Submission Date: 31 Jan 2011

Title: HYDRAULIC FRACTURING AND WATER RESOURCES: AN ASSESSMENT OF THE POTENTIAL EFFECTS OF SHALE GAS DEVELOPMENT ON WATER RESOURCES IN THE UNITED STATES

Short Title: Hydraulic fracturing effects

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Project Summary:

Shale gas is a key source of onshore domestic energy for the United States and production of this resource is increasing rapidly. Development and extraction of shale gas requires hydraulic fracturing, which entails horizontal drilling, perforation of steel casing and cement grout using explosive charges, and expansion of fractures using fluids under high pressure. Concern over potential environmental effects of shale gas development is growing and based on a recent review there is very little information in the scientific literature on potential environmental effects of hydraulic fracturing.

We propose to conduct the first broad scale, data-based assessment of the potential effects of hydraulic fracturing on water resources in the United States. We will use existing databases and analyze water quality and quantity data in shale gas play areas to assess potential effects of hydraulic fracturing.

Proposed Start and End Dates: August 2011–July 2013

Proposed Data Release Date: October 2013

Is this a resubmission? No

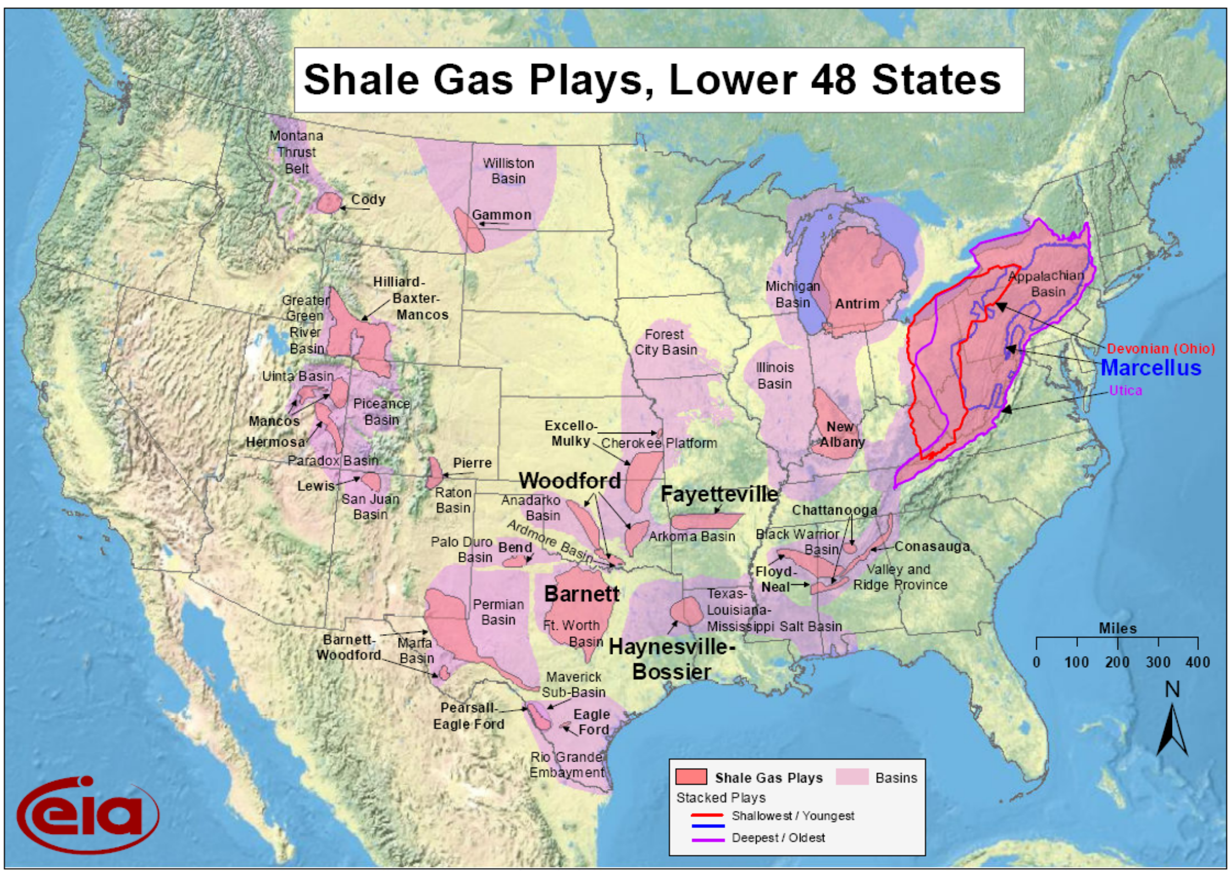
Conflicts of Interest with Reviewers: Baron, one of the Powell Center Co-Directors, is supervised by Bowen; Freeman, an Advisory Board Member, was the major advisor for Bowen's PhD program.

HYDRAULIC FRACTURING AND WATER RESOURCES: AN ASSESSMENT OF THE POTENTIAL EFFECTS OF SHALE GAS DEVELOPMENT ON WATER RESOURCES IN THE UNITED STATES

Problem Statement:

Shale Gas Development

Natural gas currently accounts for about 20% of U.S. fuel consumption with increasing trends reported (U.S. Department of Energy 2009). U.S. sources of shale gas are currently estimated to contain enough fuel to extend domestic supplies of natural gas by 26 years (U.S. Department of Energy 2009). The most promising shale gas formations occur from 200-13,500 feet below the surface and range in thickness from 50 to 600 feet in basins ranging in area from 5,000-95,000 square miles (U.S. Department of Energy 2009, Arthur et al. 2008). Shale gas formations are found throughout much of the U.S. (Figure 1.) The largest of these is the Marcellus Shale, which underlies all of West Virginia; most of Pennsylvania; large portions of Ohio, Kentucky, and New York; and parts of Virginia, Tennessee, and New Jersey.



Source: Energy Information Administration based on data from various published studies.
Updated: March 10, 2010

Figure 1. Shale gas plays in the coterminous United States.

Most shale gas occurs primarily as methane (about 90%) in macropores (natural fractures) and networks of nanometer-sized micropores, and adsorbed to organic materials and minerals, in relatively impermeable layers of sedimentary rock (Ambrose et al. 2008, U.S. Department of Energy 2009, Natural Gas Supply Association 2010). The natural rate of gas flow through most gas shale formations is on the order of 0.00001–0.01 millidarcies (mD; 1 Darcy equivalent to 0.9869233 μm^2) over millions of years (U.S. Department of Energy 2009); thus, gas shales are known as "tight" gases. Because maximum exposure of hydrocarbon-bearing rock in a vertical well is limited by the formation's thickness (typically 50–600 feet), producing natural gas economically from gas shale has required advancing not only the knowledge of geological formations, but also technologies for extraction, including directional drilling and hydraulic fracturing (known as "fracing" by the industry and "hydrofracking" in the popular media).

Briefly, these extraction processes first entail drilling a vertical well to a point about 500 feet above where the well bore must change from vertical to horizontal in order to access the target formation. That well's vertical terminus then becomes a "kick-off" point for commencing the turn from vertical to the horizontal (or lateral) leg of the well. Each lateral well can range from 2000–6000 feet in length, (U.S. Department of Energy 2009), thus increasing the exposure of the well bore to the gas-bearing strata by orders of magnitude. One to eight (usually 3 to 6) lateral wells can be drilled from each well pad. Steel casings are inserted into the wellbore at various stages of drilling and cement grouts are pumped in the annular space between the steel and the well bore to seal off the casings from the surrounding or overlying aquifers to prevent contamination with drilling chemicals or migration of salty water into any freshwater aquifers. The casings and cement grout also maintain wellbore integrity (prevent collapse) and preclude gas from migrating up the wellbore. Once the casings are in place, perforating guns (shape charges) are inserted into the horizontal leg of the well to perforate the steel casing and surrounding cement grout to facilitate communication with surrounding rock. Subsequently, fracing commences in stages (usually 300- to 500-foot sections of the horizontal leg) by pumping a fracing fluid into the perforated section of the wellbore under extreme pressure (typically 5,000–10,000 psi) to counteract the overburden pressure and then begin to fracture the surrounding rock, thus creating new fracture pathways in the gas-producing formation. The fracing fluid is primarily composed of water, sand, and a small percentage of chemicals: the sand serves to "prop" open the fractures created in the shale so that gas may flow into the wellbore, and the chemicals serve several purposes—to prevent corrosion, to inhibit the growth of algae and bacteria, to reduce friction, and to keep the sand in suspension. After fracing is completed, any residual water (flowback water) is removed, a temporary seal is emplaced, and the process is repeated for several more frac stages. When the last frac stage is completed the temporary plugs are removed, a wellhead is emplaced, and gas collection commences. During gas production a small amount of natural formation fluid is produced (produced water) and this fluid is stripped from the gas before entering the gas pipeline. The produced water is temporarily stored onsite and removed periodically for proper disposal or reuse.

Concerns About Shale Gas Development

Whereas shale gas holds great promise for helping the U.S. meet its current and future energy needs, our extensive search of peer-reviewed literature, agency reports, and Internet sites turned up mostly general summaries on the environmental effects of developing this energy source, and most of what we did find largely came from news articles and activist Websites (Colborn et al., in press; Flatow 2010; Svoboda 2010; Wilson 2010; also see http://www.water-contamination-from-shale.com/). The sheer volume of reports, however, suggests that there are both known and unknown linkages between shale gas development and deleterious impacts on public and environmental health. Possible effects include contamination of aquifers and surface waters from drilling and fracing chemicals; cross-contamination of aquifers through faulty well construction, casing installation, and pressure related blow-outs; release of methane and other greenhouse gases into aquifers or the atmosphere (termed 'stray gas'); unintended seismic events from injection of spent drilling fluids, flowback, and produced waters; deleterious effects on wildlife and habitats; and effects of soil erosion and airborne dust, including toxic dusts. Here we focus on water resources.

Public concern over potential effects of hydraulic fracturing is affecting regulations and development of shale gas resources in some areas of the U.S. Pennsylvania has required drilling companies to disclose the contents of their fracing fluids since 2008 (Susquehanna River Basin Commission 2010), but there is no Federal law requiring disclosure. Wyoming passed regulations in 2010 that require detailed disclosure of the chemicals used in hydraulic fracturing and other operations. In New York, the governor recently vetoed a hydrofracing moratorium for that state, although he did place a temporary ban on drilling the Marcellus Shale until July 2011, during which time a supplemental environmental impact statement will be completed (Benjamin 2010). Meanwhile, many bans on fracing are taking place at the township and county level (O'Toole 2010). Internationally, a recent risk assessment report by the Tyndall Centre for Climate Change Research has recommended that European Union Countries delay shale gas exploration and development until additional studies are completed in the United States (Wood et al. 2011).

Known and Potential Effects on Water Quality

Many of the chemicals used in fracing fluids are known to have direct or indirect effects on human and ecosystem health, including cancer and endocrine disruption (Colborn et al., in press; U.S. Environmental Protection Agency 2004:4–9). For example, at a Marcellus Shale drilling site in Pennsylvania, a 13,000-gallon spill of fracing gel entered a nearby river and caused a fish kill. The gel's components have been shown to cause skin cancer in animals and deleterious effects on the central nervous system of people who breathe or swallow the fluids, and they are listed as possible human carcinogens (Lustgarten 2009b). The drilling wastes produced from Marcellus Shale wells are also potentially hazardous, as they often contain radionuclides, high levels of total dissolved solids (TDS, or salts), and other contaminants (New York State Department of Environmental Conservation 2009). Radionuclides, such as radium, are also of concern in flowback waters. Additionally, if flowback water is treated at a domestic water treatment plant and if the flowback water contains organic matter, it may react with chlorine used for disinfection of drinking water and produce trihalomethane as a reaction byproduct. Both radionuclides and trihalomethanes are regulated by EPA and thought to cause adverse health effects (see http://water.epa.gov/action/advisories/drinking/drinking_index.cfm). It is not clear whether fracing brines discharged into surface waters increase the risk of trihalomethanes forming in supplies of drinking water. However, radionuclides can be well above acceptable levels in Marcellus Shale wastes; e.g., 267 times the limit considered safe for disposal and thousands of times greater than what is considered safe to drink (Lustgarten 2009c).

Contaminants associated with shale gas development could enter water in several ways. First, fracing fluids and drilling wastes can be spilled into surface waters. Known problems leading to spills have included breaks in pipelines (often at failed joints or seams), failures of blowout preventers, leaky storage tanks, trucking accidents, overflow of waste lagoons, and others, including human negligence (Myers 2010, Myler 2010, Spadoni 2010). Contamination of surface waters also has occurred due to intentional discharges of fracing fluid flowback (typically, about 1/3 of the fracing fluid flows back out of or is withdrawn from a wellbore and must be disposed of or recycled) and drilling wastes. Disposal of either waste may entail delivering it to an appropriate wastewater treatment plant (one that has industrial pre-treatment capabilities), where it is presumably treated and then mixed with treated human septic waste before being discharged into surface waters or recycled back to the gas industry. There are reports, however, of both brines and wastes being only partially treated before being released (Caruso 2011). Evidence of drilling waste in the environment includes a preliminary study conducted in 2010 that revealed extremely high conductivity levels (a measure of TDS) in some regions of Pennsylvania where densities of shale-gas wells are high (Velinsky 2010, Belardo 2010). There is also circumstantial evidence (foul odors, rainbow-colored slicks, foam) that fracing wastes may have been sprayed on roads to diminish the dust raised by truck traffic (Federman 2009). Because fracing a single well usually entails hundreds of trips by large, heavy tanker trucks (Harber 2010), surface water quality also may be affected by concomitant soil erosion and dust. In addition, dusts are created by surface disturbances and processing activities at well pads, and often standard road-treatment chemicals are used to keep dust down on roads, all of which can enter and contaminate surface waters.

Another avenue for water contamination is underground escape of hazardous components (fracing fluids, as well as TDS, iron, radionuclides, oil, methane, and heavy metals) into aquifers. There is a growing body of official records that report wells contaminated with fracing chemicals (or by-products of those chemicals), petroleum odors, high levels of methane, salts, and black sediments (Pittsburgh Geological Society 2004, Lustgarten 2009a, Bair et al. 2010, Myers 2010, Svoboda 2010). Many such occurrences were due to defective wellbore casings and improper cement jobs. Indeed, a study conducted to determine the cause of an explosion that destroyed a home in Bainbridge, Ohio, found that a faulty wellbore casing allowed methane to enter the homeowner's well (Bair et al. 2010). What remains unclear is whether contaminants also may migrate along subterranean fractures or well casings from deeper fraced zones into water supply aquifers.

Known and Potential Effects on Water Supplies

Another potentially significant effect of developing shale gas is the large amount of water required—in some cases well over 3 million gallons per well (U.S. Department of Energy 2009; also see http://www.marcellus-shale.us/Water-Mgmt-Plan_SW-PA.htm). The water must be withdrawn from local aquifers (preferred) and/or surface waters and then piped or trucked to the well pad. In the Marcellus Shale, 4–7 million gallons of water are being used over a 2- to 5-day period to frac each production well (Susquehanna River Basin Commission 2010). The Marcellus Shale is located in a relatively well-watered region; in arid and semi-arid portions of the country, water used for fracing could represent a greater proportion of available water supplies. Additionally, water supplies are potentially affected by post processing of frac waters through recycling, injection into waste wells, or processing at treatment plants for disposal into the environment.

Current Activities

Public concern and anecdotal evidence of potential contamination of surface waters from shale gas development prompted Congress in 2010 to direct the Environmental Protection Agency to conduct a study on the relationship between hydraulic fracturing and drinking water to be completed by 2012. Components of the EPA study include:

- Compilation and analysis of background data and information
- Characterization of chemical constituents relevant to hydraulic fracturing
- Field investigations, case studies, and computational modeling
- Technological solutions for risk mitigation and decision support

The EPA study work plan is in review and will be released in early spring 2011. As part of the EPA study, the U.S. Geological Survey is identified as a collaborator and data source.

A USGS response to a congressional inquiry on "…potential adverse health and environmental impacts on water supply and water quality attributed to the extraction of natural gas in shale deposits" highlighted ongoing efforts associated with the USGS Energy Resources Program Produced Waters Project, efforts to coordinate activities among USGS Water Science Centers, and a small number of studies or potential studies in specific geographic areas. Though not formal or exhaustive, additional recent inquiries within USGS suggest that there is not currently a study underway to summarize existing data for evaluating the potential effects of shale gas development on water resources.

We propose here to conduct the first broad-scale data reconnaissance and targeted assessment of potential effects of shale gas development and hydraulic fracturing on water resources in the U.S. The study will use existing data on water resources and shale gas development and focus on a limited set of variables that can be assessed across different shale gas play areas. The study will be executed in collaboration with the USEPA and will support their efforts.

Proposed Activities:

General Approach

For surface waters, we will work with regional experts and select paired watersheds and/or before-after datasets within plays that represent two conditions: 1) high density shale gas development and hydrofracturing activity and 2) little or no shale gas development activity. An additional criterion for site selection is availability of long-term water quantity and quality information through NWIS, STORET, or other databases of documentable quality. Examples of key response variables include surface water total dissolved solids (or specific conductance as a surrogate), chloride, and discharge. Additional relevant information is anticipated to vary by location and will be included opportunistically to supplement response variable data that is available across multiple sites.

For groundwater, we will employ the same general strategy for data mining but will focus on before/after datasets with our primary parameters of interest being methane, chloride, and water level. These parameters have been shown to be the primary response variables, and methane and chloride showed statistically significant increasing trends in monitoring wells in the Piceance Basin, Colorado (Thyne 2008)

Data

The core data resources will be the USGS National Water Information System and EPA STORET database. Within NWIS and STORET we will evaluate and use both surface water quantity and quality data as well as ground water depths and quality, as available. Data on shale gas development activity will be sourced from regional experts and State oil and gas commissions. Additional data resources relevant to the work include National Oil and Gas Assessment Reports, data from ongoing USGS place-focused studies, and new information collected as part of the 2010-2012 EPA study.

Analytical Approach

We anticipate analyzing time series data for treatment and control watersheds (or aquifers) using a Before-After-Control-Impact design (Stewart-Oaten and Bence 2001) with modification or adaptation as required to compensate for data limitations.

Participants:

Individuals were selected for the working group based on their content knowledge and expertise in a wide range of specialties relevant to the assessment.

Table 1. Participants (see Figure 1 for reference to plays)

Participant	**Expertise**
Zack Bowen, U. S. Geological Survey, FORT *#	Aquatic Ecology, project management
David Mott, U. S. Geological Survey, Wyoming Water Science Center*	General hydrology and water quality, project management
Tanya Gallegos, U. S. Geological Survey, Colorado*	Civil and environmental engineering, produced waters associated with energy development
Douglas Beak, U.S. Environmental Protection Agency, Oklahoma*	Environmental chemistry, contaminant fate, transport, and availability, EPA data sources
Kent Becher, U. S. Geological Survey, Texas*	Surface and groundwater hydrology, data for the Texas shale gas play Regions
Brian Cade, U. S. Geological Survey, Colorado*+	Statistical design, analysis, and modeling, data for the Piceance and Paradox Basin plays
Robert Puls, U.S. Environmental Protection Agency, Oklahoma*	Transport, fate, and remediation of inorganic contaminants in ground water systems, EPA data
James Petersen, U. S. Geological Survey, Arkansas*	Hydrology and Water Quality statistics, data for the Fayetteville Play
Bill Kappel, U. S. Geological Survey, New York*	Hydrologist, data for the northern portion of the Marcellus play
Joel Galloway, U. S. Geological Survey, North Dakota*	Hydrologist, data for the Williston Basin

Melanie Clark, U. S. Geological Survey, Wyoming*	Water Quality Specialist and data for the Green River basin plays
Robert McDougal, U. S. Geological Survey, Colorado*	Geophysics, remote sensing, environmental effects of energy development
TBD, U. S. Geological Survey, Oklahoma**	Water Quality Specialist or Hydrologist, data from the Woodford and Excello-Mulky plays
TBD, U. S. Geological Survey, Michigan**	Water Quality Specialist or Hydrologist, data from the Antrim play
TBD, U. S. Geological Survey, Georgia**	Water Quality Specialist or Hydrologist, data from the Black Warrior Basin plays
TBD, U. S. Geological Survey, Indiana or Kentucky**	Water Quality Specialist or Hydrologist, data from the New Albany basin play
TBD, U. S. Geological Survey, Utah**	Water Quality Specialist or Hydrologist, data from the Uinta and Paradox basin plays

* Confirmed, ** Unconfirmed, + Technical Liaison to Powell Center Computing Staff, # Party Responsible for Adherence to Powell Center Data and Information Policy

Data to Be Used for Proposed Analysis:

The primary data sources for surface and ground water information will be the USGS National Water Information System and EPA STORET databases. Data for shale gas development activity will be obtained from regional experts through State oil and gas commissions.

Timetable of Activities:

This study will use the people and data resources of the USGS in collaboration with other agencies to address a question of National importance. We anticipate a substantial coordination effort, outreach to regional experts in different shale gas play areas, and intensive work to compile and analyze existing data. Initial work will entail refining the study design, identifying regional experts in shale gas play areas across the U.S., and selecting sites. To maximize efficiency, we will engage in initial regional expert recruiting and data compilation during the spring and summer of 2011, prior to the official start of Powell Center-funded activities. Start date is flexible but optimally not prior to July 2011.

August–October 2011 — Finalize list of regional experts. Consultation among working group and regional experts on study design and potential sites. Compile and prepare datasets for analyses and conduct exploratory data analysis.

November 2011 — First workgroup meeting. Three working days to assess initial results and refine analysis approach and methods. Distribute data analysis and writing responsibilities for winter 2011. Determine titles and primary

	responsibilities for additional products to be developed as part of the working group activity.
December–April 2012	Continue data analysis and writing tasks. Coordination through regularly scheduled conference calls and email communication.
May 2012	Second workgroup meeting. Three working days to finish compilation of results; review and discussion of draft products. Determine and assign required work to complete products.
June–January 2013	Continue data analysis and writing tasks. Coordination through regularly scheduled conference calls and email communication.
February 2013	Review and determine requirements to finalize draft products.
March–July 2013	Complete manuscripts and review process. Submit products for publication.

Anticipated Results and Benefits:

The primary product of this study will be a manuscript detailing our data-based assessment of potential effects of hydraulic fracturing and shale gas development on water resources in the U.S. This manuscript will be submitted to a top-tier outlet for publication. Additional products will be developed based on the working group members' assessment of priorities and feasibility. Additional products could include manuscripts or reports on 1) a more detailed characterization of one or more shale gas play areas based on geology and water resources; 2) an intensive evaluation of water budgets associated with shale gas development at one or more sites; 3) a framework for life cycle assessment of shale gas; or others.

In addition to primary products, this working group will have several benefits. The proposed activities will:

1. Support collaboration with USEPA and other agencies on an issue of National importance
2. Help establish an interdisciplinary network of people and capacities to work on shale gas issues
3. Result in a summary of existing and ongoing research across shale gas play areas
4. Provide a framework and potential catalyst for additional research and monitoring activities within USGS—what can we do with what we have and what are the gaps?
5. Help fulfill requests from Congress for assessment information on hydraulic fracturing and shale gas development.

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For privacy, curricula vitae and budget purposefully omitted.