Will water scarcity in semiarid regions limit hydraulic fracturing of shale plays?

Bridget R Scanlon, Robert C Reedy and Jean Philippe Nicot

Bureau of Economic Geology, Jackson School of Geosciences, The University of Texas, Austin, 10100 Burnet Road, Austin, TX 78758, USA

E-mail: bridget.scanlon@beg.utexas.edu

Received 10 July 2014, revised 27 October 2014
Accepted for publication 29 October 2014
Published 8 December 2014

Abstract

There is increasing concern about water constraints limiting oil and gas production using hydraulic fracturing (HF) in shale plays, particularly in semiarid regions and during droughts. Here we evaluate HF vulnerability by comparing HF water demand with supply in the semiarid Texas Eagle Ford play, the largest shale oil producer globally. Current HF water demand (18 billion gallons, bgal; 68 billion liters, bL in 2013) equates to ~16% of total water consumption in the play area. Projected HF water demand of ~330 bgal with ~62 000 additional wells over the next 20 years equates to ~10% of historic groundwater depletion from regional irrigation. Estimated potential freshwater supplies include ~1000 bgal over 20 yr from recharge and ~10 000 bgal from aquifer storage, with land-owner lease agreements often stipulating purchase of freshwater. However, pumpage has resulted in excessive drawdown locally with estimated declines of ~100–200 ft in ~6% of the western play area since HF began in 2009–2013. Non-freshwater sources include initial flowback water, which is ~5% of HF water demand, limiting reuse/recycling. Operators report shifting to brackish groundwater with estimated groundwater storage of 80 000 bgal. Comparison with other semiarid plays indicates increasing brackish groundwater and produced water use in the Permian Basin and large surface water inputs from the Missouri River in the Bakken play. The variety of water sources in semiarid regions, with projected HF water demand representing ~3% of fresh and ~1% of brackish water storage in the Eagle Ford footprint indicates that, with appropriate management, water availability should not physically limit future shale energy production.

Keywords: hydraulic fracturing, water scarcity, shale gas, brackish water, groundwater, unconventional energy, water energy nexus

1. Introduction

With increasing energy production from unconventional shale plays requiring large amounts of water to support hydraulic fracturing (HF), there is concern about limited water supplies. A recent global analysis of water resources relative to shale plays indicates that an estimated ~40% of shale resources are in arid areas or in areas of high–extremely high water stress, including China, Mexico, and S Africa, ranked 1st, 6th, and 8th in terms of shale gas production, respectively [1–3]. Extreme droughts exacerbate water shortages, with an estimated 15% of global shale resources in areas exposed to high–extremely high drought stress [1]. The USA is the global leader in unconventional oil and gas (O&G) production with initial development of the technology for producing O&G from low permeability shales in the Barnett shale play in Texas using HF and horizontal drilling [4]. In addition, private ownership of mineral rights has incentivized rapid expansion of production in the USA in contrast to government ownership in most other countries. The USA ranks 5th globally in terms of technically recoverable shale gas and 2nd
in terms of shale oil resources and was classified as medium to high water stress in the global analysis [1]. An earlier report on USA resources indicates that ~50% of the 39,000 wells hydraulically fractured (January 2011–May 2013), that consumed ~100 billion gallons (bgal, ~380 billion liters, bl) of water, are in high or extremely high water stress areas [5]. The highest shale oil producing plays are in semiarid regions or in regions with low precipitation (Eagle Ford, 34% of USA production in 2013; Bakken, 29%; and Permian Basin, 23%).

Water scarcity is often defined as water demand exceeding water supply. Water demand for HF can be estimated fairly accurately in the USA from commercial and public databases (e.g. IHS Enerdeq database, FracFocus) [4–6]. However, there is considerable uncertainty in future demands based on projected O&G production in these plays (estimated ultimate recovery, EUR). Previous studies indicate that ~10,000 more wells will be drilled throughout the 20–30 yr life of the Barnett play [7], ~40,000 more wells in the Bakken [5], and 50,000 in the Eagle Ford [6, 8].

HF water supply is more difficult to assess than HF water demand because the reporting requirements for water sources used for HF in the USA are limited to some states (Pennsylvania, W Virginia, supporting information, SI, section 4, available at stacks.iop.org/ERL/9/124011/mmedia). Surface water supplies are more readily estimated from monitoring data; however, groundwater supplies depend in part on how they are defined. Many studies restrict groundwater supplies for HF to the water flux into the aquifer or recharge, often based on coarse resolution (0.5–1 degree) global models, such as PCR-GLOBWB in the Aqueduct water scarcity product [1, 5, 9]. Others define groundwater supplies based on water storage in aquifers [10]. Water supplies for HF are also impacted by water use in other sectors, particularly irrigation in semiarid regions [11].

Various strategies have been proposed to enhance resilience of HF to water constraints, including trading water among sectors and shifting to non-freshwater sources. Similar approaches are being considered for power generation [12]. Some studies emphasize the potential for trading with irrigated agriculture, considering that this sector is often the largest water consumer in semiarid regions [13, 14]. To date, most HF water has been derived from freshwater resources [5]; however, recent advances in HF technology allow use of more saline water, even as high as 285,000 mg L$^{-1}$ total dissolved solids (TDS) [15]. While there is much emphasis on reuse (little or no treatment) or recycling (with treatment) of flowback/produced (FP) water, some studies show that flowback water (typically produced within 1–2 weeks after well completion) or water produced from the formation along with O&G (produced water), both referred to generically as FP water, represent a small percentage of HF water demand [4, 16]. Even in the Marcellus Shale, where almost 100% of the water is recycled, recycling accounts for ≤10–30% of the required HF water based on volumes of typical flowback (mean 0.44 × 10$^6$ gal/well, 1.7 × 10$^6$ L/well) and produced water (0.74 × 10$^6$ gal/well, 2.8 × 10$^6$ L/well) from wells in Pennsylvania [17] relative to mean HF water use throughout the play (4.4 × 10$^6$ gal/well 16.7 × 10$^6$ L/well) [5]. Brackish groundwater provides another alternative to freshwater with some referring to the ‘sea of brackish water’ in the subsurface; however, characterization of this resource is limited in terms of quantity and quality of water that can be recovered [18].

The objectives of this study were to address the following questions:

1. How does water use for HF compare with that for other sectors?
2. What is the projected demand for HF water for O&G production?
3. Is HF in semiarid regions vulnerable to water constraints, i.e. does water demand exceed supply?
4. What impacts does HF water use have on water resources?
5. What strategies can O&G operators adopt to enhance resilience of HF to water constraints?

This study focused on water use for HF in the Eagle Ford shale play, the top ranked shale-oil producer and 4th ranked shale-gas producer in the USA in 2013 [19, 20]. It builds on a previous analysis that quantified water demand to date for HF in the Eagle Ford play [6]. Water use for HF was considered relative to that for irrigation and municipal sectors. Future HF water demand was projected for the next 20 yr. Water constraints were assessed by comparing HF water demand with estimated freshwater supplies from groundwater recharge and storage from groundwater models [21, 22]. Impacts of HF water use on water resources were evaluated by considering HF water use to date and also the life cycle of shale gas. Adaptive strategies to enhancing resilience of HF water supplies evaluated include use of brackish groundwater, reuse/recycling of FP water, and use of municipal waste water. Results from the Eagle Ford play were compared with those in other semiarid regions, including the Permian Basin play in Texas and Bakken play in N Dakota/Montana. This comprehensive analysis is designed to answer the question of whether HF in semiarid regions will be limited because of water constraints.

2. Materials and methods

2.1. Eagle Ford Shale Play

Unconventional O&G production in the Eagle Ford Play (~9500 mi$^2$, 24 600 km$^2$ area) began in 2008 (figure 1). Water use for HF in the play totaled 40 bgal (150 bL) for 8301 wells (2009–2013) [6].

Precipitation in the Eagle Ford play ranges from 19.5 inches/yr (495 mm yr$^{-1}$) in the west to 38.6 inches/yr (980 mm yr$^{-1}$) in the east (figure S1). Total population in the play area was ~0.2 million in 2010 in the mostly rural 16 county area. Nearby major cities include San Antonio (population 2.2 million) and Laredo (population 236 000) (figure S2). Land use/land cover consists of shrubland (45%), pasture (25%), grassland (8%), forest (7%), and cropland (5%) (figure S2). Most cropland and some pasture are irrigated. Major rivers include, from west to east, the Rio Grande, Nueces, Frio, Atascosa, San Antonio, and Guadalupe rivers. Major aquifers

B R Scanlon
in the region include the Carrizo–Wilcox aquifer and the Gulf Coast aquifer system, and minor aquifers include the Queen City, Sparta and Yegua-Jackson aquifers (figures 2, S3) [23]. Groundwater Conservation Districts (8 GCDs) manage regional groundwater according to Texas Senate Bill 1, an omnibus water bill passed in 1997 (figure S4).

2.2. Data sources and analyses

HF water demand was compared with water supplies at the play and county and square mile grid levels while also considering water use in other sectors to assess vulnerability to water constraints (figure 3). Additional details on data sources are available in SI, section 6. HF water demand or use was based on water use to date (2009–2013) in the Eagle Ford [6]. Information on wells used to supply water for HF was obtained from the Texas Dept. of Licensing and Regulation. HF water use was compared with that for other sectors based on the most recent data from the Texas Water Development Board [24]. Future HF water use was estimated by assuming that the highest established well density (HEWD) for HF wells in each of the seven production zones (2 oil, 2 volatile oil condensate, 2 condensate, and 1 dry gas) or county/production zone intersections (40) would apply to the entire play (SI, section 6, tables S1, S2). Primary sources of HF water include surface water and groundwater from aquifer recharge, aquifer storage, and cross-formational flow from adjacent aquifers; however, the latter was neglected in this analysis. Data on water diversions from the Rio Grande for mining were obtained from the Rio Grande Water Master. Renewable groundwater supplies for HF were estimated from aquifer recharge rates using a global model (PCR GLOBWB) as used in recent studies [1, 5, 25], regional recharge rates from groundwater chloride data [26], and groundwater availability models (GAMs) [27–29]. Groundwater supplies from aquifer storage were estimated from GAMs [22, 27, 28] and include drainable storage (water that would be drained under gravity, aquifer thickness × specific yield) in aquifer outcrop zones and compressible storage (water released from compressible storage: storativity × head decline) in downdip confined sections of aquifers (figure 2, SI, section 9, figure S11).

Impacts of HF on groundwater resources were evaluated using groundwater level monitoring data from 131 wells from the Texas Water Development Board (TWDB) database. Flow duration curves and baseflow were estimated for 20 streamflow gages using the length of record to determine which streams are perennial and could be impacted by HF groundwater pumpage. Net impact of HF on water resources was examined...
by comparing water use for shale gas extraction with water use for cooling in natural gas power plants [30].

Alternatives to freshwater sources for HF were evaluated, including flowback/produced (FP) water (SI, section 11), brackish groundwater, and municipal waste water. FP water volumes were estimated for individual wells from 2009–2013. The ratio of FP to HF water was calculated to evaluate what percentage of HF water would be available for reuse or recycling. Brackish groundwater was estimated by integrating groundwater quality (TDS) data from TWDB with groundwater storage data from the GAMs. Availability of municipal waste water was evaluated by contacting the 20 largest municipalities in the play area. We contacted O&G operators to determine trends in HF water sourcing through the South Texas Energy and Economic Roundtable (STEER.com) and through conferences. Analyses of water demand versus supply in the Eagle Ford play were compared with water demand from literature-based estimates for the semiarid Permian Basin play in west Texas [5] and from previous analysis for the semiarid Bakken play in N Dakota and Montana [6]. Water demand in the

Figure 2. (a) Outcrop and recharge areas for aquifers in the Eagle Ford play area. Major aquifers include the Carrizo–Wilcox and the Gulf Coast (Jasper and Evangeline) and minor aquifers include the Queen City, Sparta, and the Yegua-Jackson. The primary water source in the western region of the Eagle Ford play is the confined section of the Carrizo Sand, represented by the cross-hatched area. Except for the outcrop area lying mostly to the northwest of the Eagle Ford play area, little information regarding water quality is available for the Wilcox units. The Queen City and Sparta aquifers also have equivalent water-bearing units west of the Frio River, although these units are not designated as aquifers in the west because of poor water quality (figure S3) [22]. We did not include water supplies for HF from these units. (b) Cross sections A-A’ and (c) B-B’. Values shown in the cross section aquifer units represent approximate groundwater total dissolved solids (TDS) concentrations and dashed vertical lines represent approximate locations of transitional areas between different TDS concentration zones.
Permian Basin was compared with water supplies from groundwater storage, including brackish water from the GAMs and discussions with operators through the Permian Basin Petroleum Association. Water demand in the Bakken was compared with reservoir storage in the Missouri River [31].

3. Results and discussion

A schematic (figure 4) shows the main components of the Eagle Ford play area, including the Eagle Ford Shale unit at depth, a typical HF well (~2 miles deep and 1 mile lateral), an injection well for disposal of FP water, a shallow dipping confined aquifer typical of the Gulf Coast aquifers, and various sources of water, including recharge in the aquifer outcrop and fresh and brackish groundwater storage. HF water demand was compared with water supplies based on production to date (2009–2013) and projected production throughout the play life (~20 yr) at the play level, county level, and where feasible at the one square mile grid level to assess water scarcity.

3.1. How does water demand for hydraulic fracturing compare with that for other sectors?

Water demand or use for HF in the Eagle Ford in 2013 (17.8 bgal, 67 bL) is assumed to be mostly consumptive because of limited recycling as discussed later. At the state level, HF water demand in the Eagle Ford in 2013 represents 0.3% of statewide water withdrawal (5200 bgal, 20 000 bL, 2012) and 0.5% of statewide water consumption (3900 bgal, 15 000 bL, 2012), assuming 85% of irrigation and 40% of municipal water use is consumptive [32]. The latest year with reported state water use data is 2012. At the play level, HF water use with 2012 water use data results in HF representing 13% of water withdrawal and 16% of water consumption. The dominant water user in the play is irrigation, accounting for 62–65% of demand was compared with water supplies based on production to date (2009–2013) and projected production throughout the play life (~20 yr) at the play level, county level, and where feasible at the one square mile grid level to assess water scarcity.
water consumption (2011–2012), followed by municipal (10–12%), and steam electric power (7–13%) (figure 5).

3.2. What is the projected water demand for hydraulic fracturing?

Total HF drilling during the remaining life of the play (∼20 years) was estimated based on the current highest established well density (HEWD) to be 50 700–70 400 wells, resulting in ∼42 000–62 000 wells remaining after subtracting the 8300 wells drilled to date [6] (table S3; figure S6), bounding the previous estimate of 50 000 wells [8]. Multiplying 2013 drilling (3512 wells) by 20 and subtracting 8300 would result in a similar estimate (62 000 wells). These projections would result in ∼223–333 bgal (844–1260 bL) of additional HF water based on average 2013 HF water use/well in each production zone (oil, volatile oil, condensate, and dry gas) (table S3), representing ∼6–8 times HF water use to date (∼40 bgal, 150 bL, 2009–2013) [6]. To assess water constraints for HF, we used the upper bound for HF water demand (∼330 bgal, 1250 bL) as a conservative estimate (table 1).

3.3. How does water demand for hydraulic fracturing compare to freshwater supplies?

The dominant HF water supplies in the Eagle Ford play include aquifer recharge and freshwater storage (table 1). The focus on freshwater derives in part from reports that many landowners stipulate use of their fresh groundwater as part of lease agreements to generate an additional revenue stream to land owners and the sole revenue stream to landowners with severed mineral rights. Long-term (1960–2000) mean recharge rates from simulated drainage below the root zone in the PCR-GLOBWB model totaled 49 bgal yr⁻¹ (185 bL yr⁻¹) for the Eagle Ford play area (table S5), ∼170% greater than HF water demand in 2013 (18 bgal, 68 bL) but 65–72% less than total water withdrawal in the play area in 2011 (175 bgal, 662 bL) and 2012 (142 bgal, 538 bL) (table S3). Regional recharge rates from groundwater chloride data in the Carrizo–Wilcox aquifer totaled 43 bgal yr⁻¹ (163 bL yr⁻¹) [26]. Sources of recharge include diffuse recharge from percolation below the root zone and focused recharge beneath losing streams (e.g., Leona, Nueces, and Frio rivers) [33, 34].

Simulated recharge in regional GAMs in outcrop areas in the play totaled ∼60 bgal yr⁻¹ (227 bL yr⁻¹; table S5). All of these recharge estimates refer to aquifer outcrop zones; however, most O&G water supply wells in the western part of the play are in the deeper confined parts of the aquifers (1000–7000 ft deep, 300–2000 m) (figure S5). Net flow to the downdip confined aquifer was estimated to be ∼34% of the outcrop recharge for the Carrizo–Wilcox aquifer, the dominant aquifer in the west, based on the GAM [26]. Applying the percentage of deep recharge in the Carrizo aquifer (34%) to other confined aquifers in the play as an estimate results in net recharge of ∼20 bgal yr⁻¹ (76 bL yr⁻¹), which is similar to HF water use in 2013 (17.8 bgal) but is ∼86–89% less than total water withdrawal in 2011 and 2012 in the play area. Therefore, relying on recharge alone for HF is inadequate because recharge is not uniformly distributed in the play (figure S10) and most of the HF water supply wells are in the deep confined aquifers with very low recharge rates.

The largest water source for HF is groundwater storage in the play area. A previous study of water sources for irrigation pumpage in the confined portion of the Carrizo–Wilcox aquifer indicates that ∼60% of the pumped water was derived from aquifer storage, which is not sustainable and has resulted in groundwater depletion [21]. Freshwater extends far downdip in the Carrizo aquifer in the western part of the play, reflecting high permeability sands but is much more limited in the east [35] (figures 2(b), (c), S9). Drainable freshwater
storage in the unconfined portions of the aquifers, estimated from integration of TDS data (figures S19–S23) with storage from the GAMs, totaled ~6000 bgal (22,700 bL, tables 1 and S6); however, most HF water supply wells are completed in the confined portions of the aquifers, with compressible freshwater storage of ~3800 bgal (14,400 bL) in the play area (table S6). Projected total HF water demand (330 bgal, 1200 bL) represents ~3% of freshwater storage (9800 bgal, 37,000 bL) at the play level (table S4). The projected 20 yr water demand from all sectors (~1400 bgal based on average 2000–2012 withdrawals) is mostly irrigation (62%) and municipal (12%) use, and represents ~14% of total freshwater storage in the play (table S4). Projected HF water demand at the county level ranges from <1–27% of total freshwater storage (figure 6, table S4). Projected water withdrawal for all sectors at the county level represents 1–36% of total freshwater storage for all counties except Frio (111%) and Zavala (262%) counties which are dominated by irrigation (90–95% of county water use).

A secondary source of water for HF is the Rio Grande for counties adjacent to the river, mostly Webb County. Diversions from the Rio Grande for mining in 2011–2013 ranged from 1.1 to 2.3 bgal yr\(^{-1}\) (4.2–8.8 bL yr\(^{-1}\); table S8). Assuming this water is available for HF, it could provide HF water for ~230–500 wells/yr assuming an average water use of 4.8 \times 10^6 \text{gal/well}, 18.2 \times 10^6 \text{L/well} [6] (figure S12). However, there is limited drilling near the Rio Grande and operators do not normally transport water more than ~5–10 miles.

3.4. How vulnerable is water use for hydraulic fracturing to drought?

The 2011 drought was the most extreme on record for Texas, with precipitation in the play only 42% of the long-term mean (12.3/29.3 inches, www.prism.oregonstate.edu). Droughts generally have a much greater impact on surface water than groundwater; however, reported diversions from the Rio Grande for mining for 2011 were similar to those in 2012 and 2013 (table S8). Drought should not markedly impact water demand for HF or groundwater supply, particularly for the confined aquifers which have been recharging for several thousand years [36]. The main impact of the 2011 drought was related to increased water demand for irrigation (figure 5, table S2). The increase in water withdrawal related to irrigation from 2010 to 2011 (33 bgal, 125 bL) due to the 2011 extreme drought is similar to total HF water use for 2012 and 2013 combined (30 bgal, 114 bL). However, the main irrigation region, the Winter Garden region, is mostly north of the Eagle Ford play area and generally does not compete with HF water use (figures 1 and 4).

3.5. What legal issues impact hydraulic fracturing water use?

In addition to physical availability of water, legal access to water and regulations governing water resources need to be considered. Legal challenges relate to groundwater ownership in Texas, with current law providing that landowners have a ‘vested property right’ to groundwater in place [37]. Therefore, regulations, including reduced permits by Groundwater Conservation Districts that would restrict landowners’ access to groundwater, may constitute ‘a taking’ and would have to be compensated [38]. These recent rulings call into question the scope and authority of GCDs. In addition, because of confusing language in the Texas Water Code (SI, section 9), it is not clear whether groundwater produced for HF activities is exempt from GCD regulation. While groundwater use for O&G exploration in Texas is exempt from regulation, confusion results from whether to consider HF part of exploration or production.

Groundwater management by the GCDs is based on estimates of desired future conditions (DFCs) for aquifers within groundwater management areas that result from joint-planning efforts by multiple GCDs (Texas Water Code §36.108). In Groundwater Management Area 13, covering most of the Eagle Ford play (figure S4), the desired future condition is a not-to-exceed area-average drawdown of 23 ft (7 m) across the GCD by 2060. However, localized
drawdown in pumping centers will likely exceed this amount. This desired future condition translates to modeled available groundwater of \( \sim 150 \text{ bgal yr}^{-1} \) (570 bL yr\(^{-1}\)) from the GAMs to honor the drawdown limitation and planning horizon. The 2013 HF water use (18 bgal, 68 bL) corresponds to \( \sim 12\% \) whereas total withdrawal from all sectors (142 bgal, 538 bL) represents \( \sim 95\% \) of the annual modeled available groundwater in this region. These desired future conditions will be revised in 2016 and should reflect groundwater pumpage for HF in the region.

3.6. What impacts does hydraulic fracturing water use have on water resources?

Groundwater level monitoring data from 131 wells in the play area indicate that water levels have declined to a maximum depth of \( \sim 200 \text{ ft} \) \((\sim 60 \text{ m})\) in the west and mostly \( \leq 50 \text{ ft} \) \((15 \text{ m})\) in the east (figures 7, 8, and S13). Greater declines in the west may be related to the deeper O&G water supply wells completed mostly in confined aquifers relative to shallower wells in the east, many of which may be completed in unconfined aquifers (figure S5). The specific yield for most of the unconfined aquifers is \( \sim 0.15 \) whereas the average storativity of the confined Carrizo–Wilcox aquifer in the west is 0.0012 (table S7). The ratio of the volumetric extent of cones of depression in confined versus unconfined aquifers is equivalent to the ratio of specific yield to storativity, about a factor of 1000 in many cases [39] (SI, section 9). A crude estimate of the impacts of HF water use to date (2009–2013) on groundwater levels in the confined Carrizo–Wilcox aquifer in the west was based on the assumption that all HF water was sourced from compressible aquifer storage within a mile of HF wells (figure 7). While water-level declines are small in much of the region, with 69% of western play area having no declines, 74% \( \leq 25 \text{ ft} \) \((7.6 \text{ m})\) decline, and 81% \( \leq 50 \text{ ft} \) \((15 \text{ m})\) decline, large declines (mostly 100–200 ft, 30–60 m) were found in 6% of the land area (figure 7). These estimates of water-level declines are generally consistent with the limited water-level monitoring data and coincident with high density of HF wells.

Impacts of past irrigation pumpage can be used as an extreme example of potential impacts of future HF water use in the region. Irrigation in the Winter Garden district lowered groundwater levels by up to 330 ft \((100 \text{ m})\) regionally during the past century, decreasing water storage by \( \sim 4000 \text{ bgal} \) (15 000 bL) in the Carrizo–Wilcox aquifer (figure S14). Irrigation pumpage reversed groundwater discharge in much of the region and changed some rivers (Atascosa, Frio, and San Antonio rivers) from gaining to losing [21]. No land subsidence has been recorded in this region in response to groundwater depletion, most likely because the sediments are generally indurated. Projected HF water use over the 20 yr life of the play is \( \sim 10\% \) of groundwater depletion from past irrigation. The lack of subsidence from past depletion suggests that HF pumpage should not cause subsidence. HF pumpage may not impact rivers in the west, which are already

![Figure 7](image-url)
lossing, but could impact river flow in the east which are mostly perennial (figure S15, table S9).

3.7. What is the net impact of hydraulic fracturing water use considering life cycle assessment (LCA)?

Previous studies emphasize the net impact of HF water use on water resources using a LCA of gas production [16, 40, 41]. The primary market for natural gas is thermolectric power generation, with natural gas representing ~50% of power generation in Texas in 2012 (SI, section 10, figure S16). Most natural gas power plants in Texas have combined cycle generators (NGCC, 170 out of 215 TWh, 80%) with consumptive cooling water requirements totaling ~32 bgal (121 B.L.) in 2012 (~0.19 gal kwh⁻¹) [30]. Power generation at NGCC plants in Texas in 2012 (170×10¹² Wh) corresponds to 580×10¹² Btu of energy (3.412 Btu Wh⁻¹ of electricity) requiring 1318×10¹² Btu of natural gas assuming 44% fuel efficiency of NGCC power plants in Texas (i.e. 44% of the energy goes to electricity with the remaining 56% to waste heat). The amount of water required to extract Eagle Ford shale gas is estimated to be 1.5 gal/10⁶ Btu [6]. If the natural gas required to power all Texas NGCC power plants during 2012 had been produced entirely from the Eagle Ford, this would represent ~2 bgal (7.6 B.L) of water to extract the gas (1318×10¹² Btu × 1.5 gal/10⁶ Btu = ~2.0 bgal of water). Therefore, water consumption for extracting the gas represents ~6% of the cooling water consumed at the NGCC power plants (2.0 bgal/32 bgal), similar to the estimate of 6% for the Marcellus shale gas in Pennsylvania [40]. In addition, recent replacements of retiring coal steam turbine plants with NGCC plants, which have 1/3rd of the cooling water requirements, result in a net savings of water in the state [32, 42]. However, this water savings does not occur where the gas is produced in the west but where the power is generated, mostly in the central and eastern parts of the state.

Many suggest that the net impact of HF water use on water resources and the hydrologic cycle is much greater than that of other sectors, such as irrigation, because FP water in Texas is mostly disposed of in deep injection wells and removed from the hydrologic cycle (figure S5). However, in the Eagle Ford play, most of the water used for HF is not part of the active hydrologic cycle to begin with as it is mostly derived from deep confined aquifers that have been recharging for several thousand years [36]. In addition, previous studies indicate that methane combustion from natural gas in the Marcellus Shale play puts water vapor back into the hydrologic cycle (5.7×10⁶ gal/well, 22×10⁶ L/well) that more than compensates for HF water use (3.6 mgal/well, 14×10⁶ L/well) [40]. Similar calculations for the Eagle Ford indicate that water vapor from methane combustion alone based on methane production to date is equivalent to ~90% of HF water use in the play (SI, section 10), ignoring water vapor generated by combustion of other hydrocarbons produced in the play.

3.8. What strategies can O&G operators adopt to increase resilience of hydraulic fracturing to water constraints?

Operators are considering various approaches to reduce vulnerability of HF to water constraints and reduce impacts of HF on water resources. The basic approaches include reducing water demand, increasing water supplies (particularly non-freshwater supplies), and intersectoral transfers (primarily from irrigation to HF). Water demand can be reduced by changing HF fluid types as shown by a recent analysis indicating ~55–110% higher water demands associated with slickwater HF relative to cross-link gel HF; however, these changes in HF fluid types generally occurred in the early stages of Eagle Ford play development [6]. Water demand can also be reduced through reuse-recycling of FP water. Non-freshwater sources include brackish water and municipal waste water.

3.8.1. Flowback/produced water. Small FP water volumes generally do not support reuse/recycling requirements. FP/HF...
ratios are generally <5% within the first month of well completion in all production zones, making it difficult to collect sufficient water to support recycling for HF (figures 9, S18). Most FP water is disposed of in the ~700 active UIC Class II injection wells in the 18 county area, including and extending beyond the 16 counties in the Eagle Ford play (figure S5). The quality of the FP water is not highly saline, with reported values of ~40,000 mg L\(^{-1}\) TDS. Some operators are doing a limited amount of recycling; however, there is no formal reporting of these volumes. Portable treatment units are used to treat the FP water, particularly for reducing boron levels, which must be managed for the cross-link gel HF fluid additives. The logistics of recycling is complicated because of the low FP volumes. The economics of recycling is also generally not favorable with relatively low injection well disposal costs.

To promote reuse/recycling of FP water the Texas Railroad Commission modified their rules in March 2013. The new rules allow operators to recycle FP fluids on their own leases or they can transfer those fluids for recycling to another operator without the need for a permit [43]. Some operators report that these new rules promote increased reuse/recycling of water.

3.8.2. Brackish groundwater resources. There is an estimated ~35,000 bgal (130,000 bL) of brackish water in unconfined sections of aquifers and ~45,000 bgal (170,000 bL) of compressible brackish groundwater storage in the confined sections of the aquifers in the Eagle Ford play area, totaling 80,000 bgal (300,000 bL, figure 10, tables 1, S4, S10). Projected 20 yr HF water demand represents 0.4% of brackish groundwater storage, suggesting sufficient water at a play level. At the county level, projected HF water use is ≤16% of total brackish water storage (table S4). Projected total water demand by all sectors represents ~2% of brackish water storage at the play level and ranges from 0–13% of brackish water storage, with the exception of Frio (35%) and Zavala (78%) counties where irrigation is dominant and DeWitt county (62%) where brackish water is limited.

A previous survey of operators in 2010 indicated that ~20% of the HF water use throughout the play was brackish [44]; however, HF water use has expanded greatly since that time. To avoid impacting shallower domestic wells, many operators report drilling into deeper units to limit the potential for competition for shallow groundwater. Some operators indicate that 60–80% of their water use is brackish (e.g. Marathon Oil Company reported 85% of their water use in 2012 was non-freshwater, [45]); however, there is no formal reporting of this water source. Another operator reported flowing artesian production from a 6000 ft (1800 m) deep well in the eastern part of the play (DeWitt County) with TDS of ~36,000 mg L\(^{-1}\). Water treatment is often required to make the water compatible with HF fluid additives. To incentivize use of brackish groundwater, the Pecan Valley GCD recently revised their regulations to allow up to 20 times more groundwater pumpage if brackish water is withdrawn from the aquifer (SI, section 9).

3.8.3. Municipal waste water. Some municipalities are selling their waste water to intermediary companies to provide water to operators (SI, section 11). For example, Laredo Utilities Department contracted 5 x 10\(^6\) gal d\(^{-1}\) (19 x 10\(^6\) L) which could be used to HF 380 wells/yr (4.8 mgal/well) or could supply ~50% of HF water in Webb county based on 2012 HF water use (table 1). However, infrastructure needs to be built to transport this water to HF sites. Most municipal waste water was previously disposed of in surface water bodies using a National Pollution Discharge Elimination System permit. The Texas state water plan projects continually increasing municipal water demand in the future; therefore, municipalities may require this waste water to meet their own future water demands.
3.8.4. Purchasing water from irrigation. Intersectoral water transfers have been proposed in semiarid regions, primarily purchasing water from the irrigation sector [13, 14]. However, the dominant irrigation region in the Eagle Ford play (Winter Garden region) is generally not collocated with the highest density of HF wells (figures 1 and 4), reducing the feasibility of intersectoral water transfers within the play. However, another study suggested that increasing irrigation efficiency in the Lower Rio Grande Valley, downstream of the Eagle Ford play, could provide ∼250–500 bgal water/yr for HF, though infrastructure development would be required to transport the water to HF sites [46].

3.9. Overall water supply versus demand and related uncertainties for the Eagle Ford Play

The previous discussions of water demand versus supply focused on fresh and brackish water separately. However, projected HF water demand is a small percentage of total water resources at both the play (0.4%) and the county (0.1–6%) levels. Projected total water demand for all sectors (HF, irrigation, municipal and other) is also a small percentage of total available water at the play level (1.6%) as well as at the county level for most counties (0.2–7%), excluding two counties with high irrigation demands (Frio: 27%, Zavala: 60%), and one county (Maverick) that has essentially no modeled available groundwater resources in the play (table S4). Mapping the relationship between demand and supply indicates that there should not be problems with available water throughout much of the play, with the highest demands relative to supplies focused where irrigation demand is currently high in the northwest (figure 11).

Uncertainties in water demand to date (2009–2013) are considered relatively low because of the reporting requirements and availability of multiple databases [6]. The analysis of water demand in the Eagle Ford play is hindered by lack of reporting requirements for the source of water used for HF (e.g. surface water, groundwater, recycled FP water) or the quality of the water used (fresh versus brackish). Uncertainties in projected HF water demands are considered high because they are based on the assumption that the HEWD to date will apply to entire O&G production zones. A much more granular analysis based on square mile productivity and considering production economics, such as that available for the Barnett play [7], is required to improve estimates of projected HF water demand. This level of analysis is currently being conducted for a project funded by the Sloan Foundation [47]. Uncertainties in water demand for other sectors also need to be considered and are considered high for irrigation. Current studies funded by TWDB are evaluating remote sensing approaches to improve these estimates [48].

Data on water supplies in the Eagle Ford rely heavily on GAMs for the region. These models were designed to assess mostly freshwater resources in aquifers; however, the Bigford and Laredo Fms. which are stratigraphically equivalent to the Queen City and Sparta, respectively, west of the Frio River are not considered aquifers and recharge and storage estimates are considered less reliable west of the Frio River. The emphasis of these models is on fresh water and estimates of brackish water are not as reliable because of limited data availability. Future models should be developed that focus on brackish water resources and integrate data being collected by industry in these regions. A recent analysis of geophysical logs in the Eagle Ford play supports the estimated volumes of brackish water in these regions [49] (figure S24). While comparisons of water demand versus supply in this study have been limited, future modeling would provide more comprehensive comparisons that would include all the water sources, including groundwater from recharge and fresh and brackish water storage, and leakage from adjacent geologic units. More detailed models may be required for assessing water demand versus supply at the level of municipalities. The impact of pressure loss in confined aquifers on well yields is not known in detail. In particular, how many water wells would be required to produce similar water volumes and would water production be economical?

While the current water level monitoring network has been invaluable in documenting impacts of water use in the play on groundwater depletion, this network should be expanded and should be designed to provide detailed information in critical areas, such as those in the vicinity of municipal well fields.

4. Comparison with shale plays in other semiarid regions

The semiarid Permian Basin in west Texas includes conventional and unconventional production, with HF water use totaling 10.4 bgal (39 bL) from 9308 wells for 2.5 years (2011–mid-2013) [5]. Water use for conventional production has shifted from predominantly fresh (85%) in 1995 to brackish and produced water (80%) in 2010 based on a survey of operators in 2010 [44]. HF water use may follow a similar trend, with many current lease agreements stipulating freshwater use to provide revenue streams to landowners. Some use the term ‘water play’ to refer to the water markets in this region. A reconnaissance analysis from GAMs indicates large volumes of brackish groundwater resources in the underlying aquifers (figure S25), totaling an estimated 360 bgal (1360 bL) in compressible storage (table S11) [50]. Uncertainties in the location and accessibility of these brackish resources should decrease with increased exploration and production. Collocated unconventional and conventional energy production means that the large volume of produced water with conventional oil production (volumetric produced water to oil ratio of ~8 from 2009–2012, table S12, similar to that in the USA [51], may provide additional water for HF in the region, if it is not used for water flooding for conventional oil production. Presentations in a recent symposium sponsored by the Railroad Commission of Texas on reuse/recycling of water indicated increasing trends in some companies to use brackish and FP water and discontinue use of freshwater [52] (SI, section 12).

The Bakken play is the second largest shale oil producer in the USA with HF water use of 16 bgal (60 bL) for 7868 wells from 2005 through 2013 [6]. Low precipitation rates in the Bakken play in North Dakota and Montana (mean 14.6
inches/yr (370 mm yr$^{-1}$), 1981–2010, PRISM precipitation, figure S26) might suggest that HF production could be vulnerable to water constraints. However, the Missouri River provides a major source of water in the region, with the Sakakawea Reservoir (7800 bgal (30 000 bL) storage capacity, figure S27) located in the middle of the Bakken play, though regulatory issues currently limit access to this water source, which is controlled by the USA Army Corps of Engineers. Additional water is provided by groundwater with water depots in different regions of the play. In addition, low population density and limited irrigation, particularly in the North Dakota region of the play, reduces water stress in the region (table S13).

5. Conclusions

(1) Water demand for HF in the Eagle Ford (18 bgal in 2013) represents 16% of consumptive water use in the play area. Maximum projected HF water use over the next 20 yr is 330 bgal from 62 000 additional wells, representing ∼8 times HF water use to date. Projected HF water use represents ∼10% of historic groundwater depletion resulting from irrigation in the adjacent Winter Garden region over the last century.

(2) Water supplies for HF include groundwater recharge, estimated to be ∼60 bgal yr$^{-1}$ in the aquifer outcrop area and ∼20 bgal yr$^{-1}$ in the deep confined aquifers.

(3) Additional water supplies are provided by fresh groundwater storage, with projected HF water use (330 bgal) representing ∼3% of groundwater storage in the play.

(4) While regional impacts of water pumpage to support HF are small, localized impacts can be large with estimated water level declines of ∼100–200 ft in ∼6% of the western play area.

(5) The net impact of HF water use based on life cycle of natural gas is low, with HF water use for gas extraction representing ∼6% of water consumed at the power plants.

(6) Brackish groundwater may provide a viable alternative to freshwater with projected HF water use representing 0.4% of the estimated 80 000 bgal of brackish groundwater storage.

(7) There is limited potential for reuse or recycling of flowback or produced water because of small volumes (<5% of HF water requirements in the first month) in the Eagle Ford play.

(8) Evaluation of HF water use in the semiarid Permian Basin play in Texas indicates increasing use of brackish groundwater and recycling of produced water, which benefits from large volumes of produced water from collocated conventional oil production (volumetric water: oil ratio of ∼8). In the Bakken play in N Dakota and Montana, water inputs from outside this dry basin through the Missouri River provide a large potential
resource for HF, although currently limited because by regulatory restrictions.

(9) The comprehensive analysis of Eagle Ford water issues and comparison with other semiarid plays indicates that, with proper management, water should not constrain HF in these semiarid regions.

Acknowledgments

We would like to acknowledge the Jackson School of Geosciences, the Shell University of Texas Unconventional Research (SUTUR) program, BP, and the Mitchell Foundation for funding this study. We would also like to acknowledge free access to the Enerdeq database provided by IHS. We are grateful for reviews by Walt Ayers (Texas A&M Univ.), Jim Bradbury (James D Bradbury PLLC), Ron Green (Southwest Research Institute), Robert Mace (TWDB), William Mullican (Mullican & Associates), and two anonymous reviewers.

References

[1] Reig P, Luo T and Proctor J N 2014 Global Shale Gas Development: Water Availability and Business Risks (Washington, DC: World Resources Institute) p 80 (www.wri.org) January 2013
[2] US Energy Information Administration (EIA) 2013 Technically Recoverable Shale Oil and Shale Gas Resources: An Assessment of 137 Shale Formations in 41 Countries Outside the United States (Washington, DC: US Energy Information Administration) variably paginated
[3] Boyer C, Clark B, Jochen V, Lewis R and Miller C K 2011 Shale gas: a global resource Oilfield Rev. 23 28–39
[4] Nicot J P and Scanlon B R 2012 Water use for shale-gas production in Texas US Environ. Sci. Technol. 46 3580–6
[5] Freyman M 2014 Hydraulic fracturing & water stress: water demand by the numbers: shareholder, lender & operator guide to water sourcing CERES Report (www.ceres.org)
[6] Scanlon B R, Reedy R C and Nicot J P 2014 Comparison of water use for hydraulic fracturing for shale oil and gas production versus conventional oil Environ. Sci. Technol. 48 12386–93
[7] Browning J et al 2013 Barnett study determines full-field reserves, production forecast Oil Gas J. 111 88–95
[8] Gong X, McVay D A, Ayers W B, Tian Y and Lee J 2013 Assessment of Eagle Ford Shale oil and gas resources Soc. Petrol. Engin. SPE-167241-MS 26
[9] Reig P, Shiao T and Gassett F 2013 Aqueduct Water Risk Framework. Working Paper (Washington, DC: Water Resources Institute WRI). Available online at (www.wri.org/publication/aqueduct-waterrisk-framework) p 16
[10] MacDonald A M, Bonsor H C, Dochartaigh B E O and Taylor R G 2012 Quantitative maps of groundwater resources in Africa Env. Res. Lett. 7 7
[11] Siebert S, Burke J, Faurès J M, Frenken K, Hoogeveen J, Doll P and Portmann F T 2010 Groundwater use for irrigation—a global inventory Hydrol. Earth Syst. Sci. 7 3977–4021
[12] Tidwell V C, Macknick J, Zemlick K, Sanchez J and Woldeyesus T 2014 Transitioning to zero freshwater withdrawal in the US for thermoelectric generation Applied Energy 131 508–16
[13] Gaudet G, Moreaux M and Withagen C 2006 The Alberta dilemma: optimal sharing of a water resource by an agricultural and an oil sector J. Env. Econ. Manag. 52 548–66
[14] Kuwayama Y, Olmstead S M and Krupnick A J 2013 Water resources and fossil fuel development Res. Future Discuss. Paper 13-34 41
[15] LeBas R, Lord P, Luna D and Shaham T 2013 Development and use of high-TDS recycled produced water for crosslinked-gel-based hydraulic fracturing Soc. Petrol. Eng. SPE 163824 9
[16] Clark C E, Horner R M and Harto C B 2013 Life cycle water consumption for shale gas and conventional natural gas Environ. Sci. Technol. 47 11829–36
[17] Lutz B D, Lewis A N and Doyle M W 2013 Generation, transport, and disposal of wastewater associated with Marcellus Shale gas development Water Resour. Res. 49 647–56
[18] Feth J H 1965 Selected references on saline ground-water resources of the United States US Geol. Surv. Circular 499 30
[19] Grape S 2014 Manager of Reserves Data. Energy Information Administration, EIA; personal communication, January 2014
[20] US Energy Information Administration (EIA) 2014 Annual Energy Outlook Early Release Overview; Rept. DOE/EIA (Washington, DC: US Energy Information Administration (EIA)) p 18
[21] Huang Y, Scanlon B R, Nicot J P, Reedy R C, Dutton A R, Kelley V A and Deeds N E 2012 Sources of groundwater pumpage in a layered aquifer system in the Upper Gulf Coastal Plain, USA Hydrogeol. J. 20 783–96
[22] Kelley V A, Deeds N E, Fryar D G and Nicot J P 2004 Groundwater availability models for the Queen City and Sparta aquifers Final Report Prepared for the Texas Water Development Board. variably paginated
[23] George P G, Mace R E and Petitrossian R 2011 Aquifers of Texas Texas Water Development Board Report No. 380 172
[24] TWDB (https://www.twdb.state.tx.us/waterplanning/waterusersurvey/estimates/)
[25] Wada Y, van Beek L P H, van Kempen C M, Reckman J, Vasak S and Bierkens M F P 2010 Global depletion of groundwater resources Geophys. Res. Lett. 37 L20402
[26] Reedy R C, Nicot J-P, Scanlon B R, Deeds N E, Kelley V A and Mace R E 2009 Groundwater recharge in the Carrizo–Wilcox aquifer: chapter 3 Aquifers of the Upper Coastal Plains of Texas (Austin, TX: Texas Water Development Board) pp 185–203
[27] Deeds N E, Yan T, Singh A, Jones T L, Kelley V A, Knox P R and Young S C 2010 Final report groundwater availability model for the Yegua-Jackson Aquifer Final Report Prepared for the Texas Water Development Board variably paginated
[28] Chowdhury A H and Mace R E 2003 A groundwater availability model of the Gulf Coast aquifer in the lower Rio Grande Valley, Texas: numerical simulations through 2050 Texas Water Development Board Report October 2003 171
[29] Chowdhury A H, Wade S, Mace R E and Ridgeway C 2004 Groundwater availability model for the central part of the Gulf Coast aquifer—numerical simulations through 1999 Texas Water Development Board Report 163
[30] Scanlon B R, Reedy R C, Duncan I, Mullican W F III and Young M Y 2013 Controls on water use for thermoelectric generation: case study Texas US Environ. Sci. Tech. 47 11326–34

[31] Denholm A 2014 Lake Sakakawea reservoir storage, US Army Corps of Engineers, personal communication, February 2014

[32] Scanlon B R, Duncan I and Reedy R C 2013 Drought and the water energy nexus in Texas Environ. Res. Lett. 8 045033

[33] Green R T, Bertettin F P, Wilcox B P and McGinnis R N 2008 Investigation of the groundwater systems in the Wintergarden Groundwater Conservation district, phase II Final Contract Report Prepared for the Wintergarden Groundwater Conservation District 108

[34] Moore G W, Barre D A and Owens M K 2012 Does shrub removal increase groundwater recharge in southwestern Texas semiarid rangelands? Rangeland Ecol. Manage. 65 1–10

[35] Hamlin H S 1988 Depositional and ground-water flow systems of the Carrizo–Upper Wilcox, South Texas The University of Texas at Austin Bur. Econ. Geol. Rep. Inv. 175 61

[36] Castro M C and Goblet P 2003 Calibration of regional groundwater flow models: working toward a better understanding of site-specific systems Water Resour. Res. 39 1172

[37] Texas Supreme Court Case 2014 Edwards Aquifer Authority vs Day, February 2014

[38] Bragg vs Edwards Aquifer Authority 2014 San Antonio Court of Appeals now on appeal to Texas Supreme Court.

[39] Alley W M, Reilly T E and Franke O L 1999 Sustainability of ground-water resources US Geol. Surv. Circ. 1186 79

[40] Laurenzi I J and Jersey G R 2013 Life cycle greenhouse gas emissions and freshwater consumption of Marcellus Shale gas Environ. Sci. Technol. 47 4896–903

[41] Jiang M, Hendrickson C T and VanBriesen J M 2014 Life cycle water consumption and wastewater generation impacts of a Marcellus shale gas well Environ. Sci. Technol. 48 1911–20

[42] Grubert E A, Beach F C and Webber M E 2012 Can switching fuels save water? A life cycle quantification of freshwater consumption for Texas coal- and natural gas-fired electricity Environ. Res. Lett. 7 11

[43] Railroad Commission of Texas (www.rrc.state.tx.us)2014 Rule No. 3.98 of the Texas Oil and Gas Division regulations

[44] Nicot J-P, Hebel A, Ritter S, Walden S, Baier R, Galusky P, Beach J A, Kyle R, Symanek L and Breton C 2011 Current and projected water use in the Texas mining and oil and gas industry: Bureau of Economic Geology Report No. 090480939 prepared for Texas Water Development Board 357

[45] Marathon Oil Company (www.marathonoil.com/) Social_Responsibility/Environmental_Stewardship/Water_Management/

[46] Cook M A, Stillwell A S, King C W and Webber M E 2013 Alternative water sources for hydraulic fracturing in Texas ASCE world environmental and water resources congress 2013 Showcasing the Future 2818–32

[47] Ikonnikova S 2014 Univ. of Texas, Bureau of Economic Geology, personal communication

[48] Caldwell T G 2014 Univ. of Texas, Bureau of Economic Geology, personal communication

[49] Hamlin H S and de La Rocha L 2014 Using electric logs to estimate salinity and map resources of fresh and brackish groundwater Geol. Soc. Am. Abs. with Programs Paper No. 285-10

[50] Guyton L B G Associates 2003 Brackish groundwater manual for Texas regional water planning groups Report Prepared for the Texas Water Development Board 188

[51] Veil J A and Clark C E 2010 Produced water volume estimates and management practices Soc. Petrol. Eng. SPE #125999 8

[52] Railroad Commission of Texas 2014 (www.rrc.state.tx.us/about-us/commissioners/craddick/water-recycling-symposium/)

[53] Shelkholeslami B A, Schlottman B W, Seidel F A and Button D M 1991 Drilling and production of horizontal wells in the Austin Chalk J. Petrol. Technol, July 1991 p 773