Evolving Water Management Practices in Shale Oil & Gas Development

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Abstract

Advances in horizontal drilling coupled with hydraulic fracturing have unlocked trillions of cubic feet (billions of cubic meters) of natural gas and billions of barrels (millions of cubic meters) of petroleum in shale plays across the United States. There are over 72,000 unconventional well sites in the United States, with anywhere from 2 to 13 million gallons (7500 to 49000 cubic meters) of water used per unconventional well. While unconventional wells produce approximately 35% less waste water per unit of gas than conventional wells, the sheer number of wells and amount of oil and gas being produced means that water use has increased by as much as 500% in some areas. Such large water demands give rise to questions about water management, including acquisition, transportation, storage, treatment, and disposal. While these issues vary by play, some key concerns include competition for drinking water sources, impacts of fresh and wastewater transportation, the extent of wastewater recycling, contamination, and the effects of various treatment and disposal methods on communities and watersheds. These concerns have not been fully resolved, yet there is a noticeable, and largely quantifiable, evolution of management practices toward operating more sustainably and with smaller regional impacts. Here we explore water management issues as they arise throughout the unconventional drilling process, particularly focusing on how practices have changed since the beginning of the shale boom and how these issues vary by play.

Keywords: water management; shale; hydraulic fracturing; unconventional oil and gas; environmental impacts

Introduction

The oil and gas industry has been working with shales, horizontal wells, and hydraulic fracturing for a long time. The first shale gas well was hand-dug in 1821 in New York, the first horizontal well was drilled in the 1930s, and the first hydraulic fracture was performed in 1947 (King, 2012). However, initial drilling and fracturing methods were not advanced enough to economically produce shale plays on a large scale (Horton, 1981). Greater research into shales and hydraulic fracturing was spurred by Department of Energy funding during the energy crises of the 1970s (e.g. Komar et al., 1976; Vortman, 1976; McCann and Schuster, 1977; Nuckols, 1979). Then, in 1997, Mitchell Energy began successfully producing gas from the Barnett Shale in the Fort Worth Basin of Texas using horizontal drilling and staged hydraulic fracturing (Montgomery et al., 2005). Their methodology was soon applied to other organic-rich shales such as the Haynesville in Louisiana, the Fayetteville in Arkansas, and the Bakken in North Dakota. In 2004, Range Resources completed the first Marcellus well as a fallback after deeper formations failed to show promise (Carter et al., 2011); they subsequently modified techniques from the Barnett to complete over 400 Marcellus wells in Pennsylvania (GWPC, 2014). The Marcellus Shale has since been identified by the Energy Information Administration as the largest natural gas resource in the United States (USEIA, 2014).

One major contributor to today's success with shale plays is the advancement of horizontal, or directional, drilling. The contact area between a vertical well and a shale formation is limited by the vertical thickness of the rock. In contrast, a directional well can be drilled along the horizontal extent of the target formation, meaning the well is effectively only limited by the length of lateral that can be drilled. A comparison of vertical and directional wells is shown in Figure 1. Having a larger contact area between wellbore and target formation is of particular importance in shales, as their permeability is so low that large volumes of rock must be intersected to produce economic volumes of hydrocarbons.

The other major component of success in shale plays is the development of hydraulic fracturing techniques. Hydraulic fracturing is used to address the low permeability of shale formations and involves pumping water into the target formation at pressures high enough to fracture the rock. This water also contains a proppant, usually sand, that flows into the fractures then props them open once water pressure has been lowered. Other additives can include friction reducers, thickeners, corrosion and scale inhibitors, acids (to clean perforations), and antibacterial agents (GWPC, 2014). The fracturing process creates high-permeability flow paths into the shale, allowing more gas to flow out of the rock and into the wellbore. Hydraulic fracturing in horizontal shale wells proceeds in stages, wherein a segment of the

lateral is blocked off, the production casing (tubing that lines the lateral segment of the well) is perforated, and the rock around that section of the well is fractured. This process is repeated along the length of the lateral (Figure 1). After the rock has been fractured, pressure is lowered and the water that was initially injected flows back up the well for up to a few weeks; this water is known as flowback water. Flowback water is chemically nearly identical to the fracturing fluid that was injected. After flowback water has been recovered, briny water will continue to be produced over the lifetime of the well; this water is known as produced water. Produced water is much saltier than fracturing fluid and generally contains salts from the fractured rock formation. However, the term “produced water” is sometimes used as an all-inclusive term to describe any water that flows into the well.

Combined horizontal drilling and staged hydraulic fracturing has opened up huge reserves of shale oil and gas throughout the United States that were formerly thought to be unrecoverable (Figure 2). Although the cost of drilling a horizontal shale well is approximately 2-3 times higher than that of a vertical well, the initial gas production can be 3-4 times greater (Engelder and Lash, 2008). The economic development of shale resources has brought along an unprecedented energy boom, unlocking trillions of cubic feet (billions of cubic meters) of natural gas and billions of barrels (millions of cubic meters) of petroleum (USEIA, 2013). It has also made the U.S. the largest producer of natural gas in the world, with domestic crude oil production recently exceeding foreign oil imports for the first time in decades (USEIA, 2014).

The explosion of shale oil and gas exploration and production has led to a number of environmental concerns. Many of these involve water, as 2-13 million gallons (7500 to 49000 cubic meters) of water can be required to complete an unconventional shale well, and there are over 72,000 well sites in the United States (GWPC, 2014). Although unconventional wells produce about 35% less waste per unit of gas than conventional wells, the increased number of wells and amount of production has meant a 500% increase in water use for some regions (Lutz et al., 2013). Furthermore, 47% of hydraulic fracturing in the United States occurs in high water stress regions, and over 55% of hydraulically fractured oil and gas wells are in drought-stricken regions (Freyman, 2014), making water management a critical component of continued development. Potential concerns include encroachment on drinking water supplies, contamination of groundwater or surface water from spills or leaks, habitat disturbance, and impacts of water transportation. This paper will explore these issues with a focus on how water management practices have evolved since the beginning of the shale boom and how issues vary by region and shale play.

Figure 1: Illustration showing a traditional, vertical, hydraulically fractured well next to a modern well that combines directional drilling and hydraulic fracturing for production from shales. Modified from Soeder and Kappel, 2009.

Figure 2: Shale oil and gas plays in the United States (USEIA, 2011).

Water Sources

Municipal or tap water can be a convenient water source for drillers mainly because it is clean. Between 2008 and 2010, tap water accounted for almost 30% of hydraulic fracturing water in parts of Pennsylvania (Abdalla and Drohan, 2010). Chemicals and proppants needed for fracturing fluid can be mixed directly with the water, or it can be used for drilling mud. However, in some regions fresh drinking water is scarce, and using tap water to drill means competing with household users for a limited supply. Tap water is also relatively expensive since it must be purchased from a municipal provider who has treated it enough to be potable; water does not necessarily need to be this clean in order to be used for drilling and hydraulic fracturing. Furthermore, municipal hookups (such as fire hydrants) are not always located conveniently to drilling sites, which generally results in water haulers filling their trucks at a hookup and then driving as far as necessary to access a well pad. Resulting truck traffic from multiple

water haulers coming and going can damage roads and create noise and traffic (see Transportation section).

Raw stream and river water are becoming a more common option for drillers in areas where water shortages are not a problem, such as the Marcellus and Utica Shale regions. In the Susquehanna River basin, which underlies the Marcellus, surface water had already become a larger source for drillers than municipal water by 2010 (Veil, 2010). These sources are cheaper than municipal water and are still relatively clean. Permits and fees are sometimes required, but not always. Using nearby surface waters reduces transportation costs by either reducing the length of truck trips or eliminating them altogether by using a temporary overland pipeline. Such pipelines have been employed to pump and transport water from a surface source to impoundments at well pads until all wells in an area are complete, after which the pipelines are removed. Depending on how much water withdrawal is allowed, direct pumping from streams could potentially have downstream effects on flow level and habitat (NYSDEC, 2011).

Acid mine drainage (AMD) is another potential water source for drillers in regions with legacy water quality problems from mining, including the Marcellus and Utica regions. Using AMD reduces freshwater demand and puts the mine-affected water into a waste stream, meaning it will be treated and/or disposed of instead of continuing to contaminate the watershed. The Pennsylvania Department of Environmental Protection has been encouraging this practice by removing larger-scale liability for drillers who opt to use the mine drainage (PADEP, 2013). AMD is typically treated before being used for hydraulic fracturing fluid, and some companies have turned AMD into an asset by treating and then selling it to drillers (Kargbo et al., 2010; CONSOL, 2012). Some research has also indicated that mixing AMD with hydraulic fracturing wastewater could help remove radioactive elements from the water by precipitation, making it easier to then recycle flowback and produced water (Kondash et al., 2013).

Seawater and briny groundwater have also been successfully used in hydraulic fracturing, both offshore and onshore. Seawater has been used successfully offshore without any pretreatment prior to mixing with fracturing chemicals and proppants, and it has been considered for onshore projects in arid regions as well (Bukovac et al., 2009). Brines account for up to 80% of fracturing water used in some areas of Texas, such as the Permian Far West, as freshwater is scarce and in high demand for drinking water (Nicot et al., 2012). Brines generally come from aquifers that are considered too salty to be used for drinking water, though where to draw the line between a brine and treatable water is frequently debated. However, brine use and freshwater use vary considerably by play; the Eagle Ford and other plays in eastern Texas only use up to 20% brine and 80-95% freshwater (Nicot et al., 2012).

Water Transportation

As mentioned previously, trucking is the traditional mode of transporting water to unconventional well sites. Trucking allows for flexibility in both water source location and well pad location, though longer trips are more costly. Additionally, water trucks add to the traffic already created by other drilling equipment and products being moved to and from the well site. Between 100 and 650 truck trips are required to bring all fluids for drilling, completion, and hydraulic fracturing to a well site and then remove wastewater; with the addition of all other truck trips required to bring equipment, prepare the well pad, etc., the total number of truck trips ranges from 625-1148 (NYSDEC, 2011).

Direct piping from a water source to a well pad is an alternative to trucking water. Local sources, such as streams and rivers described previously, can be tapped and transported via temporary overland pipelines that are only kept in place until wells are completed. However, longer, more permanent pipelines are now being used to bring water from more remote locations to areas of high demand. Some of these pipelines are built by the operators that intend to use them, while others are built by third parties that then sell water subscriptions to operators in need of drilling and fracturing water (EID, 2012).

The use of centralized impoundments to store freshwater creates a dual water transportation system in which water is initially transported to and stored at an impoundment before being sent out as needed to well pads located generally within a 4-mile (6-kilometer) radius (NYSDEC, 2011). Either trucks or pipelines can be used for filling the central impoundment, with temporary pipelines generally being used to send water from the impoundment to individual well pads. Using trucks for just the initial filling of the impoundment minimizes the time and spatial extent of truck traffic impacts, but ideally a water pipeline would be used to fill the impoundment as well. A pipeline between a water source and a central impoundment also allows for water to be pumped only during high flow periods and then stored in the impoundment until it is needed by surrounding well pads (NYSDEC, 2011; EID, 2012). This optimized pumping schedule creates a buffer between the water source and the needs of individual wells, minimizing potential negative impacts on stream habitat and drinking water supply.

Alternative Fluids and Additives

One way to remove the bulk of water management problems from unconventional production is to use alternative fluids for hydraulic fracturing. Waterless fracturing fluids are currently being researched and

175 deployed, including a propane gel fracturing fluid that has been used in Texas and Canada (StateImpact
176 Texas and Texas Tribune, 2013), liquid carbon dioxide fracturing fluids that have been used in numerous
177 locations across North America, and nitrogen gas and foam fracturing fluids (Gandossi, 2013). The
178 benefits of these techniques extend beyond removing water management issues. Nitrogen fracture
179 stimulations in some basins have been shown to produce more in-zone seismic events and greater
180 fracture complexity than a traditional slickwater fracture treatment (Hall and Kilpatrick, 2010). Both
181 propane and carbon dioxide allow for hydrocarbons to flow more freely than water does, and carbon
182 dioxide is even used to enhance well production in traditional wells. Furthermore, propane gel and
183 liquid carbon dioxide do not dissolve salts to the same extent that water does, meaning they will bring
184 fewer salts from the reservoir rock to the surface. The potential to incorporate carbon storage into
185 carbon dioxide fracturing has also been discussed. However, using these alternative fluids requires
186 modification to the fracture fluid chemistry, mixing process, injection process, etc., slowing their
187 potential acceptance into mainstream use.

188 Additionally, non-water ingredients can be added to standard water-based fracturing fluids to reduce
189 the amount of water required. One such additive is guar gum, which thickens the fracturing water and
190 can reduce water usage by up to 45% (StateImpact Texas and Texas Tribune, 2013). Finally, some
191 companies have developed nontoxic hydraulic fracturing fluids from food-industry ingredients to
192 minimize risk of damage should a spill or leak occur (Scranton Times-Tribune, 2013a).

193 **Groundwater Impacts and Protection**

194 One of the most highly contested issues related to drilling and hydraulic fracturing is whether these
195 processes contaminate drinking water aquifers. Such debate often centers on whether methane found
196 in drinking water wells and aquifers is preexisting or the result of drilling-induced migration from deeper
197 formations that are being tapped for production. Researchers have come to very different conclusions
198 on this subject. Some show a correlation between methane in groundwater and the presence of nearby
199 gas wells (e.g. Jackson et al., 2012), while others have found a correlation between certain landscape
200 features and methane in groundwater (e.g. Molofsky et al., 2013). Conflicting conclusions have also
201 been drawn regarding the isotopic fingerprinting of methane gas found in groundwater, with authors
202 inferring different origins of the methane based on their isotopic analyses (e.g. Osborn et al., 2011 and
203 Molofsky et al., 2013). Another question is to what extent drilling and hydraulic fracturing fluids pose a
204 risk to groundwater and surface water due to potential spills or leaks at the surface. Those who feel the

205 risk is high often cite the *number* of spill or leakage incidents, while those arguing that risk is low cite the
206 *percentage* of wells that have officially documented spills or leaks. Despite the continuation of debate
207 on these issues, there are approaches to drilling that can minimize and help detect groundwater
208 disturbance.

209 Initial drilling extends from ground level to a few hundred feet deep (generally still thousands of feet
210 (hundreds or thousands of meters) above the target zone), using either air or mud as a circulating fluid
211 to remove cuttings from the wellbore. After surface drilling is complete, the surface casing is set in place
212 to protect any shallow drinking water aquifers from contaminants migrating from deeper formations.
213 However, since surface drilling must be completed before any casing can be set, surface drilling
214 necessarily involves drilling directly through any shallow aquifer rock that is present. This portion of the
215 drilling process has been known to cause temporary turbidity in nearby drinking water wells (NYSDEC,
216 2011). Additionally, when air is used as a circulating fluid, it has the potential to move from the wellbore
217 into aquifers, increasing pressure gradients and causing faster, uncharacteristic groundwater flow (Geng
218 et al., 2013). Drilling with mud seems to be less likely to cause these problems, as it has higher viscosity
219 than air, the circulating mud particles preferentially cake along high permeability portions of the
220 wellbore, and lost circulation materials (fibers designed to prevent fluid flow into surrounding rock) can
221 be added to the fluid.

222 Most contamination issues occur at the surface (e.g. from spills) rather than at depth (Brantley et al.,
223 2014). Such spills have brought up the issue of how to store fluids, chemicals, and wastewater at drilling
224 sites. While impoundments are common for storing water before it is used, they pose potential
225 problems if used for wastewater. Heavy rainfall can flood impoundments, causing them to overflow, and
226 leakage through impoundment liners can be difficult to detect before contamination occurs. Thus, there
227 has been a trend toward storing wastewater in tanks rather than impoundments, especially for storing
228 produced water over the lifetime of the well (Scranton Times-Tribune, 2013b). Tanks are less susceptible
229 to weather than impoundments, though they are still vulnerable to extreme weather events
230 (Rueschhoff, 2013). Leaks from tanks are also easier to detect and could potentially be remedied before
231 they negatively impact groundwater or surface water. Some states have required that wastewater be
232 stored in tanks rather than impoundments, and the Center for Sustainable Shale Development has made
233 storing wastewater in tanks one of its best management practices required for certification (CSSD,
234 2013).

There are some concerns that hydraulic fracturing fluid could migrate up from the target formation into drinking water aquifers, but regional studies have not found this to be occurring (Warner et al., 2012). Hydraulic fractures rely on the stress state at depth to propagate vertically (Zoback, 2010). At the typical depth of a shale reservoir, vertical stress is greater than horizontal stresses, meaning fractures will propagate vertically, opening outwards in the direction of least principal stress. However, as depth decreases, horizontal stresses start to exceed vertical stress, meaning fractures will begin to propagate horizontally. This means that hydraulic fractures are unlikely to continue propagating vertically at shallow enough depths to create direct conduits between target formations and drinking water aquifers, unless those aquifers are exceptionally deep. The limited vertical extent of hydraulic fractures measured with microseismic reinforces this theory and suggests that the volume of fracturing fluid further constrains vertical propagation of fractures (Fisher and Warpinski, 2011; Flewelling et al., 2013). Greater research into the time scales of possible mixing and characteristics of preexisting conduits (such as faults or abandoned wells) would need to be examined to determine if or when this potential migration could become an issue.

In order to determine that groundwater problems are in fact the result of drilling or fracturing activities, pre-drilling baseline water quality data must be available. Colorado and Wyoming now require drillers to carry out baseline and post-completion groundwater testing to ensure that no contamination has occurred, and Pennsylvania requires the same if a driller wishes to exonerate itself from accusations of water contamination (ALS, 2013). Companies are also doing such testing voluntarily to limit their own liability in cases of preexisting groundwater contamination (CBS News, 2012).

Wastewater

In Pennsylvania, municipal wastewater treatment facilities saw a greater than 100-fold increase in drilling-related disposal at their facilities after Marcellus production took off in 2008 (Lutz et al., 2013). However, municipal facilities are not designed to handle water with high total dissolved solids (TDS), particularly bromide. While bromide is not harmful as a diluted salt, it reacts with chlorine during the water treatment process to create trihalomethane, a known carcinogen. After enactment of regulations, a marked decrease in the use of municipal treatment facilities was seen, with drilling-related disposal returning to pre-Marcellus levels (Lutz et al., 2013) and studies of river water confirming a decrease in bromide levels (Wilson and VanBriesen, 2012). Industrial treatment facilities are able to handle the high TDS in shale wastewaters, and their usage rate has remained fairly constant since the beginning of the

shale boom (Lutz et al., 2013). The treated water from industrial facilities can either be reused or discharged into surface waters.

In regions where geology and regulations allow, such as Texas and Oklahoma, deep injection of wastewater is generally the most common disposal method (Nicot et al., 2014). In fact, over 95% of all wastewater from oil and gas extraction in the U.S. is disposed of via injection, with about 55% being used for enhanced recovery of hydrocarbons and about 39% being injected into underground injection control (UIC) disposal wells (Clark and Veil, 2009). Additionally, UIC wells are used to dispose of water that is too contaminated for efficient recycling or that is the by-product of treating a larger volume of water for recycling. Some Marcellus wastewater is sent to UIC wells, but the greatest number of UIC wells in the region are in Ohio, meaning that water must be transported potentially long distances to be disposed of in a UIC well (Lutz et al., 2013). Furthermore, underground injection of wastewater fluids has been correlated with increased seismic activity (earthquakes), and any undocumented abandoned wells could allow for wastewater to leak from the injection zone into aquifers or up to the surface (Justinic et al., 2013; Keranen et al., 2013; Kim, 2013).

Recycling wastewater is increasingly common, especially in the Marcellus region where fewer UIC wells are available nearby. In Pennsylvania, the total rate of recycling has increased from 13% to 72% as of 2011, most likely due to regulations limiting the amount of drilling wastewater that could be processed in municipal wastewater facilities (Lutz et al., 2013; Maloney and Yoxtheimer, 2012). Specific recycling rates of 71% for drilling fluids, 90% for flowback water, and 56% for produced water were recorded in Pennsylvania for 2011 (Maloney and Yoxtheimer, 2012). Recycling water provides for both disposal of wastewater and sourcing of water for future wells, which could be of great potential benefit in regions with limited natural water supplies. Additionally, companies have recorded cost savings of 200-400 thousand dollars per well by using recycled water instead of acquiring water from other sources (Range Resources, 2010; Bloomberg, 2013). However, these benefits depend heavily on the shale play. The average amount of water that is recovered from a Marcellus well is only about 6-8% of the initial volume injected for hydraulic fracturing, so even with 100% recycling, other water sources will usually still be needed (Hansen et al., 2013). Yet, some Barnett wells can return up to 350% of the initial volume injected, increasing the potential benefits of recycling (Nicot et al., 2014). Despite many regions in Texas suffering from water shortages, recycling rates in Texas tend to be lower, with some regions, such as the Permian Far West, recycling 0% of their wastewater (Nicot et al., 2012); this is partially due to the availability and low cost of UIC wells. However, in the Anadarko Basin of Texas, 20% of initial water

needs are met by recycled or reused water, highlighting the extreme variation in water management strategies by shale play. To further encourage recycling in the state, the Texas House passed a bill in 2013 clarifying wastewater liability and eliminating long-term liability for operators who treat wastewater and return it to drillers (Texas HB 2767, 2013).

Alternative methods of wastewater disposal include spraying on roads for dust suppression and deicing, and spraying on land. Regulations on using oil and gas wastewater brines for dust suppression and deicing of roads vary by state, and regulations differ for flowback fluid versus produced brines, with produced brines generally being the only fluids permitted for road spreading (OH DNR, 2004; ND DH, 2013). Some states do not specify whether any type of hydraulic fracturing waste or produced brines may be used on road surfaces but instead examine potential use of wastewaters on a case-by-case basis (CGA, 2013). Certain industries, such as agriculture and sewage treatment, have been known to spray wastewater on land for irrigation. However, the high salinity of oil and gas wastewater makes it poorly suited to irrigation, and the application of such waters to soil has been shown to damage plant life (Adams, 2011).

Transportation must be considered not only for source water but for wastewater as well. There are fewer options for wastewater transportation, as there are more regulations to prevent potential environmental contamination. In the Marcellus region, most wastewater is trucked to treatment facilities, injection sites, or new well locations if the water is to be reused. However, wastewater pipelines are used in North Dakota and were recently approved in Texas, allowing for wastewater to be piped directly to disposal well locations (Texas SB 514, 2013). While such pipelines must be monitored for leaks, they do have the potential to greatly reduce truck trips associated with water disposal.

Conclusions

Water management practices have generally improved since the beginning of the shale oil and gas boom. More sustainable water sourcing is being implemented, transportation has become more efficient, storage is being done more carefully, and recycling has increased. Additionally, water monitoring has increased and researchers are now addressing the extent to which oil and gas operators are and are not responsible for water quality and quantity issues. However, there will always be water risks in unconventional hydrocarbon development, and this trend toward improved water management will need to continue in order for unconventional production to remain sustainable, particularly in regions with limited freshwater availability. Water management approaches will also need to be tailored

326 to the shale plays in which they are applied, as variation in local and regional water supply, disposal
327 options, competing users, and even the physical properties of the shale can all influence water
328 management issues.

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References

- Abdalla, Charles W. and Joy R. Drohan. Marcellus Education Fact Sheet: Water Withdrawals for Development of Marcellus Shale Gas in Pennsylvania. Pennsylvania State University, College of Agricultural Sciences, Cooperative Extension. 2010. <http://pubs.cas.psu.edu/FreePubs/pdfs/ua460.pdf>
- Adams, Mary Beth. Land Application of Hydrofracturing Fluids Damages a Deciduous Forest Stand in West Virginia. *Journal of Environmental Quality* vol. 40, pg. 1340-1344, 2011.
- ALS. State Fracking Regulations. 2013. Viewed 24 January 2014. http://www.alsglobal.com/en/Our-Services/Life-Sciences/Environmental/Capabilities/North-America-Capabilities/USA/~/_link.aspx?id=9BAE6061073747A68560BE4D6F56F26A&z=z
- Bloomberg, "Halliburton Cut Fracking Water Costs by \$400,000 a Bakken Well," by David Wethe. 5 March 2013. <http://www.bloomberg.com/news/print/2013-03-06/halliburton-cut-fracking-water-costs-by-400-000-a-bakken-well.html>
- Brantley, Susan L., David Yoxtheimer, Sina Arjmand, Paul Grieve, Radisav Vidic, Jon Pollak, Garth T. Llewellyn, Jorge Abad, and Cesar Simon. Water resource impacts during unconventional shale gas development: The Pennsylvania experience. *International Journal of Coal Geology*. Posted ahead of print 10 January 2014.
- Bukovac, Tomislav, Daniel Rafael Perez, Rafik Belhaouas, Alexandru Dragomir, and Zoran Krilov. Successful Continuous Multi-Stage Hydraulic Fracturing Using a Seawater-Based Polymer-Free Fluid System Executed from a Supply Vessel; Black Sea Offshore. 8th European Formation Damage Conference, Scheveningen, The Netherlands. Society of Petroleum Engineers. 27-29 May 2009.
- Carter, Kristin M., John A. Harper, Katherine W. Schmid, and Jaime Kostelnik. Unconventional natural gas resources in Pennsylvania: The backstory of the modern Marcellus Shale play. *Environmental Geosciences*, v. 18, no. 4, pg. 217-257, 2011.
- CBS News, "Digging into the practice of fracking," by David Pogue (video). 30 December 2012 http://www.cbsnews.com/8301-3445_162-57561263/digging-into-the-practice-of-fracking/
- Center for Sustainable Shale Development (CSSD). Performance Standards. 2013. <https://www.sustainableshale.org/wp-content/uploads/2014/01/Performance-Standards-v.-1.1.pdf>

362 Connecticut General Assembly (CGA). State Policies on Use of Hydraulic Fracturing Waste as a Road
363 Deicer. 2013. <http://www.cga.ct.gov/2013/rpt/2013-R-0469.htm>

364 CONSOL Energy. CONSOL Corporate Responsibility Report, pg. 45, 2012.
365 [http://www.consolenergy.com/CorporateResponsibilityReport/2012New/files/assets/basic-](http://www.consolenergy.com/CorporateResponsibilityReport/2012New/files/assets/basic-html/page45.html)
366 [html/page45.html](http://www.consolenergy.com/CorporateResponsibilityReport/2012New/files/assets/basic-html/page45.html)

367 Clark, C.E. and J.A. Veil. Produced water volumes and management practices in the United States. Rep.
368 ANL/EVS/R-09/1, Argonne National Laboratory. 2009. <http://www.osti.gov/scitech/biblio/1007397>

369 Energy In Depth – Marcellus (EID). “Seneca Resources Gets Innovative to Reduce Impacts,” by Nicole
370 Jacobs. 11 June 2012 [http://energyindepth.org/marcellus/seneca-resources-gets-innovative-to-reduce-](http://energyindepth.org/marcellus/seneca-resources-gets-innovative-to-reduce-impacts/)
371 [impacts/](http://energyindepth.org/marcellus/seneca-resources-gets-innovative-to-reduce-impacts/)

372 Engelder, T. and G.G. Lash. Marcellus Shale play’s vast resource potential creating stir in Appalachia: The
373 American Oil and Gas Reporter, pg. 7, May 2008.

374 Fisher, K. and N. Warpinski. Hydraulic fracture-height growth: Real data. Society of Petroleum Engineers
375 Annual Technical Conference and Exhibition, SPE 145949, 2011.

376 Flewelling, Samuel A., Matthew P. Tymchak, and Norm Warpinski. Hydraulic fracture height limits and
377 fault interactions in tight oil and gas formations. Geophysical Research Letters, vol. 40, pg. 3602-3606,
378 2013.

379 Freyman, Monika. Hydraulic Fracturing and Water Stress: Water Demand by the Numbers. Ceres Report.
380 2014. [http://www.ceres.org/resources/reports/hydraulic-fracturing-water-stress-water-demand-by-the-](http://www.ceres.org/resources/reports/hydraulic-fracturing-water-stress-water-demand-by-the-numbers/view)
381 [numbers/view](http://www.ceres.org/resources/reports/hydraulic-fracturing-water-stress-water-demand-by-the-numbers/view)

382 Gandossi, Luca. An overview of hydraulic fracturing and other formation stimulation technologies for
383 shale gas production. JRC Technical Report, European Commission, Joint Research Centre, Institute for
384 Energy and Transport, European Union. 2013.
385 [http://publications.jrc.ec.europa.eu/repository/bitstream/111111111/30129/1/an%20overview%20of%](http://publications.jrc.ec.europa.eu/repository/bitstream/111111111/30129/1/an%20overview%20of%20hydraulic%20fracturing%20and%20other%20stimulation%20technologies%20(2).pdf)
386 [20hydraulic%20fracturing%20and%20other%20stimulation%20technologies%20\(2\).pdf](http://publications.jrc.ec.europa.eu/repository/bitstream/111111111/30129/1/an%20overview%20of%20hydraulic%20fracturing%20and%20other%20stimulation%20technologies%20(2).pdf)

387 Geng, Xiaolong, Nicholas C. Davatzes, Daniel J. Soeder, Jagadish Torlapati, Rebecca S. Rodriguez, Michel
388 C. Boufadel. Migration of high-pressure air during gas well drilling in the Appalachian Basin. 2013.
389 Journal of Environmental Engineering. Posted ahead of print 25 July 2013.

390 Groundwater Protection Council (GWPC). FracFocus Chemical Disclosure Registry. <http://fracfocus.org>.
391 Visited 4 June 2014.

392 Hall, Morris and Jo Ellen Kilpatrick. Surface Microseismic Monitoring of Slick Water and Nitrogen
393 Fracture Stimulations, Arkoma Basin, Oklahoma. Society of Petroleum Engineers Unconventional Gas
394 Conference, Pittsburgh, PA, 23-25 February 2010.

395 Hansen, Evan, Dustin Mulvaney, Meghan Betcher. Water Resource Reporting and Water Footprint from
396 Marcellus Shale Development in West Virginia and Pennsylvania. EarthWorks Oil and Gas Accountability
397 Project. 2013. http://www.earthworksaction.org/files/publications/FINAL_marcellus_wv_pa.pdf

398 Horton, A. I. A comparative analysis of stimulations in the eastern gas shales, report DOE/METC 145:
399 U.S. Department of Energy, Morgantown Energy Technology Center, 1981.

400 Jackson, Robert B., Avner Vengosh, Thomas H. Darrah, Nathaniel R. Warner, Adrian Down, Robert J.
401 Preda, Stephen G. Osborn, Kaiguang Zhao, and Jonathan D. Karr. Increased stray gas abundance in a
402 subset of drinking water wells near Marcellus shale gas extraction. PNAS. Published ahead of print 24
403 June 2013.

404 Justinic, Ashley Howe, Brian Stump, Chris Hayward, and Cliff Frohlich. Analysis of the Cleburne, Texas,
405 Earthquake Sequence from June 2009 to June 2010. Bulletin of the Seismological Society of America, vol.
406 103, no. 6, pg. 3083-3093, 2013.

407 Kargbo, David M., Ron G. Wilhelm, and David J. Campbell. Natural Gas Plays in the Marcellus Shale:
408 Challenges and Potential Opportunities. Environmental Science and Technology, vol. 44, pg. 5679-5684,
409 2010.

410 Keranen, Katie M., Heather M. Savage, Geoffrey A. Abers, and Elizabeth S. Cochran. Potentially induced
411 earthquakes in Oklahoma, USA: Links between wastewater injection and the 2011 M_w 5.7 earthquake
412 sequence. Geology. Posted ahead of print 26 March 2013.

413 Kim, Won-Young. Induced seismicity with fluid injection into a deep well in Youngstown, Ohio. Journal of
414 Geophysical Research: Solid Earth, vol. 118, 3506-3518, 2013.

415 King, George E. Hydraulic Fracturing 101: What Every Representative, Environmentalist, Regulator,
416 Reporter, Investor, University Researcher, Neighbor, and Engineer Should Know About Estimating Frac

417 Risk and Improving Frac Performance in Unconventional Gas and Oil Wells. Society of Petroleum
418 Engineers, Hydraulic Fracturing Technology Conference. 2012.

419 Komar, C.A., W.K. Overbey Jr., and R.J. Watts. Prediction of fracture orientation from oriented cores and
420 aerial photos, West Poison Spider field, Casper, Wyoming. Technical Report, Morgantown Energy
421 Research Center, U.S. Energy Research and Development Administration. 1976.
422 <http://www.osti.gov/scitech/biblio/7365846>

423 Kondash, Andrew J., Nathaniel R. Warner, Ori Lahav, and Avner Vengosh. Radium and Barium Removal
424 through Blending Hydraulic Fracturing Fluids with Acid Mine Drainage. Environmental Science and
425 Technology, vol. 48, no. 2, pg. 1334-1342, 2014.

426 Lutz, Brian D., Aurana N. Lewis, and Martin W. Doyle. Generation, transport, and disposal of wastewater
427 associated with Marcellus Shale gas development. Water Resources Research vol. 49, no. 2, pg. 647-656,
428 2013.

429 Maloney, Kelly O. and David A. Yoxtheimer. Production and disposal of waste materials from gas and oil
430 extraction from the Marcellus Shale play in Pennsylvania. Environmental Practice, vol. 14, no. 04, pg.
431 278-287, 2012.

432 McCann, R.P. and C.L. Schuster. Frac mapping by surface electrical techniques. Massive hydraulic
433 fracturing symposium, Sandia Labs, Norman, OK, 28 February 1977.
434 <http://www.osti.gov/scitech/biblio/7096523>

435 Molofsky, Lisa J., John A. Connor, Albert S. Wylie, Tom Wagner, and Shahla K. Farhat. Evaluation of
436 Methane Sources in Groundwater in Northeastern Pennsylvania. Groundwater, vol. 51, no. 3. pg. 333-
437 349, 2013.

438 Montgomery, S.L., D.M. Jarvie, K.A. Bowker, and R.M. Pollastro. Mississippian Barnett Shale, Fort Worth
439 Basin, north-central Texas: Gas-shale play with multi-trillion cubic foot potential. American Association
440 of Petroleum Geologists Bulletin, v. 89, no. 2, pg. 155–175, 2005.

441 North Dakota Department of Health (ND DH). Guidelines for the Use of Oilfield Salt Brines for Dust and
442 Ice Control. 2013.
443 http://www.ndhealth.gov/wq/gw/pubs/icedustcontrolusingoilfieldbrine_20130321.pdf

444 New York State Department of Environmental Conservation (NYSDEC). Revised Draft: Supplemental
445 Generic Environmental Impact Statement on the Oil, Gas, and Solution Mining Regulatory Program: Well
446 Permit Issuance for Horizontal Drilling and High-Volume Hydraulic Fracturing to Develop the Marcellus
447 Shale and Other Low-Permeability Gas Reservoirs. 2011. <http://www.dec.ny.gov/energy/75370.html>

448 Nicot, Jean-Phillippe, Robert C. Reedy, Ruth A. Costley, and Yun Huang. Oil and Gas Water Use in Texas:
449 Update to the 2011 Mining Water Use Report. Bureau of Economic Geology. Prepared for Texas Oil and
450 Gas Association. 2012.
451 http://www.twdb.state.tx.us/publications/reports/contracted_reports/doc/0904830939_2012Update
452 [MiningWaterUse.pdf](http://www.twdb.state.tx.us/publications/reports/contracted_reports/doc/0904830939_2012Update_MiningWaterUse.pdf)

453 Nicot, Jean-Philippe, Bridget R. Scanlon, Robert C. Reedy, and Ruth A. Costley. Source and Fate of
454 Hydraulic Fracturing Water in the Barnett Shale: A Historical Perspective. Environmental Science and
455 Technology. Posted ahead of print 27 January 2014.

456 Nuckols, E.B. III. Cottageville (Mount Alto) gas field, Jackson County, West Virginia: a case study of
457 Devonian shale-gas production. Prepared for U.S. Department of Energy. 1979.

458 Ohio Department of Natural Resources (OH DNR). Spreading Oil-Field Brine for Dust and Ice Control in
459 Ohio. 2004. <http://oilandgas.ohiodnr.gov/portals/oilgas/pdf/Brine.pdf>

460 Osborn, Stephen G., Avner Vengosh, Nathaniel R. Warner, and Robert B. Jackson. Methane
461 contamination of drinking water accompanying gas-well drilling and hydraulic fracturing. Proceedings of
462 the National Academy of Sciences, vol. 108, no. 20, pg. 8172-8176, 2011.

463 Pennsylvania Department of Environmental Protection (PADEP). Utilization of Mine Influenced Water for
464 Natural Gas Extraction Activities. 2013.
465 <http://files.dep.state.pa.us/Mining/Abandoned%20Mine%20Reclamation/AbandonedMinePortalFiles/>
466 [MIW/Final MIW White Paper.pdf](http://files.dep.state.pa.us/Mining/Abandoned%20Mine%20Reclamation/AbandonedMinePortalFiles/MIW/Final_MIW_White_Paper.pdf)

467 Range Resources. "Range Answers Questions on Hydraulic Fracturing Process." 2010.
468 [http://www.rangeresources.com/Media-Center/Featured-Stories/Range-Answers-Questions-on-](http://www.rangeresources.com/Media-Center/Featured-Stories/Range-Answers-Questions-on-Hydraulic-Fracturing-Pr.aspx)
469 [Hydraulic-Fracturing-Pr.aspx](http://www.rangeresources.com/Media-Center/Featured-Stories/Range-Answers-Questions-on-Hydraulic-Fracturing-Pr.aspx)

470 Rodriguez, Rebecca S. Evolving Water Management Practices in Shale Gas Development. American
471 Association of Petroleum Geologists, Annual Convention and Exhibition. Pittsburgh, PA. 21 May 2013.
472 http://www.searchanddiscovery.com/pdfz/documents/2013/80315rodriguez/ndx_rodriguez.pdf.html

473 Rueschhoff, Austin. Oil and Gas Operations and Colorado's Floods: The Colorado Oil and Gas
474 Conservation Commission Tackles the Issues. University of Denver Water Law Review. 2013.
475 [http://duwaterlawreview.com/oil-and-gas-operations-and-colorados-floods-the-colorado-oil-and-gas-](http://duwaterlawreview.com/oil-and-gas-operations-and-colorados-floods-the-colorado-oil-and-gas-conservation-commission-tackles-the-issues/)
476 [conservation-commission-tackles-the-issues/](http://duwaterlawreview.com/oil-and-gas-operations-and-colorados-floods-the-colorado-oil-and-gas-conservation-commission-tackles-the-issues/)

477 Scranton Times-Tribune. "Energy industry develops nontoxic fracking fluids," by Kevin Begos. 4 February
478 2013a. [http://thetimes-tribune.com/news/gas-drilling/energy-industry-develops-nontoxic-fracking-](http://thetimes-tribune.com/news/gas-drilling/energy-industry-develops-nontoxic-fracking-fluids-1.1439389)
479 [fluids-1.1439389](http://thetimes-tribune.com/news/gas-drilling/energy-industry-develops-nontoxic-fracking-fluids-1.1439389)

480 Scranton Times-Tribune. "State DEP moving closer to finalizing oil and gas rules," by Laura Legere. 11
481 February 2013b. [http://www.thetimes-tribune.com/news/state-dep-moving-closer-to-finalizing-oil-and-](http://www.thetimes-tribune.com/news/state-dep-moving-closer-to-finalizing-oil-and-gas-rules-1.1442738)
482 [gas-rules-1.1442738](http://www.thetimes-tribune.com/news/state-dep-moving-closer-to-finalizing-oil-and-gas-rules-1.1442738)

483 Soeder, D. J. and W.M. Kappel. Water resources and natural gas production from the Marcellus Shale:
484 U.S. Geological Survey Fact Sheet 2009–3032, 2009. <http://pubs.usgs.gov/fs/2009/3032/>

485 StateImpact Texas and Texas Tribune. "Waterless Fracking Makes Headway in Texas, Slowly," by Kate
486 Galbraith. 27 March 2013. [http://stateimpact.npr.org/texas/2013/03/27/waterless-fracking-makes-](http://stateimpact.npr.org/texas/2013/03/27/waterless-fracking-makes-headway-in-texas-slowly/)
487 [headway-in-texas-slowly/](http://stateimpact.npr.org/texas/2013/03/27/waterless-fracking-makes-headway-in-texas-slowly/)

488 Texas House Bill HB 2767, Chapter 122. Treatment and Recycling for Beneficial Use of Certain Oil and
489 Gas Waste. Passed May 2013.
490 ftp://ftp.legis.state.tx.us/bills/83R/billtext/html/house_bills/HB02700_HB02799/HB02767F.htm

491 Texas Senate Bill SB 514, Subchapter T. Saltwater Pipelines. Passed May 2013.
492 ftp://ftp.legis.state.tx.us/bills/83R/billtext/html/senate_bills/SB00500_SB00599/SB00514F.htm

493 U.S. Energy Information Administration (USEIA). Shale Gas and Oil Plays, North America. U.S.
494 Department of Energy. May 2011.
495 http://www.eia.gov/pub/oil_gas/natural_gas/analysis_publications/maps/maps.htm

496 U.S. Energy Information Administration (USEIA). Technically Recoverable Shale Oil and Shale Gas
497 Resources: An Assessment of 137 Shale Formations in 41 Countries Outside the United States. U.S.
498 Department of Energy. 2013. <http://www.eia.gov/analysis/studies/worldshalegas/pdf/fullreport.pdf>

499 U.S. Energy Information Administration (USEIA). U.S. Crude Oil and Natural Gas Proved Reserves, 2012.
500 Report to U.S. Department of Energy. April 2014.
501 <http://www.eia.gov/naturalgas/crudeoilreserves/pdf/uscrudeoil.pdf>

502 Veil, John A. Water Management Technologies Used by Marcellus Shale Gas Producers. Prepared for
503 United States Department of Energy, National Energy Technology Laboratory. July 2010.
504 http://fracfocus.org/sites/default/files/publications/water_management_in_the_marcellus.pdf

505 Vortman, L.J. Ground surface motion from detonation of liquid explosive in a hydraulic fracture in oil
506 shale. Technical Report, Sandia Labs, U.S. Energy Research and Development Administration. 1976.
507 <http://www.ntis.gov/search/product.aspx?ABBR=SAND740131>

508 Warner, Nathaniel R, Robert B. Jackson, Thomas H. Darrah, Stephen G. Osborn, Adrian Down, Kaiguang
509 Zhao, Alissa White, and Avner Vengosh. Geochemical evidence for possible natural migration of
510 Marcellus Formation brine to shallow aquifers in Pennsylvania. Proceedings of the National Academy of
511 Sciences. Published ahead of print 9 July 2012.

512 Wilson, Jessica M. and Jeanne M. VanBriesen. Oil and gas produced water management and surface
513 drinking water sources in Pennsylvania. Environmental Practice, vol. 14, no. 04, pg. 288-300, 2012.

514 Zoback, Mark D. Reservoir Geomechanics. Cambridge University Press. 2010.