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Water Footprint of Hydraulic Fracturing

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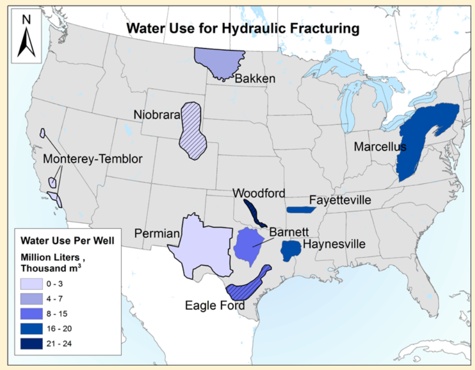
Supporting Information

ABSTRACT: We evaluated the overall water footprint of hydraulic fracturing of unconventional shale gas and oil throughout the United States based on integrated data from multiple database sources. We show that between 2005 and 2014, unconventional shale gas and oil extraction used 708 billion liters and 232 billion liters of water, respectively. From 2012 to 2014, the annual water use rates were 116 billion liters per year for shale gas and 66 billion liters per year for unconventional oil. Integrated data from 6 to 10 years of operation yielded 803 billion liters of combined flowback and produced water from unconventional shale gas and oil formations. While the hydraulic fracturing revolution has increased water use and wastewater production in the United States, its water use and produced water intensity is lower than other energy extraction methods and represents only a fraction of total industrial water use nationwide.



INTRODUCTION

The rapid rise of unconventional shale gas and oil production through hydraulic fracturing has intensified water use for the oil and gas industry in the United States.[1−10] Previous research has provided a wide range of water use, with reports for specific basins or small groups of them.[2−4,6,8,11−13] Yet few studies have evaluated the overall volume of water used for hydraulic fracturing and the volume of wastewater generated from unconventional oil and gas production.[7,10,14−17] The increasing volume of oil and gas wastewater, which typically contains high levels of toxic elements, has become a major national concern owing to the rise of induced seismicity in areas of deep-well injection[2,18−20] and the environmental and human health risks associated with the disposal of oil and gas wastewater to unlined impondments[21,22] or streams and rivers without adequate treatment.[23,24] While several of the previous studies have evaluated portions of the water cycle of oil and gas production including water intensity for processing and electricity generation,[2,3,6−8,25] this study focuses on the water use and wastewater generation from hydraulic fracturing and their relationship to energy production.

Here we report, for the first time, an integrated and comprehensive evaluation of both water use and flowback-produced waters (FP) generated as part of unconventional shale gas and oil (shale oil, tight sand) production across the United States. One of the challenges of generating such a complete data set is the lack of a single and reliable data source and fragmentation of the information distributed among different sources. In this study, we thus integrate and compare data from multiple sources including FracFocus,[11,13] DrillingInfo,[26] EIA,[27] state agencies,[28−30] industry sources,[31] and previous publications[2−4,6−10,15] in order to generate a complete data set of water use and FP water as normalized to the energy content of oil and shale gas production. Metrics reported for this study include water use per well (with a distinction between gas and oil wells), shale gas and oil production, water use intensity (WUI; water use normalized to gas and oil energy content, L/GJ), produced water volume per well, produced water intensity (PWI; volume of produced water per energy content or per volume of oil), and the overall water footprint of hydraulic fracturing. Water footprints associated with hydraulic fracturing observed in this study could be used to project future water allocations and produced water volumes in other basins worldwide that are expected to develop unconventional oil and shale gas resources.

DATA SOURCES AND METHODS

Water Use per Well. Well water use data were extracted from the EPA's Analysis of Hydraulic Fracturing Fluid Data from the FracFocus Chemical Disclosure Registry 1.0 and SkyTruth's FracFocus Chemical Database Download.[11,12] Because FracFocus does not report well orientation, median water use per well is reported for both vertical and horizontal (each individual lateral segment) unconventional wells (Table 1; average values reported in Table S5). Additionally, water use data from the EPA report were compared with state databases,[32,33] other studies,[3,6−9,17] and values reported by Chesapeake Energy.[31] For most unconventional shale gas and oil plays, the FracFocus data were in agreement with other sources (see comparison in Table S1).

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Table 1. Median Water Use ($\times10^6$ L/well, $\times10^6$ gallons/well), Average Flowback and Produced (FP) water ($\times10^6$ L/well, $\times10^6$ gal/well), WUI (L/GJ), and PWI (L/GJ) among the Prominent Unconventional Shale Gas and Oil Formations[a]

shale gas	water use (median)	flowback and produced water	water use intensity (WUI)	produced water intensity (PWI)		
Barnett	14.42, 3.80	12.40, 3.28	7.40	6.36		
Eagle Ford	13.7, 3.61	25.87, 6.83	5.38	10.16		
Fayetteville	20.06, 5.29		9.32			
Haynesville	19.45, 5.13	17.51, 4.63	3.22	2.90		
Marcellus	16.12, 4.25	5.20, 1.37	3.14	1.01		
Niobrara	1.51, 0.39	5.68, 1.50	0.73	2.73		
Woodford	23.77, 6.27		8.58			
unconventional oil	**water use (median)**	**flowback and produced water**	**water use intensity (WUI)**	**produced water intensity (PWI)**	**FP water/oil ratio**	**water use/oil ratio**
Bakken	7.49, 1.97	12.25, 3.24	4.99	8.17	0.36	0.22
Permian	3.06, 0.80		2.42			0.13
Monterey-Temblor	0.30, 0.07	14.30, 3.78	1.60	76.43	3.22	0.07
Eagle Ford	15.06, 3.97	22.75, 6.01	7.53	11.38	0.56	0.37
Niobrara	1.32, 0.34	8.04 ,2.12	1.11	6.79	0.44	0.07
Woodford	7.79, 2.05		7.15			0.74

[a]Also, for unconventional oil, the ratios of FP water to oil production and water use to oil production are shown.

Table 2. Calculated Number of Wells, Total Water Use ($\times10^9$ L, x10^9 gal), Gas Production ($\times10^{12}$ cubic feet), Oil Production ($\times10^6$ bbl), and Flowback and Produced (FP) water ($\times10^9$ L, $\times10^9$ gal) for the Major Unconventional Shale Gas and Oil Formations

shale gas	number of wells	total water use	total gas production	total oil production	total flowback and produced water
Barnett	16874	243.32, 64.27	23.44	46.62	209.24, 55.27
Eagle Ford	5846	80.08, 21.15	8.01	723.52	151.22, 39.94
Fayetteville	5850	117.35, 31.00	9.04		
Haynesville	3172	61.70, 16.29	13.75	0.19	55.541, 14.67
Marcellus	8307	133.91, 35.37	30.41	47.59	43.20, 11.41
Niobrara	2281	3.44, 0.90	3.02	104.04	12.95, 3.41
Woodford	2861	68.01, 17.96	5.58	29.58	
unconventional oil	**number of wells**	**total water use**	**total gas production**	**total oil production**	**total flowback and produced water**
Bakken	9704	72.68, 19.20	1.97	2065.16	118.92, 31.41
Permian	9857	40.81, 10.77	5.24	1915.64	
Monterey-Temblor	703	0.35, 0.09	0.02	32.69	16.73, 4.41
Eagle Ford	7156	107.78, 28.47	3.19	1829.58	162.84, 43.01
Niobrara	2418	5.26, 1.38	1.97	456.04	32.02, 8.45
Woodford	680	5.30, 1.39	0.48	44.88	

Water, Oil, and Gas production. The DrillingInfo Desktop Application[26] was used to develop type curves for each of the unconventional oil and shale gas target formations. Type curves for FP, oil, and gas production reported by DrillingInfo cover the entire production history of the wells in each formation; thus, estimated ultimate recovery (EUR) was assumed to be the cumulative of all production from the type curve for each play. In many cases, this covers 10+ years (Bakken, Barnett, Fayetteville, Haynesville, and Permian), but in others, less than 10 years of production data were available (Eagle Ford, 6 years; Marcellus, 9 years; Niobrara, 8 years). We include the Permian basin instead of the individual formations (Bone Spring, Spraberry, Wolfcamp) for comparison to production data from the EIA's Drilling Productivity Report.[27] In order to separate unconventional from conventional wells, type curves were made for only horizontal wells in DrillingInfo (see Table S7 for percentages of horizontal wells).[17]

Total Oil and Gas Well Counts. Using a combination of state government data,[28−30,32,34] EPA's FracFocus report,[11] previous reports,[6−9,35] and the Baker and Hughes well count data from 2012 to 2014,[36] a complete count of wells in each unconventional play was developed (Table 2).

Water per Energy Intensity. Water use and produced water data were normalized by the energy content of extracted shale gas and unconventional oil and associated liquids. This was done by converting from EUR (BBL or MCF) to GJ of energy. Energy content of natural gas was defined as 1.0836 GJ/MCF (1.027×10^6 BTU/MCF), whereas oil had an energy content of 6.0679 GJ/BBL (5.751×10^6 BTU/BBL).[37] Additionally, we accounted for all associated hydrocarbons (see SI).

RESULTS AND DISCUSSION

Water Use. Analysis of the EPA's FracFocus database reveals large variations in water use, with typically higher water use for shale gas (a range of 13.7 to 23.8 $\times 10^6$ L per well, 3.6 to 6.3 $\times10^6$ gal per well, excluding data from Niobrara formation) relative to unconventional oil (1.3 to 15.1 $\times 10^6$ L per well, 0.3 to 4.0 $\times 10^6$ gal per well excluding data from the Monterey-Temblor formation) extraction (Table 1). These values are consistent with data reported in previous studies for some of

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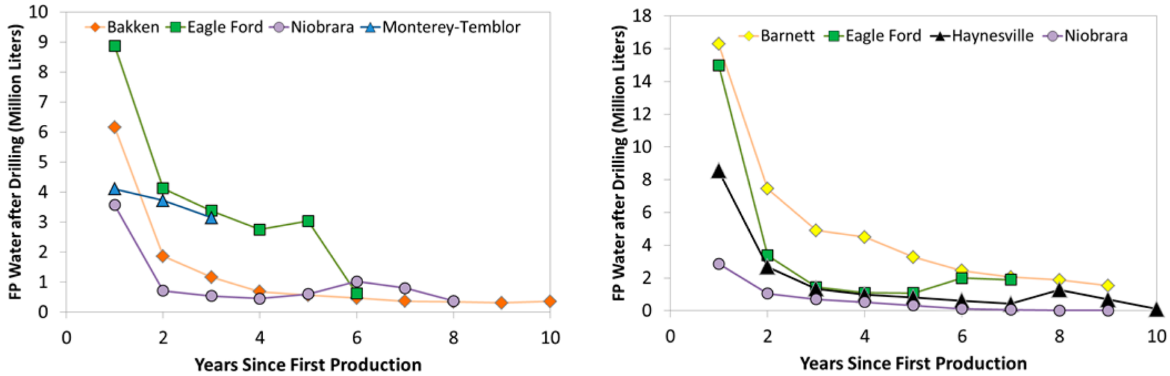

Figure 1. Decline curves of Flowback and Produced (FP) water over the course of well production for unconventional oil (left) and shale gas (right) formations. Note: For the Barnett shale, data from DrillingInfo[26] were used in the figure, while data from Nicot et al.[6] were used for the calculation of total FP water.

the plays included in this study, particularly with water use data reported recently by Gallegos et al.[17] (Table S1). For the Eagle Ford, Niobrara, and Woodford plays that extract both shale gas and oil, we show differential water use values for hydraulic fracturing shale gas and oil wells (Table S1). Our analysis shows that water use per well did not change significantly with time from 2011 to 2013 (Table S6).

Between 2005 and 2014, an estimated total of 940×10^9 L (940×10^6 m^3, 248×10^9 gal) was used to hydraulically fracture wells in the 10 formations included this study (Table 2). Hydraulic fracturing for shale gas (708×10^9 L, 708×10^6 m^3, 187×10^9 gal) has used three times more water than unconventional oil wells (232×10^9 L, 232×10^6 m^3, 61×10^9 gal). The Barnett Shale led the United States with a total water use of 243×10^9 L (64×10^9 gal) over the course of its production history. Because of its location in a semi-arid region of Texas and the growing stress on both ground and surface water resources with population growth, water use for future well development in the Barnett formation could be a limiting factor.[6,9] In the Monterey-Temblor Formation, water use per well (0.3×10^6 L, 0.08×10^6 gal) and total water use (0.35×10^9 L, 0.35×10^6 m^3, 0.09×10^9 gal) are relatively low. This can be largely attributed to most hydraulic fracturing (well stimulation) occurring on vertical wells in higher permeable formations as opposed to horizontal wells in other plays.[30,32]

Overall, we estimate that between 2012 and 2014 the annual water use for hydraulic fracturing in the United States was 116×10^9 L (31×10^9 gal) per year for shale gas and 66×10^9 L (17×10^9 gal) per year for unconventional oil (combined 183×10^9 L or 48×10^9 gal per year; Table S8). This estimated water use is 0.87% of the total industrial water used in the United States (2.07×10^{13} L, 5.5×10^{12} gal per year) and only 0.04% of the total fresh water use per year (4.23×10^{14} L, 1.11×10^{14} gal per year) in the United States.[38]

Flowback and Produced Water. Flowback water is typically the first water produced from a well following hydraulic fracturing and is made up of injected hydraulic fracturing fluids blended with formation water (a range of 1.8 to 4.1×10^6 L, 0.5 to 1.1×10^6 gal for the Marcellus shale after 90 days)[16] and is typically associated with high rates of oil and gas production. Over time the produced water that is generated with gas and oil is composed of almost entirely of the formation water,[39] and the production rates gradually decrease parallel to the oil and gas production (Figures S9 and S10).[14] While it is possible to distinguish flowback from produced water based on water chemistry, data reported by producers to government agencies typically does not distinguish the two types of fluids, and thus, we report here combined volumes as flowback and produced waters (FP water). Previous studies have evaluated the FP water volume after a relatively short period, whereas in this study, we provide a longer integrated time of FP water production between 6 to 10 years.[7,9,16] A comparison between the results of this study to previous studies is shown in Table S3.

In some unconventional shale gas and oil formations, the volume of FP water after 1 to 2 years exceeds the volume of water injected for hydraulic fracturing (Bakken, Eagle Ford, Niobrara, and Monterey-Temblor), while in other formations (Barnett, Haynesville, and Marcellus), the volume of produced water, even after 8 to 9 years of operation, is typically lower (Table 2). In all cases, FP water generation drops dramatically after the first year and levels off to a constant rate of production in the following years (Figure 1). Integration of all of the data over the 6 to 10 years of available data yielded a large variation of FP water volume for different shale gas formations, between 5.2×10^6 L ($1.4 \text{ x}10^6$ gal) per well for the Marcellus shale and 25.9×10^6 L ($6.8 \text{ x}10^6$ gal) per well for the Eagle Ford. Produced water from unconventional oil production had a smaller range of 8.0×10^6 L (2.1×10^6 gal) per well for the Niobrara formation to 22.7×10^6 L (6.0×10^6 gal) per well in the Eagle Ford (Table 1).

Overall, we estimate a total of 803×10^9 L (803×10^6 m^3, 212×10^9 gal) of FP water returned to the surface since the early 2000s[7] until today (2015) from unconventional shale gas and oil operations in the 10 plays included this study (Table 2). Shale gas plays in sum produced slightly less water (472×10^9 L, 125×10^9 gal) than was used for hydraulic fracturing (708×10^9 L, 187×10^9 gal), while unconventional oil wells (331×10^9 L, 87×10^9 gal) produced more FP water than was used to fracture them (232×10^9 L, 61×10^9 gal). Given the high levels of contaminants, several studies have highlighted the challenges associated with the management and disposal of FP water,[2,19,22,23] thus, the fact that the amount of generated FP water in the United States is on the same level as water use is startling.

Water Use and Produced Water Intensity. In order to compare shale gas and unconventional oil to each other and to other energy sources, the water use intensity (WUI) and produced water intensity (PWI) parameters were used. Upon normalizing water use and FP water production to energy production, the WUI of shale gas (combined dry and wet gases) had a range from 0.7 to 9.3 L/GJ, similar to the range

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obtained for unconventional oil (1.1 to 7.5 L/GJ). Our data show that WUI for both shale gas and unconventional oil did not change in most plays with time (Figures S3 and S4). WUI calculations in this study only accounted for water used in the hydraulic fracturing of wells and excluded the water use for drilling (640 to 1080 × 10^3 L, 169 to 285 × 10^3 gal per well) and cement (70 to 140 × 10^3 L, 18 to 37 × 10^3 gal per well), as well as the potential for refracturing of wells.[3,40] WUI values obtained in this study are significantly higher relative to reported WUI values for water allocation for drilling and cementing associated with conventional oil and gas extraction, (~0.7 L/GJ).[3,25] Yet, enhanced oil recovery, particularly through tertiary recovery techniques, would have a much higher WUI of 120 L/GJ.[40] Likewise, both unconventional shale gas and oil have much lower WUI values (for extraction) relative to coal (underground mine, 28.4 L/GJ; surface mine, 3.2 L/GJ) and uranium (23.8 L/GJ) extractions.[25]

The WUI for unconventional oil production can also be calculated by the volumetric ratio of water use to oil production during a time interval. The range of WUI of this metric for unconventional oil extraction by hydraulic fracturing is 0.07 (Monterey-Temblor) to 0.74 in the Woodford formation (Table 1). By comparison, the average WUI for conventional oil extraction was 8.6 over the lifetime of a well. Yet enhanced oil recovery through tertiary recovery techniques could increase the WUI to up to 300.[40]

The produced water intensity (PWI) for unconventional oil production (6.8–11.4 L/GJ) is only slightly higher than that of shale gas (1.0–10.2 L/GJ). In the Monterey-Temblor play in California, the production of FP water is much higher (PWI of 76.6 L/GJ), probably due to the relatively higher permeability of the formations in which well stimulation is occurring. The other PWI metric is the volumetric ratio of FP water to oil production. Our data indicate that the FP water to oil ratio (in barrels) varies from 0.36 to 0.56 in horizontal on-shore unconventional oil production, with an average water-to-oil ratio of 0.44. Monterey-Temblor vertical unconventional production had a higher ratio of 3.22 (Table 2). The data show that volumetric PWI values in all unconventional oil wells except the Monterey-Temblor formation remains constant during 6 to 10 years of production (Figure S8), and the significant reduction in oil production after the first year is paralleled by similar reduction in FP water production. This pattern is opposite of typical conventional oil wells, where produced water and the water–oil ratio increase with well age.[41] The FP water–oil ratios of unconventional oil wells are also lower than estimates for produced water–oil ratios of 3[42] to 7[41] reported for conventional oil in the United States.

While new exploration of unconventional shale gas and oil formations in the United States has increased the overall water use for hydraulic fracturing (a total of 940 billion liters from 2005 to 2104) and has generated new sources of highly saline and toxic wastewater (a total of 775 billion liters), our water use and produced water intensity evaluation indicates that hydraulic fracturing is not extracting more water and generating more wastewater relative to conventional oil or coal mining while normalized to the energy production.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.estlett.5b00211.

Comparisons of results to literature and industry values (Tables S1–S3), other figures detailing water use statistics (Figures S1, S2, S5), analysis of data with mean instead of median (Tables S4, S5), maps showing total water use and FP water (Figures S5–S7), time scale analysis (Figures S3, S4, S8–S11 and Tables S6, S8), supporting references. (PDF)

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Notes

The authors declare no competing financial interest.

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