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The energy-water nexus: potential groundwater-quality degradation associated with production of shale gas

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Abstract

Oil and natural gas have been the main sources of primary energy in the USA, providing 63% of the total energy consumption in 2011. Petroleum production, drilling operations, and improperly sealed abandoned wells have caused significant local groundwater contamination in many states, including at the USGS OSPER sites in Oklahoma. The potential for groundwater contamination is higher when producing natural gas and oil from unconventional sources of energy, including shale and tight sandstones. These reservoirs require horizontally-completed wells and massive hydraulic fracturing that injects large volumes (up to 50,000 m^3/well) of high-pressured water with added proppant, and toxic organic and inorganic chemicals. Recent results show that flow back and produced waters from Haynesville (Texas) and Marcellus (Pennsylvania) Shale have high salinities (≥200,000 mg/L TDS) and high NORMs (up to 10,000 picocuries/L) concentrations. A major research effort is needed worldwide to minimize all potential environmental impacts, especially groundwater contamination and induced seismicity, when producing these extremely important new sources of energy.

Keywords: shale gas; energy resource; groundwater contamination; produced water.

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1. Introduction

For more than 60 years, oil and natural gas have been the main sources of primary energy in the World, providing 63% of the USA total energy consumption in 2011 [1]. However, petroleum production, drilling operations, and improperly sealed abandoned wells have the potential to cause major contamination of groundwater in petroleum-producing states [2, 3]. Significant local groundwater contamination has resulted mainly from the improper disposal of saline water produced with oil and gas and from hydrocarbons and produced water discharging from malfunctioning equipment, vandalism, and

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accidents [3]. In 2011, approximately 3.5 billion m^3 of brine were produced with 2.0 billion bbl of domestic oil and 23.0 Tcf of natural gas. Prior to the institution of federal regulations in the 1970s, produced water was often discharged into streams, creeks, and unlined evaporation ponds. Because the produced waters were highly saline (3,000-400,000 mg/L TDS) and contained toxic metals, organic and inorganic components, and naturally occurring radioactive materials (NORMs), including ^{226}Ra, ^{228}Ra and ^{222}Rn, they have caused groundwater pollution, as documented at the USGS OSPER sites in Oklahoma, and other conventional petroleum fields [3].

Natural gas and oil production from unconventional sources that include primarily shale, coal beds, and very low permeability sandstones and carbonates (often referred to as 'tight' reservoirs) has occurred in the USA for many decades. However, recent developments in deep horizontal drilling, downhole telemetry and massive multi-stage hydraulic fracturing using 'slick water' have resulted in a rapid and significant expansion in drilling activity across the USA, and is starting to spread to Canada, Australia and other countries [4]. Production from these sources, especially that of natural gas from shale has increased rapidly, from only 0.4 Tcf in 2000, to 6.8 Tcf in 2011, close to 30% of total gas production in USA. Shale gas is projected to increase further to account for 49% of USA total gas in 2035 [1]. U.S. crude oil production has also increased, primarily from shale and 'tight' reservoirs from 5.0 Mbpd in 2008 to 5.6 Mbpd in 2011. Production of oil from unconventional sources in 2035 is projected to be 0.7 to 2.8 Mbpd, accounting for up to 36% of domestic oil production [1].

In this summary, we review and discuss the huge potential national and international resources of unconventional natural gas and oil. We emphasize the rapidly expanding gas production from shale, which started with the first horizontally-drilled and hydraulically-fractured commercial well in the Barnett Shale of Texas in 1991, and the technology spread to other basins in USA with organic-rich shale, including the Appalachian Basin, producing commercial gas by this technology from the Marcellus Shale in Pennsylvania starting in 2005 [1]. We also discuss the water requirements for the drilling and hydraulic fracturing of shale gas wells as well as the potential for groundwater contamination and induced seismicity associated with this new source of energy.

2. Shale gas resource assessments

A recent assessment of global shale gas resources and technically recoverable shale gas resources, covering 14 regions in 32 countries outside USA, was conducted for DOE by ARI [5]. Results (Table 1) show a huge gas resources base that is about twice the values estimated in 1997 by [6]. When adding the U.S. estimate of the shale gas technically recoverable resources of 862 Tcf, a total shale resource base estimate of 6,622 Tcf is obtained for the 33 countries assessed. These recoverable resources would be enough to supply the global gas requirements at current consumption rate of about 110 Tcf/year for about 60 years. Adding gas from shale to the world technically recoverable gas resources of 16,000 Tcf, as of January 2010, increases total world technically recoverable gas resources by over 40 percent to 22,600 Tcf.

These preliminary results, which carry large uncertainties, show that China, with 1275 Tcf, has the highest estimated technically recoverable shale gas resources (Table 1). The official Chinese 5-year plan is to start producing shale gas in 2015, and to increase production to 2.3 Tcf by 2020. Results also show that China is followed by the USA, Argentina, Mexico, South Africa, Australia and Canada (Table 1). In Europe, Poland and France have the highest potentials, but France likely would not be producing significant amounts of shale gas because hydraulic fracturing to obtain shale gas is banned. Russia and countries in the Middle East likely have large shale gas resources [6], but these and several other countries that have high conventional gas resources or where geological and other data needed for such resource assessments are not available were not assessed by [5].

Table 1. Data on natural gas in countries that have high assessed technically recoverable shale gas resources. Modified from [5].

	2009 Natural Gas Market (Tcf, dry basis)			Proved Natural Gas Reserves (Tcf)	Technically Recoverable Shale Gas Resources (Tcf)
	Production	Consumption	Imports (Exports)		
Europe					
France	0.03	1.73	98%	0.2	180
Norway	3.65	0.16	(2,156%)	72.0	83
U.K.	2.09	3.11	33%	9.0	20
Poland	0.21	0.58	64%	5.8	187
N. America					
USA	20.6	22.8	10% (87%)	272.5	862
Canada	5.63	3.01	18%	62.0	388
Mexico	1.77	2.15		12.0	681
Asia					
China	2.93	3.08	5%	107.0	1,275
India	1.43	1.87	24%	37.9	63
Australia	1.67	1.09	(52%)	110.0	396
Africa					
South Africa	0.07	0.19	63%	-	485
Libya	0.56	0.21	(165%)	54.7	290
Algeria	2.88	1.02	(183%)	159.0	231
S. America					
Argentina	1.46	1.52	4%	13.4	774
Brazil	0.36	0.66	45%	12.9	226
Total (33 countries)	**53.1**	**55.0**	**(3%)**	**1,274**	**6,622**
Total world	**106.5**	**106.7**	**0%**	**6,609**	

More detailed resource assessments that result in a probabilistic range of the technically recoverable resource are needed for individual prospective shale units in sedimentary basins, for parts of Maryland, New York, Ohio, Pennsylvania, Virginia, and West Virginia. The geologic concept is that black shale of the Utica Shale and adjacent units have the appropriate thermal maturity (measured by vitrinite reflectance, Ro values) to generate natural gas, natural gas liquids and oil from Type II kerogen. The source rocks generated petroleum that migrated into adjacent units, but also retained significant hydrocarbons within the matrix, in fractures and adsorbed to organic matter and clay minerals in shale. Results show that the Utica Shale contains a mean of 38 Tcf of undiscovered, technically recoverable natural gas, has a mean of 940 million bbl of unconventional oil resources and a mean of 208 million bbl of unconventional natural gas liquids. The total gas resources obtained for the Utica Shale and the overlying Marcellus Shale (122 Tcf) are about half the value reported in [1] for these shale units, indicating the uncertainties in these assessments.

3. Environmental impacts of shale gas: water use and waste water disposal challenges

Natural gas is an efficient energy source and the cleanest-burning fossil fuel, producing lower levels of particulates, mercury, sulfur dioxide and other air pollutants; it also emits only ~55% and 70% of CO_2 per unit of energy compared to coal and oil, respectively. Exploration for and production of shale gas, however, causes major local surface land disturbance, air and noise pollution, and habitat fragmentation and other ecological impacts**.** Potential contamination of surface water and groundwater are the major concerns, but communities in some impacted areas are also concerned about the possibility of induced seismicity. Except for two events (magnitude 2.8 in Oklahoma, USA, and magnitude 2.3 in England, UK), most known injection-induced earthquakes are associated with produced water disposal activities and not linked directly to hydraulic fracturing. There is evidence that recent, moderately strong earthquakes (magnitude 4.0 to 5.8) that occurred in shale gas producing areas in Arkansas, Colorado, Ohio, Oklahoma and Texas were induced by produced water disposal or other gas- and oil-related activities [8,9].

The shale gas is held in pore spaces and natural fractures or is adsorbed onto the organic material (kerogen) and minerals in the formation. Shale porosity (5-10%) is moderate, but the natural permeability of shale is extremely low (in nanodarcies) requiring horizontally-completed wells (up to 3,500 m long) and massive, multi stage hydraulic fracturing to create pathways for the gas to flow into the well at economic rates. Fracturing is carried out by injecting large volumes (~10,000-50,000 m^3/well) of water with added proppant (sand), and organic and inorganic chemicals at pressures high enough to fracture the shale, and fractures are kept open by the sand particles. Significant volumes of water, approximately 500 m^3/well for Marcellus Shale to 5,000 m^3/well for the deeper Haynesville Shale, are also used for drilling the gas wells. Because several hundred wells (Fayetteville and Haynesville Shale) and close to 1000 (Barnett and Marcellus Shale) wells were completed during peak years, the total volume of fresh water used for drilling and fracturing in some cases is high, approaching 10 million m^3/year for the Barnett and Marcellus Shale [10].

Calculations show that the total water used for drilling and fracturing shale gas wells is relatively low compared to the consumptive total water (surface and groundwater) usage in wet regions (e.g. 0.06% of available water for the Marcellus Shale); but is much higher in arid regions (0.4% for the Barnett Shale and 0.8% for the Haynesville Shale) where water needed for shale gas could be a significant constrain for gas development because its use could impact the available water supply for domestic, irrigation or other uses [10, 11]. Reclaiming produced water for reuse is rather expensive but possible where water salinity is relatively low (less than 10,000 mg/L TDS) as was demonstrated at Placerita oil field in California [12], but extremely complicated and costly for produced and flow back waters from Marcellus, Haynesville and other shale where the salinity can be higher than 200,000 mg/L TDS. The high concentrations of salts in these waters limits the use of membrane technology, but other treatment options, including distillation and crystallization are being investigated [13].

Following the completion of hydraulic fracturing, fluid pressure is lowered, causing the ‘flow back’ brine, which is a variable mixture of fracturing fluid and formation water, to return to the surface through the well casing. During the 2-3 weeks of the ‘flow back’ period for a Marcellus Shale, 10-50% of the fracturing fluid returns to the surface, initially at high rates (~1,000 m^3/day), decreasing finally to ~ 50 m^3/day. The salinity of the ‘flow back’ water is initially moderate (45,000 mg/L TDS), reflecting the composition of the fracturing water, and increasing to 170,000 mg/L TDS). This is followed by production of natural gas and produced water at a rate of approximately 2-8 m^3/day per well [10]. Our unpublished data from Haynesville (East Texas) and published results [14, 15] show that produced waters from Haynesville and Marcellus Shale are Na-Ca-Cl brines with extremely high salinities (≥200,000 mg/L TDS), high NORMs (up to 10,000 picocuries/L for total Ra) and radon concentrations.

In addition to these high salinities, NORMs and radon, produced water from shale gas will have additional chemicals, including toxic inorganic and organic compounds reported in produced water from conventional oil and gas production. The concern in the case of organics is warranted as high concentrations of toxic organic compounds, including BTEX (up to 60 mg/L), phenols (up to 20 mg/L), and polycyclic aromatic hydrocarbons (PAHs up to 10 mg/L), have been reported in produced water [17]. In addition to the natural inorganic and organic chemicals, the petroleum companies add a large number of disclosed and undisclosed chemicals, including potassium chloride, acids, bactericides, biocides, surfactants, friction reducers, and corrosion and scale inhibitors to the fracturing fluids to improve overall gas production. New York and few other states, but not the US EPA, mandate the disclosure of all chemicals used in fracturing fluids, and this would make it easier to investigate the nature, distribution, toxicity, interactions with natural fluids and rocks, fate and environmental impacts of these added chemicals [10].

Potential contamination of groundwater and surface water by the natural and added organic and inorganic chemicals and NORMs in flow back and produced waters discussed above is the major concern associated with shale gas production [17]. The concern may be warranted as results of groundwater analyses by [18] indicated that private water wells in parts of Pennsylvania and New York showed an association between shale gas operations and methane contamination of drinking water. Molofsky et al. [19], however, analysed groundwater samples from the same area of Pennsylvania and offered an alternative hypothesis that natural fractures, not shale gas operations, could be responsible for the stray methane detected in these wells. Using detailed geochemical evidence, [20] also invoked natural fractures and pathways, and not recent drilling activities, to explain connections between some shallow groundwater and deep formation water from northeastern Pennsylvania.

Studies [21] concluded that management of flow back and produced waters, as is the case for conventional oil and gas operations [22] posed the greatest risk to groundwater and surface water quality. In the case of conventional oil and gas operations, significant local groundwater contamination has resulted mainly from the improper disposal of saline produced water, leaks through production and improperly sealed legacy wells and from hydrocarbons and produced water discharging from malfunctioning equipment, vandalism, and accidents [3]. In the case of shale gas, the fracturing process, especially if accompanied by seismic events, may cause migration of fracturing fluids or formation brines through natural or artificial fissures or legacy wells connected to groundwater supplies.

It is important to emphasize that oil and gas, including shale gas, regulatory programs place great emphasis on protecting groundwater, and well construction requirements, consisting of installing multiple layers of protective steel casing and cement, are specifically designed to protect fresh water aquifers and to ensure that the producing zone is isolated from overlying formations. However, a review of all oil and gas operations in Texas (1993-2008) and Ohio (1983-2007) by Groundwater Protection Council (GWPC, 20011) reported 211(Texas) and 183 (Ohio) groundwater contamination incidents that were primarily attributed to legacy wells, waste management and disposal, and leaks of tanks and flow lines; they reported no incidents related to drilling, hydraulic fracturing, or production of shale gas.

Detailed site investigations, such as those conducted at the USGS OSPER sites in Oklahoma, that included drilling and sampling monitoring wells in contaminated and background areas and using natural and added tracers to document leakages, are needed to better assess groundwater pollution at legacy and producing petroleum sites [3]. A similar study is being conducted by the US EPA to investigate the potential effects of shale gas operations on drinking water at several sites [23]. Water quality monitoring before, during, and after hydraulic fracturing operations will be carried out at these sites, and compared with similar measurements at comparable sites that do not experience hydraulic fracturing to provide some case-specific data on impacts to water quality. This and similar detailed studies from shale gas basins worldwide are needed to minimize all potential environmental impacts, especially groundwater contamination and induced seismicity, when producing these extremely important new sources of energy.

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