased in 2011. All of these counties are located in the oil or wet-gas window of the play.

The source of water for fracking is not well documented in Texas. Fracking water in the Barnett Shale for 2005–2007 was estimated to be 60% from groundwater (range 45–100%, depending on the county), but the source varies with time.[11] East Texas, which has abundant surface water, also hosts large aquifers. Haynesville shale-gas production in Louisiana parishes bordering Texas initially relied heavily on local groundwater from the Carrizo aquifer but currently derives ~75% of water from surface water (Pers. comm., Gary Hanson, Louisiana State Univ., Shreveport) or lesser quality shallow groundwater.[19] Surface water in the Eagle Ford footprint is not as abundant as in the northeast sections of the state hosting the Barnett and Haynesville shales, and operators have relied mostly on groundwater from the Carrizo aquifer, except for use of Rio Grande water at the Mexican border.

Additional consumptive water uses related to shale-gas fracking include drilling and sand mining for proppant production, which amount to an additional ~25% water use relative to fracking water use proper[13] (Supporting Information, E). Recycling and reuse of fracking fluid was estimated to range from 5% to 10% for the Barnett Shale and ~0% for the Tx-Haynesville Shale (Supporting Information, E).

Although hydraulic-fracturing net water use in Texas, including other tight plays in West Texas (44.7 Mm^3, 36 kA, in 2008), is significantly higher than net water use for other oil and gas activities (total of 70.6 Mm^3 (57 kAF) in 2008, including fracking, drilling, and waterflooding, injection of water into an oil reservoir), oil and gas mining net water use did not dominate other mining net water uses in Texas (mining net water use total of 197 Mm^3, 160 kAF, in 2008). Aggregate mining, lignite-mine dewatering, and other minor uses represented approximately two-thirds of mining water use in 2008 (Supporting Information, I).[13] In the larger context of overall state water use, mining represented <1% of the total water use of 22 600 Mm^3 (18 300 kAF) in 2008, most of it consumptive.

Projected Water Use for Shale-Gas Development. Projections of gas production for the Barnett Shale are based on earlier projections,[12] supplemented by prospectivity updates for both gas and oil windows by Tian and Ayers.[20] Parameters used for the estimates include play area (48 000 km^2), spacing of laterals (300 m for gas and 250 m for oil), and water-use intensity of 12.5 m^3/m (1000 gal/ft), resulting in a total net water use of 1050 Mm^3 (853 kAF) in 2010–2060 (Table 1). Temporal variations in projected net water use are based on projected peak water production in 2017 at 60 Mm^3 (48 kAF), decreasing to ~0 in 2040 (Figure 4). Projections were

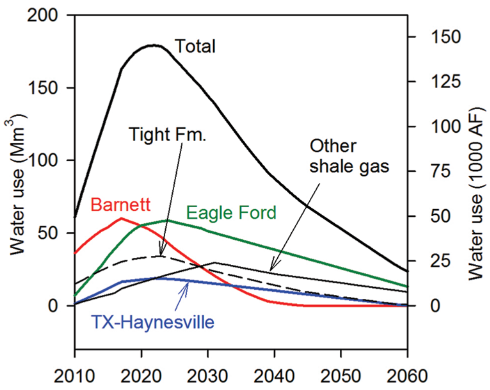


Figure 4. Time evolution in Texas of fracking net water use distributed among the Barnett, Tx-Haynesville, Eagle Ford, and other shale-gas plays to which water-use fracturing of more traditional tight formations is added.

distributed spatially by county according to their respective prospectivity. High water-use counties are outside of the core area, where it is assumed that drilling activity peaked in 2010.

Parameters required for estimating water use for the Tx-Haynesville Shale include play area (19 000 km^2), lateral spacing (300 m), and water-use intensity of 13.6 m^3/m (1100 gal/ft), resulting in a total projected net water use of 525 Mm^3 (425 kAF) peaking at 19.0 Mm^3 (15.4 kAF) in 2022 (Figure 4). Projected water-use estimates for the Eagle Ford play relied on the play area (53 000 km^2), lateral spacing (300 m for gas and 250 m for oil), and water-use intensity of 15.5 m^3/m (1250 gal/ft), resulting in a total net water use of 1870 Mm^3 (1515 kAF) (Table 1) peaking at 58 Mm^3 (48 kAF) in 2024 (Figure 4).

Projected net water use is lowest for the Tx-Haynesville and highest for the Eagle Ford shale-gas plays reflecting variations in gas reserves associated with play area. Projections for these plays are more uncertain than those of the Barnett Shale, because of their young age (2008). Recent information suggests that water-use intensity is decreasing, particularly in the Eagle Ford Shale. In addition, gas-production rates from limited drilling restricted to certain areas of the plays are assumed to represent future production rates over the entire play.

Projected water use is also contingent on gas price because drilling and completion activities are more sensitive to gas price than production. All gas plays, even those with marginal permeability, should be hydraulically fractured when gas prices exceed \$10 per thousand cubic feet (Mcf) (\$0.35/m^3), more so if the gas contains condensate, and development should be accelerated relative to that projected in this study. Conversely, if gas price remains below \$5/Mcf (\$0.18/m^3) for an extended time, water-use projections from this study may be too high. Given the current low gas price relative to that of oil in terms of energy content, more companies have become interested in condensate, whose price more closely follows that of oil and in oil-rich shale plays (northern confines of Barnett Shale, western edge of Eagle Ford Shale).

Overall annual net water use for fracking shale formations is projected to increase from the current 46 Mm^3 (37 kAF) to a peak of 145 Mm^3 (117 kAF) by 2020–2030.[13] If minor water use for tight formations (Supporting Information, I) is included, fracking annual net water use peaks at 179 Mm^3 (145 AF) (Figure 4). Several other potential gas accumulations are present in Texas and are not considered in this study, particularly those at greater depths because they are considered too speculative. Production from these formations would mean that net water use, instead of decreasing after the peak of 145 Mm^3 (117 kAF) in 2020–2030, could remain at that level or possibly higher for a longer time. Also, projections in this study are based on current fracking technologies; new or updated technologies could reduce reliance on fresh water, including use of fluids other than water (e.g., propane, N_2, CO_2), sonic fracturing with no added fluid, and other waterless approaches with specialized drilling tools.[21,22] As the cost of water increases, these methods, potentially more expensive than water fracks, could become more attractive.

Impact of Water Use on Water Resources. Impacts of water use for shale-gas production depend on local water availability and competition for water from other users. Precipitation is variable among Texas shale-gas plays, with mean annual precipitation of 1320 mm/yr (Haynesville), 790 mm/yr (Barnett), and 740 mm/yr (Eagle Ford).[23] Texas is also subject to drought/wet period cycles that may become more extreme with climate change. High precipitation in East Texas results in widespread surface water availability in the Haynesville Shale region, although its use can also impact streamflow;[24] however, most surface water is allocated, although temporary water rights can be obtained from the State. Surface water is also available in the Barnett Shale, including major rivers (Trinity and Brazos Rivers) and reservoirs; however, population growth will increase demand for this resource[11] and possibly compound stress on the aquifer whose water levels have significantly declined in past decades.[25] Surface water is not as readily available in the Eagle Ford Shale region. Several streams are ephemeral and recharge underlying aquifers (Frio and Nueces Rivers). Even when surface water is available in a region, it is often not located adjacent to shale-gas development and trucking or piping of water may be required. Although surface water is generally more renewable than groundwater, it may not be as reliable because of impacts of droughts.

Groundwater resources are generally available in each of the shale-gas plays, and, unlike surface water, groundwater is ubiquitous and generally available close to production wells. The Carrizo Wilcox and Queen City/Sparta aquifers currently provide water for the Tx-Haynesville and Eagle Ford shales. Groundwater is more readily available in East Texas, the only competition for water use in this region being industrial and municipal demands, but conflicts with other users may arise because the shallower aquifer has limited yield.[19] In the Eagle Ford Shale region, groundwater has already been partially depleted for irrigation in the Winter Garden region of South Texas, resulting in water-level declines ≥60 m over a 6500 km^2 area, disappearance of several large springs, and transition from predominantly gaining to mostly losing streams.[26] Over-abstraction of groundwater in the past for irrigation limits water availability for current and future shale-gas production. The east part of the Barnett Shale overlies the Trinity aquifer, which provides water in this region.[11] Farther west, no named major or minor aquifer exists.

The large number of hydraulically fractured wells in Texas (≥20 000) and high water use per well create the perception of large rates of water use. However, water use for shale-gas production is relatively minor (<1%) when compared to that for mostly consumptive irrigation (56%) and municipal (26%) water use in Texas in recent years. Nevertheless, water use for shale gas represents a much greater percentage of total water use over smaller areas (Table 2). Net water use for Barnett Shale core areas represented 4% of total water use in 2008.

Total net water use in core/assumed core areas of the plays is 645 Mm^3 (520 kAF) in the Barnett Shale, 69 Mm^3 (55 kAF) in the Tx-Haynesville Shale, and 100 Mm^3 (80 kAF) in the Eagle Ford Shale. The estimated groundwater fraction of total water use is 11% in Barnett, 38% in Tx-Haynesville, and 18% in Eagle Ford shale plays. Municipal water use is dominant (≥85%) in the footprint of the Barnett play in Denton and Tarrant counties and in Webb County in the footprint of the Eagle Ford play. Elsewhere water use is mixed with some irrigation and manufacturing. As compared to all county water use in 2008, net water use for shale-gas production at the county level for selected counties is projected to increase from 1% to 40% for the Barnett, 7% to 136% for the Tx-Haynesville, and 5% to 89% for the Eagle Ford in their peak years (Table 2, Supporting Information, J). The large percentage increases in water use for rural counties reflect the low initial water use in these counties (Figure S13).

Unlike municipal water use, which increases steadily with population growth, shale-gas water use represents a transient demand over ~30−40 yr. The challenge is to understand whether large aquifers, such as the Carrizo aquifer that has extensive groundwater reserves, can recover from the transient stress rapidly enough to support additional demand from population growth. For example, water levels in the Carrizo aquifer in the footprint of the Eagle Ford play have slowed their decline following the heavy irrigation pumpage of the 1960s and 1970s.[27] The less prolific Trinity aquifer overlapping the Barnett Shale footprint is still recovering from decades of pre-1950s heavy municipal pumpage.[25] The State of Texas strongly supports water planning through an array of mostly local government-like entities. The diverse stakeholders have agreed on acceptable groundwater-level declines (called desired future conditions) translated to total annual pumping (based on groundwater modeling) of 350 Mm^3 (285 kAF) from the Carrizo aquifer in the Eagle Ford Shale, to be compared to the projected annual peak of 58 Mm^3 (47 kAF) (20% additional use) for fracking (Supporting Information, J).

To mitigate increased fresh water use, some operators have started exploring brackish groundwater (lower salinity than seawater), despite limited information on this resource[28] and additional constraints, such as contamination risks during transport and increased potential of well corrosion. Development of advanced additives allows higher salinity water to be used for fracking, although ionic composition is still a limitation. In many places, brackish water is available at relatively shallow depths[29] below or above the main fresh-water aquifer. However, financial resources need to be assigned to study these aquifers to better explain their yield, water quality, sustainability, and relationship with the fresh-water section of the same aquifers.

Water Use for Shale Gas Relative to Other Energy Users. Because of limited water resources and ever-growing energy demands, quantifying water-use efficiency per raw fuel source in terms of energy content relative to other energy sources (oil, coal, uranium) is important. No recent authoritative work has documented current energy water use efficiency. Previously published work, such as DOE[30] and Gleick,[31] relies on outdated statistics. In addition to lack of recent data, difficulties arise because of varying water-use patterns. Water consumption for coal mining or makeup water for in situ recovery of uranium is distributed throughout the life of mining operations or possibly toward the end during reclamation. Fresh water use for water flooding and other enhanced oil recovery (EOR) operations is also distributed mostly during the course of oil production, with perhaps heavier use early in the operation (Supporting Information, K). On the other hand, water use for shale gas occurs mostly early in production (notwithstanding refracking), and "ultimate" water efficiency, as calculated at the end of the life of the well or of the play, differs from "instantaneous" (~annual) or "cumulative" water efficiency. The assumed ultimate water efficiency for shale gas is a function of the play's EUR. Considering only production to date, Texas shale gas has a cumulative water use efficiency of 8.3—10.4 L per gigajoule (L/GJ) if auxiliary consumption (drilling and sand mining for proppant production) is added. Mantell[32] provided shale-gas water use efficiency for a large company operating in Texas and elsewhere but likely representative of the industry, and proposed an ultimate water efficiency of 4.8 L/GJ for the Barnett Shale and 2.3 L/GJ for the Tx-Haynesville Shale. Ultimate and cumulative water use efficiency values should converge, provided that projected EURs are correct. Overall, data collected in this study (including 8.3−16.6 L/GJ for coal and 6.1 L/GJ for uranium) show that net water use for shale gas is within the same general range as that for other energy sources (Supporting Information, K).

Implications of this Study for Other Potential Shale-Gas Regions. Texas has dominated shale-gas production in the U.S. during the past decade, with the Barnett Shale being the sole producer in the early 2000s and accounting for ~66% of U.S. production 2007−2009. Because shale-gas production in Texas began much earlier than in other plays in the U.S. and elsewhere and because Texas is the top shale-gas producer in the U.S., the methodology and information on water use from this study should provide insights into projected water use in other developing or potential shale-gas plays. Water use per well varies markedly within and between plays; however, water use per length of production interval (water-use intensity) has a much smaller range (9.5−14 m^3/m, 770−1120 gal/ft) and, consequently, is a more powerful parameter to consider. Past projections for water use in the Barnett Shale are consistent with subsequent water-use data 2006−2011, providing confidence in the approach used in the study to project water use. Studies of new plays with limited development or researchers with limited access to data could make use of the range of numerical values of parameters obtained in this study and needed for preliminary estimates of water use (Supporting Information, L).

Despite the low overall net water use fraction, impacts of water use can be much greater at smaller spatial scales. Projected net water use at peak time could more than double net water use in Texas rural counties, where current demand is low. Climatic conditions for plays in Texas range from humid to semiarid. Although water is more readily available in humid settings, most is already allocated for other uses. Water is more limited in semiarid regions because of overexploitation for irrigation. Limited fresh-water resources, both surface water and groundwater, will be an important issue for shale-gas development in the semiarid southwestern U.S. Although shale gas has not been produced in large quantities outside North America, estimated reserves are high in many countries, particularly northwest China, Mexico, South Africa, and Australia;[16] however, many of these regions correspond to areas of physical water scarcity.[15] Increasing use of brackish-water resources, using produced water, and developing less water-intensive technologies to reduce reliance on water for fracking should allow shale-gas production in these water-scarce regions.

■ ASSOCIATED CONTENT

Ⓢ Supporting Information

Details discussing mining water use with additional figures, information on units used in this work, and glossary. This material is available free of charge via the Internet at http://pubs.acs.org.

■ AUTHOR INFORMATION

Corresponding Author

*Phone: (512) 471-6246; e-mail: jp.nicot@beg.utexas.edu.

Notes

The authors declare no competing financial interest.

■ ACKNOWLEDGMENTS

The work was performed with financial support from the Texas Water Development Board (TWDB) and from The University of Texas at Austin, Jackson School of Geosciences. We also thank the database provider IHS (http://www.ihs.com) for access to the Enerdeq database. We appreciate the help of colleagues Michael Young, Ian Duncan, and Brad Wolaver, who reviewed an earlier version of the paper, and input from three anonymous reviewers. Thank you to Lana Dieterich, who edited the manuscript, and to Robert Reedy, who did the graphics. Publication authorized by the Director, Bureau of Economic Geology, The University of Texas at Austin.

■ REFERENCES

(1) EIA. *Natural Gas 1998 Issues and Trends*; DOE/EIA-0560, 1998; 242 pp.

(2) EIA. *Natural Gas Gross Withdrawals and Production*; http://www.eia.gov/dnav/ng/ng_prod_sum_dcu_NUS_m.htm, 2011.

(3) DOE. *Modern Shale Gas Development in the United States: a Primer*; Report prepared by Ground Water Protection Council, Oklahoma City and ALL Consulting, Oklahoma City, for Office of Fossil Energy and NETL, U.S. Department of Energy 2009; 96 pp.

(4) EIA. *Annual Energy Outlook with Projections to 2035*; DOE/EIA-0383, April 2011; 235 pp.

(5) Osborn, S. G.; Vengosh, A.; Warner, N. R.; Jackson, R. B. Methane contamination of drinking water accompanying gas-well drilling and hydraulic fracturing. *Proc. Natl. Acad. Sci. U.S.A.* **2011**, *108*, 8172−8176.

(6) Arthur, J. D.; Bohm, D.; Cornue, D. Environmental considerations of modern shale gas development. *Soc. Pet. Eng. Pap.* **2009**, 122931.

(7) Soeder, D. J.; Kappel, W. M. Water resources and natural gas production from the Marcellus Shale. *U.S. Geological Survey Fact Sheet 2009−3032*, 2009; 6 pp.

(8) Kargbo, D. M.; Wilhelm, R. G.; Campbell, D. J. Natural gas plays in the Marcellus Shale: Challenges and potential opportunities. *Environ. Sci. Technol.* **2010**, *44*, 5679−5684.

(9) EPA. *Proceedings of the Technical Workshops for the Hydraulic Fracturing Study, Workshop 4*; March 29−30, 2011, Water Resource Management, http://water.epa.gov/type/groundwater/uic/class2/hydraulicfracturing/hfworkshops.cfm, 2011.

(10) Rahm, D. Regulating hydraulic fracturing in shale gas plays: The case of Texas. *Energy Policy* **2011**, *39*, 2974−2981.

(11) Bené, P. G.; Harden, R.; Griffin, S. W.; Nicot, J.-P. 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 to the Texas Water Development Board, http://www.twdb.state.tx.us/groundwater/models/gam/trnt_n/trnt_n.asp, 2007.

(12) Nicot, J.-P. Assessment of industry water use in the Barnett Shale gas play (Fort Worth Basin). *Trans.-Gulf Coast Assoc. Geol. Soc.* **2009**, *59*, 539−552.

(13) Nicot, J.-P.; Hebel, A.; Ritter, S.; Walden, S.; Baier, R.; Galusky, P.; Beach, J. A.; Kyle, R.; Symank, L.; Breton, C. Current and Projected Water Use in the Texas Mining and Oil and Gas Industry: The University of Texas at Austin, Bureau of Economic Geology. Report prepared for Texas Water Development Board, http://www.twdb.state.tx.us/RWPG/rpgm_rpts/0904830939_MiningWaterUse.pdf, 2011; 357 pp.

(14) Paktinat, J.; O'Neil, W.; Aften, C.; Hurd, M. Critical evaluation of high brine tolerant additives used in shale slick water fracs. *Soc. Pet. Eng. Pap.* **2011**, 141356.

(15) Smakhtin, V.; Revenga, C.; Doll, P. A pilot global assessment of environmental water requirements and scarcity. *Water Int.* **2004**, *29*, 307−317.

(16) EIA. *World Shale Gas Resources: An Initial Assessment of 14 Regions Outside the United States*; EIA, International Energy Statistics; Freedom House, Freedom in the World, 2011.

(17) RRC. *Barnett Shale Information*; http://www.rrc.state.tx.us/barnettshale/index.php, 2011.

(18) TWDB. *2009 Water Use Summary Estimates*; http://www.twdb.state.tx.us/wrpi/wus/summary.asp, 2011.

(19) Hanson, G. M. Water: a natural resource critical for development of unconventional resource plays. *Trans.-Gulf Coast Assoc. Geol. Soc.* **2009**, *59*, 325−328.

(20) Tian, Y.; Ayers, W. B. Barnett Shale (Mississippian), Fort Worth Basin, Texas: regional variations in gas and oil production and reservoir properties. *Soc. Pet. Eng. Pap.* **2010**, 137766.

(21) Friehauf, K. E.; Sharma, M. M. Fluid selection for energized hydraulic fractures. *Soc. Pet. Eng. Pap.* **2009**, 124361.

(22) van Hoorebeke, L.; Kozera, G.; Blach, M. N_2 fracs prove effective in Lower Huron. *Am. Oil Gas Reporter* Nov. **2010**, 66−70.

(23) PRISM. *1971 2000 Data Sets*; www.prism.oregonstate.edu, 2011.

(24) Entrekin, S.; Evans-White, M.; Johnson, B.; Hagenbuch, E. Rapid expansion of natural gas development poses a threat to surface waters. *Front. Ecol. Environ.* **2011**, *9*, 503−511.

(25) Harden, R. W. and Associates. Northern Trinity Woodbine Aquifer Groundwater Availability Model. Report prepared for the Texas Water Development Board. Report to the Texas Water Development Board, http://www.twdb.state.tx.us/groundwater/models/gam/trnt_n/trnt_n.asp, 2004.

(26) Deeds, N.; Kelley, V.; Fryar, D.; Jones, T.; Whellan, A. J.; Dean, K. E. Groundwater Availability Model for the Southern Carrizo-Wilcox Aquifer. Report prepared for the Texas Water Development Board, 2003; 452 pp.

(27) Huang, Y.; Scanlon, B. R.; Nicot, J.-P.; Reedy, R. C.; Dutton, A. R.; Kelley, V. A.; Deeds, N. E. Sources of groundwater pumpage in a layered unconfined-confined aquifer system in the U.S. Gulf Coast. *Hydrogeol. J.* **2012**, accepted for publication.

(28) LBG-Guyton Associates. Brackish Groundwater Manual for Texas Regional Water Planning Groups. Report prepared for the Texas Water Development Board, http://www.twdb.state.tx.us/RWPG/rpgm_rpts/2001483395.pdf, 2003; 188 pp.

(29) Alley, W. M. *Desalination of groundwater: Earth Science Perspectives*; U.S. Geological Survey Fact Sheet 075-03, 2003; 4 pp.

(30) DOE. *Energy Demands on Water Resources*; Department of Energy Report to Congress on the Interdependency of Energy and Water; Department of Energy: Washington, DC, 2006; 80 pp.

(31) Gleick, P. H. Water and energy. *Annu. Rev. Energy Environ.* **1994**, *19*, 267−299.

(32) Mantell, M. E. *Deep Shale Natural Gas: Abundant, Affordable, and Surprisingly Water Efficient*; Water/Energy Sustainability Symposium: Groundwater Protection Council (GWPC) Annual Forum: Salt Lake City, UT, 2009; 15 pp.