Development of unconventional natural gas reservoirs poses a threat to surface waters

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Abstract

Natural gas development is expanding in unconventional natural gas reservoirs around the world and poses multiple environmental threats to surface waters. Improved drilling and extraction technology used to access unconventional natural gas requires millions of gallons of water and a suite of chemicals possibly toxic to aquatic biota. There is growing concern among the scientific community and public that rapid and extensive natural gas development in the U.S. could lead to degradation of natural resources. Gas wells are often close to surface waters that could be impacted by increasing sediment runoff from pipelines and roads, alteration of stream flow from water extraction, and contamination from introduced chemicals or produced wastewaters. However, data required to fully understand these potential threats are currently lacking. Scientists therefore have the opportunity to develop novel studies that address potential changes in ecosystem structure and function that will inform sound environmental policy.

In a nutshell

- Natural gas development in unconventional natural gas reservoirs may pose environmental threats.

- Surface waters near natural gas wells are vulnerable to sediment runoff, reduced water flow, and possible contamination from introduced chemicals and produced wastewater.

- Federal and state environmental regulations may not prevent or mitigate damaging effects to surface waters.

- Quantitative data and innovative research are needed to understand possible environmental effects from natural gas development.

Introduction

Natural gas development has increased dramatically with advances in extraction technology and the need for cleaner burning fuels that help meet global energy demands. Natural gas is considered a bridge fuel to renewable energy resources because combustion releases fewer contaminants (e.g., CO_2, NO_x, SO_x) than coal or petroleum. Horizontal drilling and hydraulic fracturing, or hydrofracking, now allow development of vast shale gas reserves previously considered inaccessible or unprofitable. Shale gas production in the United States is expected to increase three fold, and will account for nearly half of all natural gas produced by 2035 (EIA, 2011). This widespread proliferation of new gas wells and use of modern drilling and extraction methods has now been identified as a global conservation issue (Sutherland et al., 2011). Here we describe the ecological threats to surface waters associated with increased natural gas development in shale basins, and highlight opportunities for research to address these threats.

Horizontal Drilling and Hydraulic Fracturing

Gas well drilling has historically used a single vertical well to access gas trapped in permeable rock formations (e.g., sandstone) where gas flows freely through pore spaces to the wellbore. Unlike these conventional sources, unconventional gas reservoirs are low permeability formations such as coal beds, tight sands, and shale that require fracturing and propping before gas can travel freely to the wellbore. Hydrofracking uses high pressure fracturing fluids, consisting of large volumes of water and numerous chemical additives, to create fractures, while added propping agents such as sand keep fractures open to allow gas flow. Though hydrofracking was first used in the 1940s, the practice was not widely applied until the 1990s, when gas prices increased and advances in horizontal drilling made the technique more productive. Horizontal drilling increases the volume of rock a single well can access, thereby reducing density of well pads required at the surface. **The horizontal leg of a gas well is fractured in discrete lengths of 300 to 500 feet, therefore there may be up to 15 separate hydrofrack 'events' along one horizontal well** (Kargbo et al. 2010). Fracturing depth depends on target formations, but varies from 150 to >4,000 m for the major shale formations in the United States (DOE, 2009)

Extent of resources

The United States currently has 72 trillion cubic meters (tcm) of potentially accessible natural gas, enough to last 110 years based on 2009 rates of consumption (EIA, 2011). Approximately 23 tcm of that gas is found in unconventional gas reservoirs, where development has increased 65% since 1998 (DOE, 2009). There are 29 shale basins spanning 20 states, which are expected to contribute 45% of the total U.S. gas produced by 2035 (Figure 1a, EIA, 2011). Furthermore, the U.S. gas supply represents only a fraction of the total global estimate of potentially accessible natural gas (459 tcm) and only 11% outside of North America has been recovered (MIT, 2010). Development of potentially accessible natural gas is expected to increase with increasing global demand and transfer of drilling technologies overseas.

Problem statement/purpose

The increase in natural gas development threatens surface water quality at multiple points, creating a need to assess and understand the overall costs and benefits of extracting the resource from shale reservoirs. Gas well development of any type creates surface disturbances from land clearing, infrastructure development, and release of contaminants produced from formation waters (e.g., brines). Use of hydraulic fracturing, however, poses additional environmental threats from water withdrawals and contamination from fracking fluid chemicals. Extraction of gas from shale formations may also produce significantly more methane than conventional wells and could have a greater greenhouse gas footprint than other fossil fuels (Howarth et al., 2011). Furthermore, gas wells can be close to streams and occur at high densities in productive areas, resulting in cumulative impacts within watersheds. Environmental and human health concerns associated with hydrofracking have stirred much debate and the practice has received attention of national media (Urbina, 2011) and researchers alike (EPA, 2004, 2011; Kargbo, 2010; Colborn et al., 2011, Osborn et al., 2011). Research addressing concerns with increased drilling and hydrofracking in shale basins have primarily focused on contaminants that threaten drinking and ground water, whereas data collection to address concerns associated with surface water and terrestrial ecosystems has been largely overlooked. Our goal is to encourage ecological studies related to the potential environmental impacts. We use data from the Fayetteville and Marcellus shale formations to demonstrate the recent increases in drilling activity, well proximity to streams, and well drainage area density relationships with stream turbidity. We also review other potential threats to aquatic freshwater ecosystems increased natural gas development and highlight challenges and opportunities for novel research.

Focus areas

The Fayetteville and Marcellus are among the most productive shale basins in the U.S. The Fayetteville shale basin covers more than 23,000 km^2 of Arkansas and eastern Oklahoma at a depth of 300-2000 m (Figure 1a). The number of gas wells there has increased nearly 50-fold, from 60 to 2,834 wells, since 2005 in a concentrated area of north-central Arkansas (Figure 1b and 1c). The Marcellus spans 240,000 km^2 at a depth of 1200 to 2500 m and underlies six states in the Upper Mid Atlantic, including much of the Appalachian basin (Figure 1d). Estimates indicate natural gas reserves in the Marcellus to be 14 tcm or 59% of the total estimated unconventional reserves in the U.S. (DOE, 2009). In summer 2010, the Marcellus had 3,758 natural gas wells with projections of up to 60,000 wells in the next 30 years (Johnson, 2011). The Marcellus formation also underlies sensitive watersheds such as the threatened Upper Delaware River, a designated wild and scenic river that supplies drinking water to >15 million people (DRBC 2008). The rapid development of gas wells in relatively concentrated areas may increase the likelihood of ecological impacts to surrounding forests and streams.

Proximity of gas well development to water resources

We initially assessed proximity of active gas wells to water resources using state well location data and the National Hydrography Dataset (NHD). Spatial analysis indicated that gas wells averaged 300 m from streams for both the Fayetteville and Marcellus shale formations, yet several hundred wells were located within 100 m of stream channels (Table 1). Gas wells averaged 15 km from public surface water drinking supplies and 37 km and 123 km from public well water supplies in the Marcellus and Fayetteville shale reservoirs, respectively (Table 1). Although wells are generally constructed far from public drinking water sources, there is potential for wastewater to travel long distances since many of the components of the produced waters are conservative (e.g. brine) and will not settle out or be assimilated into biomass. Furthermore, the NHD underestimates the density of headwater stream channels (Heine et al., 2004), so our proximity measures likely underestimate the threat to streams. Therefore, we used Geographic Information System (GIS) tools to generate detailed drainage area networks in portions of the Fayetteville and Marcellus shale reservoirs where gas well densities are concentrated. The terrain processing tools in ArcHydro Tools 9 version 1.3 (an ArcGIS extension) were used to generate drainage area lines from 10 meter digital elevation models (DEM;http://seamless.usgs.gov/ned13.php) in a subset of drainage areas in each shale play. A stream threshold of 500 (50,000 m^2) was used to define stream channels in the model. Gas well proximity was analyzed again with a subset of modeled stream drainage areas and the same subset of NHD flowlines for comparison (Table 2, Figure 2). Active gas wells were an average of 130 and 153 m from modeled drainage areas compared to 230 and 252 m from NHD flowlines in the Fayetteville and Marcellus shale reservoirs, respectively. Over 80% of the active gas wells were located within 300 m of modeled drainage areas (Table 2). Because the modeled drainage areas estimate some intermittent and ephemeral channels, the proximity of wells to stream channels (and potential for downstream impacts) is greater than reflected by NHD flowline data. This process may provide a more accurate assessment of potential stream impacts, particularly if shale gas development continues at its current rate. As well densities continue to increase, the proximity of wells to stream channels may increase, resulting in a greater risk of streamflow reductions from pumping, contamination from leaks and/or spills from produced waters or fracking fluids, and sedimentation from infrastructure development (e.g. pipelines and roads).

Environmental regulation

Environmental regulation of oil and gas drilling is complex and varies greatly among states. The Safe Drinking Water Act (SDWA) provides federal laws for protecting surface/ground waters and human health, but with the exception of diesel fuel injection, hydraulic fracturing operations are exempt as a result of the 2005 Energy Policy Act. State agencies are therefore primarily responsible for regulation and enforcement of environmental issues associated with natural gas development. The rapid growth and expansion of U.S. gas drilling has made regulation difficult and violations are common. In Pennsylvania alone, there were >1400 drilling violations from January 2008 to October 2010 (PADEP, 2010). Of these, nearly half dealt with contamination of surface waters and included direct discharge of pollutants, improper erosion control, or failure to properly contain wastes. In contrast, the Arkansas Department of Environmental Quality cited only 15 surface water violations in the Fayetteville shale in 2010; but over half dealt with permitting and discharge violations associated with natural gas development (ADEQ, 2010). The discrepancy in violations between states demonstrates the variable degree of regulation at the state level and is likely attributed to both differences in regulations and available regulatory resources. Regardless, the number and proportion of violations associated with natural gas development indicates that sediments and contaminants associated with drilling are making their way into surface waters, yet studies of ecological effects are lacking. Primary threats to surface waters and potential exposure pathways (Figure 3) include:

Sediments

Excessive sediments are one of the primary threats to U.S. surface waters (EPA, 2006) and have multiple negative effects in lotic food webs (Wood and Armitage, 1999). Gas well installation activities can negatively affect lotic ecosystems by increasing sediment inputs from well pads and supporting infrastructure (roads, pipelines, stream crossings), as well as loss of riparian area. Typically, a least 1.5-3 ha of land must be cleared for each well pad, depending on the number of wells per pad, and in high densities well pads can cumulatively alter the landscape. Land clearing and stream disturbance during well and infrastructure development can increase sediments in surface water runoff (Williams et al., 2008) resulting in increased suspended and benthic sediments in surface waters. Nutrients bound to these sediments may also have impacts on surface waters.

We identified seven streams in the Fayetteville shale with a gradient of well densities among drainage areas to test the prediction that stream turbidity would be positively related to the density of gas wells. The seven stream drainages were delineated using the ArcHydro extension in ArcMap (Version 9.3.1; ESRI, Redlands, CA). Using gas well location data from Arkansas Oil and Gas Commission, well density was quantified for each drainage area as the total number of wells divided by the drainage area. Turbidity samples were collected in April, 2009 during high spring flow (Lamotte 2020; Hach). Pearson product moment correlations identified a positive relationship between stream water turbidity and well density (Figure 4). Turbidity was not positively correlated to other land cover variables, but there was a strong negative correlation between turbidity and drainage area and percent pasture cover in the watershed (Table 3).These preliminary data suggest cumulative effects from well development and associated infrastructure may be detectable at the landscape scale.

Water withdrawal may alter flow regime

Surface waters may serve as sources for necessary drilling and fracking fluids; each well uses between 2 to 7 million gallons of source water. There is potential for fracturing of multiple wells per well pad over the life span of the well development (which may take several decades), which compounds required water use. Many gas wells are installed in regions where water is already withdrawn for agriculture and may further stress the resource. Stream flow may be negatively affected if streams are dammed to create holding ponds or if water is directly extracted for the fracturing process. The rapid and concentrated extraction of water could create regional shortages during dry periods, resulting in an altered flow regime and the further degradation of critical habitat to aquatic biota, particularly if low order streams are primary sources. A reduction in stream flow may also result in secondary effects, such as increased contaminant concentrations and reduced downstream water quality because less water is available for dilution or conversely, lower transport distances of contaminants.

Release of wastewaters

Surface water contamination from hydrofracking fluids and produced water (i.e. water flowing back out of the well along with the gas) is most likely to occur during hydrofracking or treatment and disposal processes when the potential for accidental spills and leaking is greatest. Contamination from hydrofracking wastes can also occur through inadequate waste treatment practices, improper storage, inadequately constructed impoundments or well casings, and improper disposal of solid wastes (i.e., poorly lined impoundments that are buried onsite) that may leach into nearby surface waters. Wastewater impoundment ponds can also pose a threat to exposed wildlife and livestock.

Fracturing fluids typically include a combination of additives that serve as friction reducers, cross-linkers, breakers, surfactants, biocides, pH adjusters, scale inhibitors, and gelling agents (NYSDEC, 2009). The aim of additives is to achieve an ideal viscosity that encourages fracturing and gas flow, but discourages microbial growth and corrosion that can inhibit recovery efficiency (DOE, 2009). Composition of the fracturing fluids can vary greatly among wells and shale formations. Specific content is most often proprietary, though some States require disclosure of constituents and companies may voluntarily register their chemicals. A recent Congressional investigation revealed that, over a four year period, 14 leading gas companies used over 2,500 hydrofracking products that contained 750 different chemicals, 29 of which were highly toxic or known carcinogens. Fracturing fluids used over the period totaled 780 million gallons (not including dilution water), and included lead, benzene, ethylene glycol, diesel, formaldehyde, and benzene, toluene, ethylbenzene, xylene compounds (House Committee on Energy and Commerce, 2011). The volume of fracking fluids recovered is also highly variable, but unrecovered amounts can be substantial. Only 10-30% of fracture fluids are typically recovered from wells in portions of the Marcellus Shale (NYDEC 2009). Yet information on the fate and transport of these unrecovered chemicals are lacking.

Produced waters pose a threat to surface waters because they typically contain not only fracking additives, but also elevated metals, dissolved solids (e.g, brine), organics, and radionuclides that occur naturally in geologic formation waters. Onsite waste impoundments or evaporation ponds could overflow, spill, or leach into groundwater and contaminate nearby streams. Even after treatment, total dissolved solids (TDS) are very high and remaining salts are often disposed of through land application or used as road salts, which are known to enter surface waters and contribute to increased stream salinization (Kaushal et al., 2005). Recovered wastewaters are most often transported offsite for deep well injection (aka underground injection control [UIC]) or transported to domestic wastewater treatment plants (WWTP) and/or conventional waste treatment facilities (CWTs). After fracturing, initially recovered flowback water is sometimes reused as fracking fluid for other wells. Reuse of recovered fluids is becoming more common, but still requires a significant amount of freshwater because of low recovery volumes and required dilution of concentrated flowback (i.e., chlorides, sulfates, barium, etc). Domestic WWTPs are not capable of treating the high TDS (5,000->100,000 mg/L) typical of recovered wastewater. Many WWTP have therefore been forced to limit the amount of recovered hydrofracking waste intake to remain in compliance with effluent limitations (Veil, 2010). Industrial WWTPs are better equipped to treat recovered wastes using reverse osmosis, filtration, or chemical precipitation, but such facilities are costly and not widely available. Therefore, billions of gallons of produced water are being generated annually on a national scale (Clark and Veil 2009), water treatment options are limited, and the potential ecological impacts of wastes on terrestrial and aquatic ecosystems are not well studied.

Challenges and potential for novel research

Quantifying effects of natural gas development in shale basins on surface waters is challenging because multiple companies are often working in the same geographic area using different fracturing techniques (e.g., varied and often proprietary composition of fracturing fluids) with uncoordinated timing of infrastructure development and well fracturing. In addition, the degree to which these companies adhere to best management practices, such as buffer strips and erosion control devices, varies among companies, states, and agencies. Further, wells occur across human-impacted watersheds that may confound the ability to attribute effects from gas well development.

Most studies examining effects of sediments on biological communities have focused on shifts in abundance, biomass, diversity, or community composition (Wood and Armitage, 1999). Fewer studies have examined how sediments alter species roles and their interactions (but see Hazelton and Grossman, 2009). In addition, contaminant effects are often assessed using single-species laboratory acute and chronic toxicity tests with model organisms (Cairns, 1983) and with single contaminants. Studies are needed to address toxicity of contaminant mixtures (e.g., produced water and fracking fluids) and their effects on more complex communities and ecosystems to predict effects in the real world (Clements and Newman, 2002). Sediment and contaminants associated with recovered wastewater will likely affect organism behavior and alter ecological interactions at sublethal levels (Evans-White and Lamberti, 2009). Reductions in feeding efficiencies (Sandheinrich and Atchison, 1989) can lead to negative effects on reproduction (Burkhead and Jelks, 2001) and growth (Peckarsky, 1984) and may alter the strength of species interactions causing changes in community structure. Therefore, ecologists examining the effects of natural gas extraction can contribute to scientific understanding by examining the effects of sediment and contaminants from natural gas development on community interactions.

In addition to needs for traditional bioassessments, the inevitable alteration in land use that will occur from increased drilling offers a template for conducting novel experiments in an ecosystem context. Ecosystem functions serve as integrative metrics that are suited for detecting large-scale alterations with multiple factors affecting processing rates (Bunn et al., 1999). For example, reduced stream flows, contaminants from produced wastewater and fracking fluids, and increased sediment inputs would alter ecosystem functions, such as whole-stream metabolism, decomposition of organic matter, and secondary production of macroinvertebrates. However, it is not known how natural gas development could influence biological processing rates. The potential effects may stimulate or inhibit specific ecosystem functions. For example, increased sedimentation or chemical contamination associated with natural gas well development could increase macroinvertebrate production by expanding habitat for tolerant, multivoltine taxa (Stone and Wallace, 1998) or lead to a decline in production by eliminating sensitive taxa representing a majority of community growth and/or biomass (Woodcock and Huryn, 2007). A move to incorporate ecosystem functions into mainstream biological assessment and restoration protocols is currently underway (Fritz et al., 2010), yet few studies have been conducted to inform their implementation and interpretation in context with concurrent structural changes (Young and Collier, 2009). The rapid expansion of gas development across the U.S. could provide a framework to implement concurrent structural and ecosystem experiments to inform process-based ecoassessment. Furthermore, ecological studies relating to natural gas extraction could be combined with similar studies for surface mining (Fritz et al., 2010; Bernhardt and Palmer, 2011)to gain a more holistic view of environmental costs associated with extraction of fossil fuels.

The distinct elemental composition and isotopic signatures of produced water provide unique opportunities for tracer studies that can indicate exposure to aquatic systems. Stable isotopes of strontium and carbon have been used to trace water from coalbed natural gas production wells to surface waters and hyporheic zones (Brinck and Frost, 2007). Osborn (2011) used isotopes of water, carbon, boron and radium to test for hydraulic fracturing contamination of shallow aquifers overlying the Marcellus and Utica shale formations in Pennsylvania and New York and found significant changes in methane concentrations in drinking water wells near to where gas wells have been drilled. Limited research has also suggested that methane-derived carbon is assimilated in stream food webs(Kohzu et al., 2004; Trimmer et al., 2010). Many gas bearing geologic formations also contain elevated levels of naturally occurring radioactive materials, such as radon (^{222}Rn) and Radium (^{226}Ra, ^{228}Ra) that can be used as hydrologic tracers (Genereux and Hemond, 1990). The extent to which metals, organics, or other contaminants from the drilling and hydrofracking process may ultimately enter aquatic and terrestrial food webs remains unknown.

Conclusions

Natural gas exploration will continue to increase globally. In addition to the potential threats to groundwater and drinking water sources, increasing environmental stress to surface water ecosystems is of serious concern. To date, scientific data that will inform ecologically sound development are needed to ensure protection of our water resources. Increased sediment runoff into streams, reductions in streamflow, contamination of streams from accidental spills, and inadequate treatment practices of recovered wastewaters are realistic threats. Gas wells are often close to streams, increasing the probability of harm to surface waters and preliminary data suggests potential for detectable effects from increased sedimentation. Further ecological research on impacts from developing natural gas well infrastructure are sorely needed and will inform future regulatory strategies and further our understanding of factors affecting community structure and ecosystem function.

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Table 1: Number of active, permitted, and spud natural gas wells each year since 2005 for Arkansas, New York, West Virginia, Ohio, and Pennsylvania.

	State	Total Wells	Total Operators	Distance to NHD Flowlines (mean ± SD, range, m)	Total # (percent) of wells within 100 meters of NHD Flowlines (m)	Total # (percent) of wells within 200 meters of NHD Flowlines (m)	Total # (percent) of wells within 300 meters of NHD Flowlines (m)	Distance to Public Water Wells (mean ± SD, range, km)	Distance to Public Drinking Water Intakes (mean ± SD, range, km)
Marcellus	PA	2091[1]	59	319 ± 171 (8-1172)	74 (4)	577 (28)	1141 (55)	25.83 ± 17.93 (0.32-79.60)	14.83 ± 10.06 (0.60-50.23)
	WV	1599[2]	86	214 ± 143 (1-850)	409 (26)	798 (50)	1198 (75)	52.32 ± 32.81 (0.55-125.42)	11.16 ± 5.36 (0.53-33.32)
	OH	42[3]	12	230 ± 153 (46-691)	8 (19)	23 (55)	33 (79)	71.85 ± 28.29 (26.46-138.17)	14.15 ± 8.38 (1.54-29.87)
	NY	26[4]	9	247 ± 182 (27-631)	9 (35)	12 (46)	14 (54)	10.47 ± 7.11 (2.58-34.19)	16.59 ± 9.06 (4.58-35.63)
	All States	3758		273 ± 168 (1-1172)	500 (13)	1410 (38)	2386 (64)	37.51 ± 28.88 (0.32-138.17)	13.27 ± 8.55 (0.53-50.23)
Fayetteville	AR	2834[5]	21	353 ± 241 (7-1642)	269 (10)	900 (32)	1434 (51)	123.67 ± 11.12 (78.94-156.12)	15.15 ± 7.49 (0.66-133.43)

[1] PA: Pennsylvania Department of Environmental Protection Bureau of Oil and Gas (permits and updates through 9/30/2010)
http://www.dep.state.pa.us/dep/deputate/minres/oilgas/reports.htm
--"Active" Determination: used "New Wells Drilled by Month" reports (through 9/30/2010)

[2] WV: West Virginia Geological and Economic Survey (permits through 3/31/2010 and updates through early 9/2010)
http://www.wvges.wvnet.edu/www/datastat/devshales.htm
--"Active" Determination: used spud dates

[3]OH: Ohio Department of Natural Resources Division of Mineral Resources Management (permits and updates through 9/30/2010)

http://www.dnr.state.oh.us/mineral/database/tabid/17730/Default.aspx
--"Active" Determination: used spud dates

[4]NY: New York State of Environmental Conservation (permits and updates through 9/30/2010)
http://www.dec.ny.gov/energy/1603.html
--"Active" Determination: used spud dates

[5]AR: Arkansas Oil and Gas Commission (permits and updates through 9/30/2010)
http://www.aogc.state.ar.us/ (data downloaded from: ftp://www.aogc.state.ar.us/)
---"Active" Determination: Lots of data were missing in this file. I used the following data in the following order: 1. the commencement date (if available, not always entered it their system), 2. the completion date (if available, not always entered it their system), 3. production data (may be delayed a few months), 4. total drill depth > 1 (estimated date from other prior permit statuses)

Table 2. Proximity of natural gas wells to stream channels modeled using the terrain processing tools in ArcHydro Tools 9 version 1.3 (an ArcGIS extension) to generate drainage area lines from a 10 meter digital elevation model (DEM; http://seamless.usgs.gov/ned13.php) compared to well proximity to National Hydrography flowlines.

		Subset		Previous Distances (In Marcellus, PA only)		Subset			Previous Distances (In Marcellus, PA only)		
		range (m)	mean ± SD (m)	range (m)	mean ± SD (m)	within 100m	within 200m	within 300m	within 100m	within 200m	within 300m
Marcellus*	Drainage area Lines	4-316	153 ± 56	--	--	17%	80%	100%	--	--	--
	NHD Flowlines	48-681	252 ± 114	8-1172	319 ± 171	5%	39%	70%	4%	28%	55%
Fayetteville**	Drainage area Lines	0-420	130 ± 70	--	--	32%	71%	82%	--	--	--
	NHD Flowlines	1-933	230 ± 136	7-1642	353 ± 241	12%	43%	61%	10%	32%	51%

*Processed for 615 of 3758 wells (16%), processed 42 of 559 HUC-12 Units containing well point locations (8%)

**Processed for 2372 of 2834 wells (84%), processed 55 of 84 HUC-12 Units containing well point locations (65%)

Table 3. Pearson product moment correlations and associated p-values between turbidity (NTU) and other landscape-level variables including land cover (USGS, 2006) and drainage area. Analyses were run in SigmaPlot 11.

Correlates	**r**	**p-value**
well density	0.91	0.003
drainage area	-0.86	0.01
low impact urban	0.35	0.44
wood/herbaceous	-0.63	0.12
forest	-0.36	0.42
pasture	-0.88	0.008

Figures

Figure 1: National map of all unconventional natural gas plays in the lower 48 states (a); density of wells in the Fayetteville unconventional natural gas play (b); number of gas wells installed in the Fayetteville and Marcellus plays from 2005 to present (c); and density of wells in the Marcellus shale play (d). Densities were calculated using the kernel density tool in ArcMap 9.3.1.

Figure 2. Proximity of gas wells to stream channels in a subset of the Fayetteville and Marcellus unconventional natural gas reservoirs. Blue squares represent the areas modeled using GIS in the Fayetteville shale (top; drainage area in 5,809 km^2) and the Marcellus shale (bottom; drainage area in 4,041 km^2). Maps are example areas that demonstrate differences between the National Hydrography Dataset and modeled drainage area networks.

Figure 3. Simplified diagram of potential threats of natural gas development using coupled horizontal drilling with hydraulic fluid fracturing in unconventional natural gas reservoirs. Exposure pathways that may result in structural and functional alterations to aquatic ecosystems will vary depending on geographic location and rigor of best management practices applied. UIC = underground injection control; TDS=Total dissolved solids; TENORM= technologically enhanced naturally occurring radioactive materials.

Figure 4. Well density and stream turbidity measured in April 2009 during high flows in 7 stream drainages.