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Key Points:

- A U.S. map of water volumes used to hydraulically fracture oil and gas wells, 2011–2014
- Hydraulic fracturing water volumes differ regionally across the U.S.
- Discussion of variation in water use and potential environmental implications

Supporting Information:

- Supporting Information S1

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Hydraulic fracturing water use variability in the United States and potential environmental implications

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Abstract Until now, up-to-date, comprehensive, spatial, national-scale data on hydraulic fracturing water volumes have been lacking. Water volumes used (injected) to hydraulically fracture over 263,859 oil and gas wells drilled between 2000 and 2014 were compiled and used to create the first U.S. map of hydraulic fracturing water use. Although median annual volumes of 15,275 m³ and 19,425 m³ of water per well was used to hydraulically fracture individual horizontal oil and gas wells, respectively, in 2014, about 42% of wells were actually either vertical or directional, which required less than 2600 m³ water per well. The highest average hydraulic fracturing water usage (10,000–36,620 m³ per well) in watersheds across the United States generally correlated with shale-gas areas (versus coalbed methane, tight oil, or tight gas) where the greatest proportion of hydraulically fractured wells were horizontally drilled, reflecting that the natural reservoir properties influence water use. This analysis also demonstrates that many oil and gas resources within a given basin are developed using a mix of horizontal, vertical, and some directional wells, explaining why large volume hydraulic fracturing water usage is not widespread. This spatial variability in hydraulic fracturing water use relates to the potential for environmental impacts such as water availability, water quality, wastewater disposal, and possible wastewater injection-induced earthquakes.

1. Introduction

During hydraulic fracturing, water containing chemical additives and a propping agent is injected into a low-permeability petroleum reservoir under high pressure, fracturing the formation. The propping agent holds open the fractures, allowing oil and (or) gas to flow to the well borehole, thus stimulating production. Hydraulic fracturing has improved domestic oil and gas yields from low-permeability tight-sand, shale, and coalbed reservoirs, thus lessening the dependence of the United States (U.S.) on foreign supplies of natural gas and oil [U.S. Energy Information Administration, 2015; Vidic *et al.*, 2013]. Hydraulic fracturing, however, is not without controversy; one primary concern, among several, is that it may adversely impact the environment [Brittingham *et al.*, 2014; Gregory *et al.*, 2011; Kargbo *et al.*, 2010; Mauter *et al.*, 2014; Soeder and Kappel, 2009; Vidic *et al.*, 2013]. An important key to understanding how hydraulic fracturing could potentially impact the environment is the volume of water used in this process. The volume of water injected affects the availability and consumptive use of freshwater resources, volumes of wastewater, the wastewater disposal and treatment procedures available, and the ultimate fate of this water.

Previous hydraulic fracturing water use estimates range from 1400 to 33,900 m³ per shale-gas well [Clark *et al.*, 2013; Goodwin *et al.*, 2014; Nicot and Scanlon, 2012; Scanlon *et al.*, 2014] and 8177–9009 m³ per well completed in tight-oil formations [Horner *et al.*, 2014; Scanlon *et al.*, 2014]. Analysis of historical data indicates the importance of well borehole orientation, drilling date, and target hydrocarbon on hydraulic fracturing water volumes [Gallegos and Varela, 2015a] and could account for the wide range of estimates. Individually, these previous studies provided only partial information needed to fully understand the complexity of hydraulic fracturing water use across different geologic basins. There is a need to better understand the spatial variability of water use in hydraulic fracturing in aggregate, that is, with consideration of all well types and all target oil and gas reservoirs. As such, the objective of this research is to compile comprehensive, up-to-date data on water volumes injected for hydraulic fracturing and provide a national-scale perspective of spatial trends in order to better articulate how water use is linked to the potential for environmental impacts across the United States.

2. Data and Methods

The original data sources, compilation steps, and analyses are detailed elsewhere [Gallegos and Varela, 2015a, 2015b]. In brief, the most recent data on hydraulic fracturing injection volumes were compiled from the “Well Treatment” and “Well” tables in the commercial and proprietary IHS database of U.S. Oil and Gas Production and Well Data [IHS Energy, 2014] on 29 December 2014, and include data from 01 January 2000 to 28 August 2014. Not all hydraulically fractured oil and gas wells in the United States are included here because not all well information may have been reported or acquired, many states still do not require reporting of hydraulic fracturing fluid volumes, not all wells are hydraulically fractured using water, and there may be a time lag in IHS database [IHS Energy, 2014] updates. Data were acquired from a variety of public and private sources and checked by IHS, Inc. [IHS Energy, 2014]. To our knowledge, there is no publicly available source of hydraulically fractured well data that can be used for comparison to estimate the absolute number of missing wells. Hydraulic fracturing data from the IHS database were previously analyzed and trends were compared to, and were found to be consistent with, published references [Gallegos and Varela, 2015a]. As such, the hydraulic fracturing data sets derived from the IHS database, including water volumes used to fracture oil and gas wells, were deemed accurate for computing statistics and providing an indication of tendencies of hydraulic fracturing treatments and hydraulically fractured wells within geographically and geologically defined areas (such as watersheds) and over a defined period of years [Gallegos and Varela, 2015b], as presented here.

Treatment types in the IHS database of “frac” or “refrac” were identified as hydraulic fracturing stimulation treatments. Treatment fluid types of “water,” “slick water,” “acid,” “fracturing,” “fluid,” “sand gel frac,” “My-T-Frac,” “sand acid frac,” “gel,” or “crosslink gel” were categorized as water-based fluids. The volumes of all water-based fluids were converted from original units of barrels, cubic feet, gallons, thousands of cubic feet, or quarts to cubic meters (m^3) for each hydraulic fracturing record. The water-based treatment fluid volumes were then summed for each unique oil and gas well with a borehole direction of “horizontal,” “vertical,” or “directional” in the IHS Well Table. The annual median water volume and the number of wells for each of the following well-type categories were computed and plotted as a function of the associated well-completion year: horizontal oil, horizontal gas, vertical oil, vertical gas, directional oil, and directional gas wells. Data within the 1st–99th percentile of all hydraulic fracturing water volumes for wells completed in the United States from January 2011 to August 2014 were extracted for each of the well-type categories. Each of these volumes was then spatially associated with a watershed defined by U.S. Geological Survey 8-digit hydrologic unit code (HUC) based on the well location. The averages of these water volumes used to hydraulically fracture wells within each watershed were mapped. Finally, the percentages of hydraulically fractured wells that were horizontally drilled within each watershed were used to construct a map of the concentration of horizontal wells completed across the United States from January 2011 to August 2014. Water volumes used to hydraulically fracture oil and gas wells reported and discussed here are injected volumes and do not necessarily represent consumptive use.

3. Discussion

3.1. Hydraulic Fracturing Water Use Across the United States

The first U.S. map of average water volumes injected per well for hydraulically fracturing oil and gas wells (Figure 1), derived from the most recent data in the IHS database of U.S. Oil and Gas Production and Well Data [IHS Energy, 2014], illustrates that hydraulic fracturing uses large amounts of water, though not as much as may have suspected in some areas. The water volumes used to hydraulically fracture wells averaged within a given watershed (i.e., U.S. Geological Survey 8-digit HUC) range from 10 to 36,620 m^3 per well. The highest average water use (greater than 10,000 m^3 per well) areas generally coincide with the following shale-gas formations [U.S. Geological Survey National Assessment of Oil and Gas Resources Team and Biewick, 2013] (not in any particular order): Eagle Ford and Haynesville-Bossier (Gulf Coast Basins), Barnett (Bend Arch-Ft. Worth Basin), Fayetteville (Arkoma Basin), Woodford (Anadarko and Arkoma Basins), Tuscaloosa (Gulf Coast Basins), and the Marcellus and Utica (Appalachian Basin). These average volumes reported here are consistent with other estimates ranging from about 6800 to 38,000 m^3 per well [Clark et al., 2013; Goodwin et al., 2014; Gregory et al., 2011; Horner et al., 2014; Jiang et al., 2014; Kargbo et al., 2010; Nicot and Scanlon, 2012; Scanlon et al., 2014]. In 52 out of the 57 watersheds with the highest average hydraulic

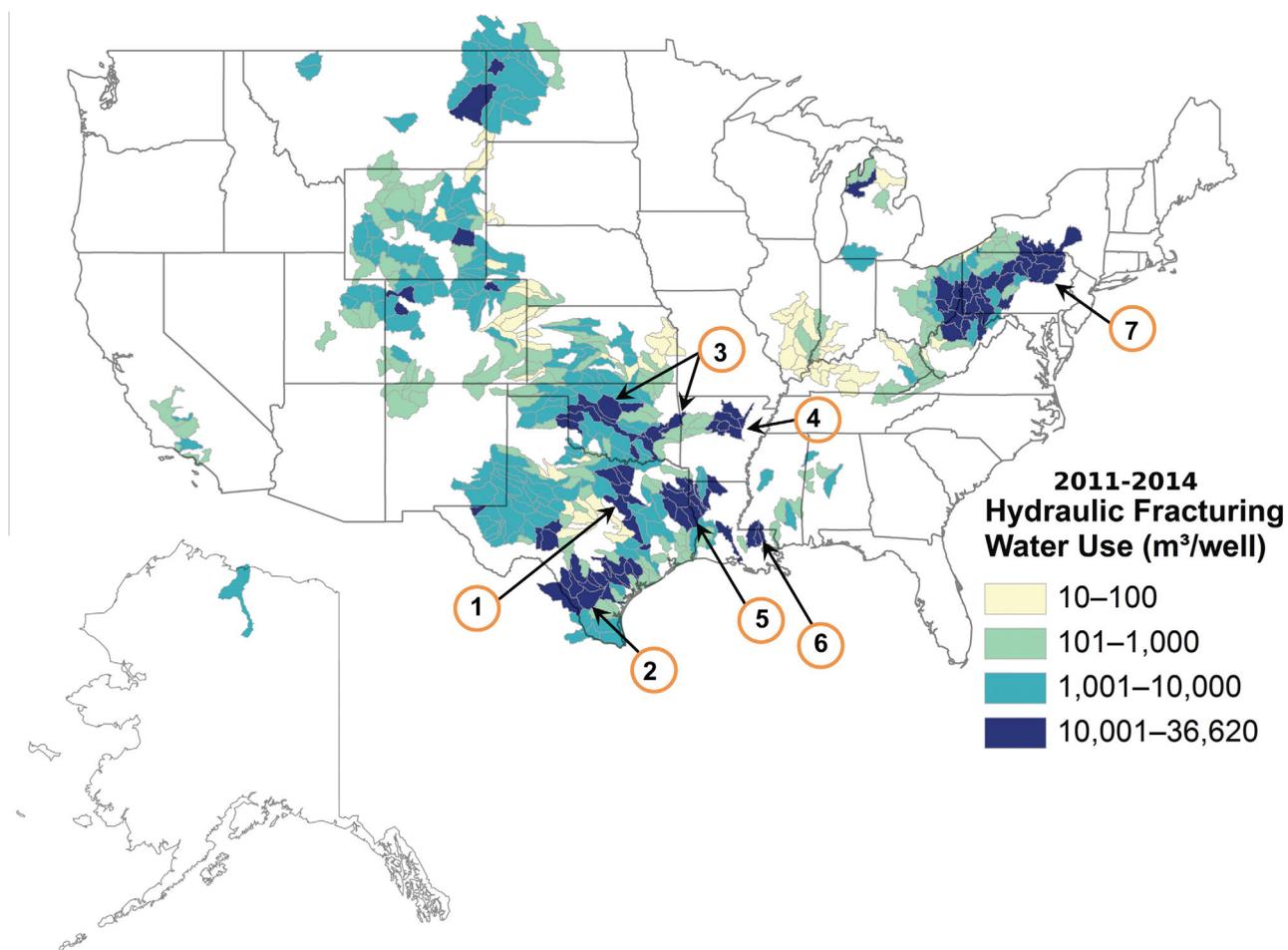


Figure 1. Average of the data within 1st–99th percentile of water volumes used (injected) per well to hydraulically fracture oil and gas wells (horizontal, directional, and vertical) drilled from January 2011 to August 2014 in watersheds (8 digit Hydrologic Unit Codes, HUCs) with at least two wells reporting water use ($n = 81,816$ wells). Shale-gas formations are numbered (not in any particular order): (1) Barnett (Bend Arch-Ft. Worth Basin), (2) Eagle Ford (Gulf Coast Basins), (3) Woodford (Anadarko and Arkoma Basins), (4) Fayetteville (Arkoma Basin), (5) Haynesville-Bossier (Gulf Coast Basins), (6) Tuscaloosa (Gulf Coast Basins), and (7) Marcellus and Utica (Appalachian Basin). Supporting information Table S1 contains data used to construct this figure.

fracturing water volumes above $15,000 \text{ m}^3$ per well, over 90% of wells were horizontally drilled, reflecting that shale-hosted continuous oil and gas resources are often developed using horizontal drilling practices, which use greater volumes of water per well. Generally, the higher water use per horizontal well reflects the longer lengths of the lateral sections of the wellbore [Nicot and Scanlon, 2012], which are designed to increase the contact area with the reservoir rock and stimulate greater oil or gas production.

Between 2000 and 2014, median national annual water volumes used to hydraulically fracture horizontal wells had increased from less than 670 m^3 to nearly $15,275 \text{ m}^3$ and $19,425 \text{ m}^3$ per oil and gas well, respectively, while median water use in vertical and directional wells (i.e., at an angle from the vertical) remained below 2600 m^3 per well (Figure 2a). Although there has been an increase in the number of horizontal wells since 2008, about 42% of new hydraulically fractured wells completed in 2014 were still either vertical or directional (Figure 2b). The ubiquity of the lower-water-use vertical and directional wells in part, explains why water use is variable across the United States. Areas of the United States with the largest hydraulic fracturing water use from 2011 to 2014 (Figure 1) usually, but not always, correlate with areas containing the greatest concentrations of hydraulically fractured horizontal wells (Figure 3) because the amount of water used for hydraulic fracturing is also directly or indirectly influenced by local or regional oil-reservoir and gas-reservoir characteristics. The reservoir extent, depth, and thickness of oil-bearing or gas-bearing strata influences the perforated interval of the well and amount of water needed to induce fractures while the porosity, permeability, temperature, pressure, and other intrinsic properties impact water saturation, fracture geometry, and hydraulic fracturing treatment fluid design [Elbel and Britt, 2000; Holditch, 2007]. For

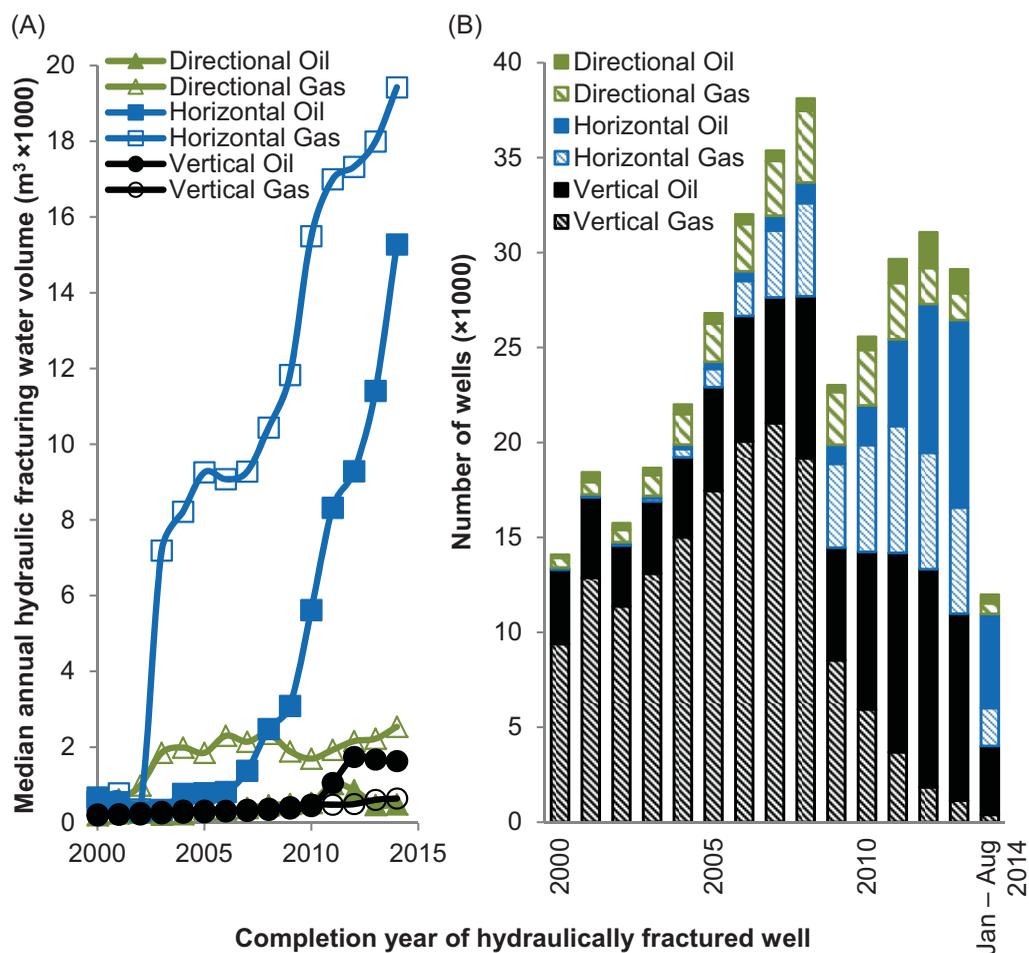


Figure 2. The (a) median national annual water volumes used (injected) per well to hydraulically fracture wells drilled from January 2000 to August 2014 delineated as a function of drill-hole direction (vertical, horizontal directional) and final status (oil or gas) ($n = 263,859$) and (b) number of hydraulically fractured wells drilled from January 2000 to August 2014 as a function of drill hole direction and final status ($n = 371,607$). Includes only well information gathered and reported by IHS, Inc. [IHS Energy, 2014] as of 28 August 2014. Note: 1 cubic meter (m³) is equal to 264.17 gallons. Supporting information Tables S2 and S3 contains data used to construct this figure.

example, shale-gas reservoirs are often hydraulically fractured using slick water, a formulation containing a large proportion of water; tight-oil reservoirs often use gel-based hydraulic fracturing treatment fluids (lower proportion of water) because they are water-sensitive formations; low-pressure formations are often hydraulically fractured using a foam-based hydraulic fracturing fluid [Elbel and Britt, 2000; Holditch, 2007].

3.2. Potential for Environmental Impacts

Although water use data have not been reported for all hydraulically fractured wells, spatial patterns of average water volumes injected into 81,816 wells in Figure 1 can help us better understand the relative ranges of water used in hydraulic fracturing on a regional basis. Coupled with local climate, geologic and hydrologic settings, and management practices, the regional differences in the amount of water used for hydraulic fracturing could translate into differences in the amounts of wastewater produced and ultimately possible differences in the potential for environmental impacts including water availability, water quality, wastewater disposal, and possible wastewater injection-induced earthquakes.

3.2.1. Water Availability

Large volumes of water extracted from ground or surface water sources for hydraulic fracturing affect public water resources and aquatic ecology [Brittingham et al., 2014; Gregory et al., 2011; Kargbo et al., 2010; Mauter et al., 2014; Soeder and Kappel, 2009; Vidic et al., 2013], although increasingly, brackish and saline waters are injected [Nicot et al., 2014]. Freshwater availability is affected by local water budgets, populations, agricultural practices, and climate. Water supply concerns can be acute in areas that are susceptible to drought

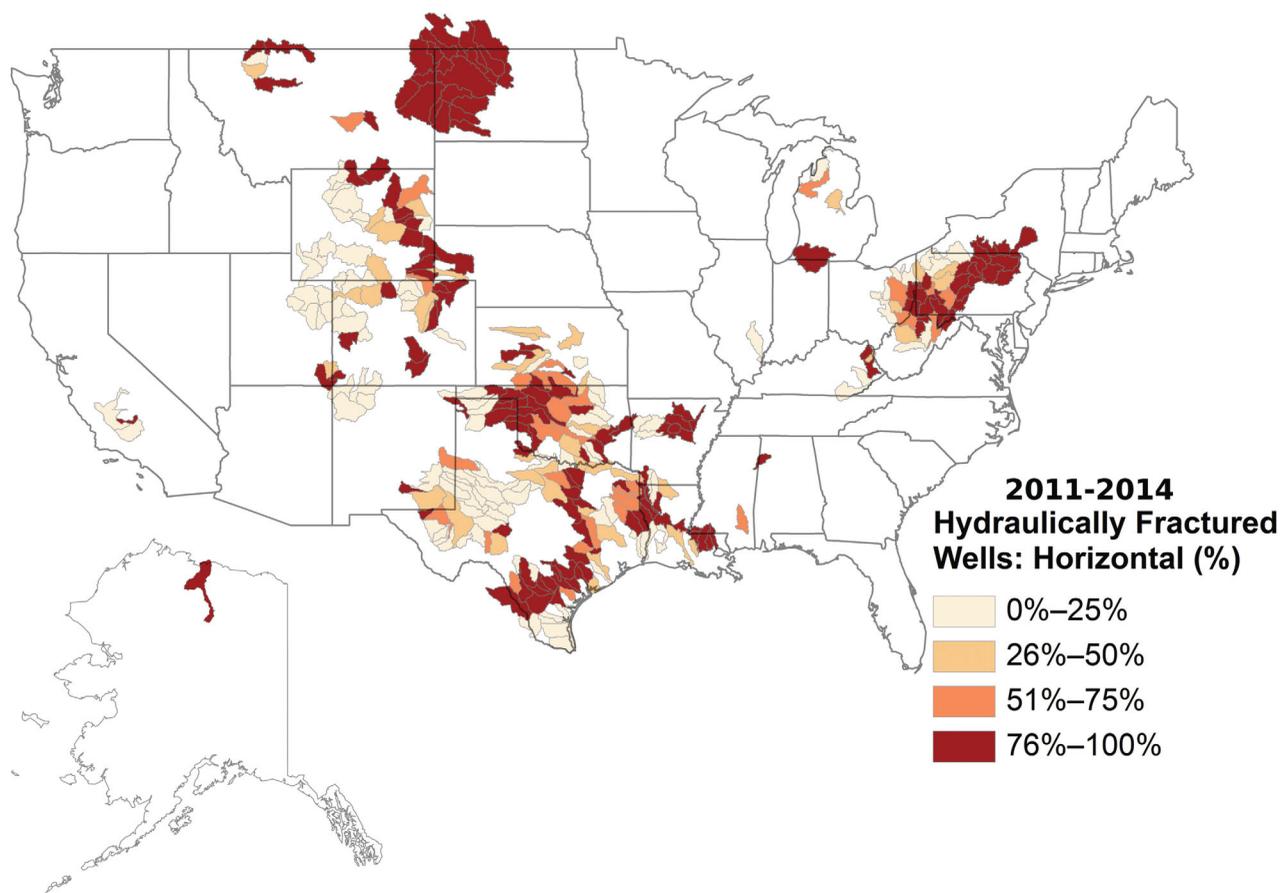


Figure 3. Percent of hydraulically fractured wells that were horizontally drilled from January 2011 to August 2014 in watersheds of the United States ($n = 47,646$). These horizontal wells represent about 47% of the total number of hydraulically fractured wells drilled during this period. Supporting information Table S4 contains data used to construct this figure.

[Vengosh *et al.*, 2014], such as areas of Texas, California, and New Mexico. The extraction of freshwater for hydraulic fracturing can also alter the hydrologic regime of rivers and streams and impact biological species through the loss of habitat, especially if the water withdrawal rate is high at a single location within a water body during a low-flow season or drought [Brittingham *et al.*, 2014].

3.2.2. Water Quality

There has been considerable concern regarding contamination of drinking water resources by chemicals either added to the hydraulic fracturing fluid or originally present in the geologic formation waters [Kargbo *et al.*, 2010] due to spills/leaks, stray gas migration, disposal of inadequately treated wastewater, or migration of hydraulic fracturing fluids or deep formation waters by hydraulic fracturing itself [Vengosh *et al.*, 2014]. To date, no definitive scientific evidence of groundwater contamination due to direct upward migration of injected aqueous fluids from oil and gas reservoirs along fractures created by hydraulic fracturing into drinking water aquifers has been reported in the scientific literature, but studies are limited [Gallegos *et al.*, 2015; Mauter *et al.*, 2014; Vidic *et al.*, 2013]. Recent publications, however, have highlighted evidence of fugitive gas migration along wellbores, likely due to faulty well construction [Darrah *et al.*, 2014; Vengosh *et al.*, 2014], suggesting the possibility of aqueous fluid migration by similar pathways and questioning the impact of large volumes of water on well integrity [Llewellyn *et al.*, 2015; Vengosh *et al.*, 2014]. Detection of changes to groundwater quality in aquifers due to direct migration of fluids from the oil and gas formations, however, is related to several factors that differ among petroleum producing regions [Mauter *et al.*, 2014]. The travel time, travel distance, and the ultimate dilution and detection of oil-related and gas-related waters in aquifers depend on: (1) the depth of the oil and gas reservoir relative to the groundwater aquifer, (2) the geology of the subsurface strata (e.g., hydraulic conductivity, porosity, fractures, extent, depth, pressure, temperature),

and (3) the volume of injected water that does not flowback to the surface (an estimated 60–95% of water injected is “lost” into the formation [Clark *et al.*, 2013; Gregory *et al.*, 2011]) relative to both the capacity of the fractured formation and the volume of the “receiving” aquifer. Thus, in some areas, the oil-related and gas-related waters are not likely to reach drinking water aquifers whereas in other areas, constituents of concern simply may not have yet reached the aquifer or have been diluted to below detection limits.

3.2.3. Wastewater Disposal and Earthquakes

The amount of water used during hydraulic fracturing poses wastewater management challenges [Gregory *et al.*, 2011; Kargbo *et al.*, 2010; Soeder and Kappel, 2009] because an estimated 5–40% of the water injected during hydraulic fracturing flows back to the surface (termed “flowback”) [Clark *et al.*, 2013; Gregory *et al.*, 2011]. In addition to differences in injected volumes, the volume and chemical compositions of oil and gas wastewaters (i.e., the flowback water along with the water coproduced during the oil and gas production, termed “produced water”) vary somewhat from region to region [Warner *et al.*, 2013], depending on differences in hydrology, geology and well-completion practices. These oil and gas wastewaters are stored at the surface and then disposed of, or treated and possibly recycled or reused. Despite the emergence of small-scale mobile wastewater treatment units specially designed to treat oil and gas wastewaters on site, deep-well disposal is currently the cheaper and often most expedient method of dealing with wastewaters, except in areas where deep-disposal wells are lacking or water is scarce. For example, in portions of the Appalachian Basin, where deep-disposal wells are limited, operators recycle produced water for hydraulic fracturing of subsequent oil and gas wells, whereas deep-well injection is the disposal method of choice in Texas, where there are thousands of deep-disposal wells [Gregory *et al.*, 2011; Vidic *et al.*, 2013]. The disposal of the wastewater into deep wells following hydraulic fracturing, however, has triggered seismicity in some areas [Zoback, 2012]. Small earthquakes could occur when large volumes of fluid are injected over long periods of time, under high pressure, particularly in locations with active faults or faults in brittle rock formations [National Research Council, 2013; Zoback, 2012]. The likelihood of induced seismic events, therefore differs on a regional basis given variations in geology (e.g., existence of faults, pore pressures, capacity of the geologic formation, rock type), disposal and recycling practices, and in the amount of water used and wastewaters produced during hydraulic fracturing.

3.2.4. Recycling Challenges and Opportunities

Recycling and reuse of hydraulic fracturing wastewaters eliminates some of the challenges of water availability and disposal, however, both can be difficult to implement in some regions because the permitting processes and water law can be prohibitively complex. Each state has site-specific issues (i.e., drought and abundant land area versus plentiful water and scarce land area) that contribute to unique regulations and permitting structure sometimes consisting of multiple permitting bodies for regulating the use, treatment, disposal, recycling, and reuse of wastewaters, depending on location [Mauter *et al.*, 2014; Romo and Janoe, 2012]. Regional variations in regulatory structures also mean that decisions regarding hydraulic fracturing including wastewater management and disposal practices, recycling, and underground fluid injection may fall under different regulations and jurisdictions [Horner *et al.*, 2014; Romo and Janoe, 2012]. As such, even if recycling and reuse of hydraulic fracturing flowback and produced wastewaters is technically and economically feasible and supported by industry and the public, the ability of operators to do so can be influenced by state and local regulatory and legal aspects.

4. Summary

This national-scale perspective shows that the amount of water used (injected) per well to hydraulically fracture oil and gas wells varies across the United States. Dissimilarity in water use stems from distinctions in well borehole configuration, hydrocarbon type, target oil or gas reservoir characteristics, and the completion year of the well. On a regional basis, the average water volume used per oil and gas well for hydraulic fracturing therefore depends on the concentrations and distribution of well types accessing oil or gas reservoirs within a geologic basin. Differences in local geology, hydrology, proximity to freshwater sources, existence and location of water treatment facilities, chemical makeup of flowback and produced wastewaters, management practices, land availability for surface storage, and availability of deep-disposal wells [Mauter *et al.*, 2014] coupled with the disparity in volumes of water injected could translate into possible differences in the potential for environmental impacts. Regional variations in regulatory structures also mean that decisions regarding hydraulic fracturing including wastewater management and disposal practices, recycling,

and underground fluid injection may fall under different regulations and jurisdictions. Because hydraulic fracturing is not a one-size-fits-all operation, assumptions and generalizations regarding water use in hydraulic fracturing operations and the potential for environmental impacts should be made with caution.

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