Environmental water and air quality issues associated with shale gas development in the Northeast[1]

Development of Marcellus shale for natural gas resources involves a variety of activities that can potentially impact environmental water and air quality. Some of these impacts are well-documented, while others involve more complicated relationships and/or could result from cumulative effects of multiple development activities over time and space. Through a review of research and experience in the Marcellus shale region and elsewhere, the environmental water and air quality working group has identified potential environmental impacts and relates them to natural gas development activity. Here, we illustrate the state of scientific knowledge of these impacts, their causes, and strategies for preventing and mitigating negative environmental consequences by providing a sample of annotated references and scientific literature. We also identify broad areas of particular research need, including interdisciplinary research (e.g. economics; sociology; governance) that could help stakeholders better understand environmental risk and define effective management strategies.

In addition to the overview of environmental water and air quality issues provided below, the working group suggests the following guiding questions that will serve as the basis for discussion during the conference sessions:

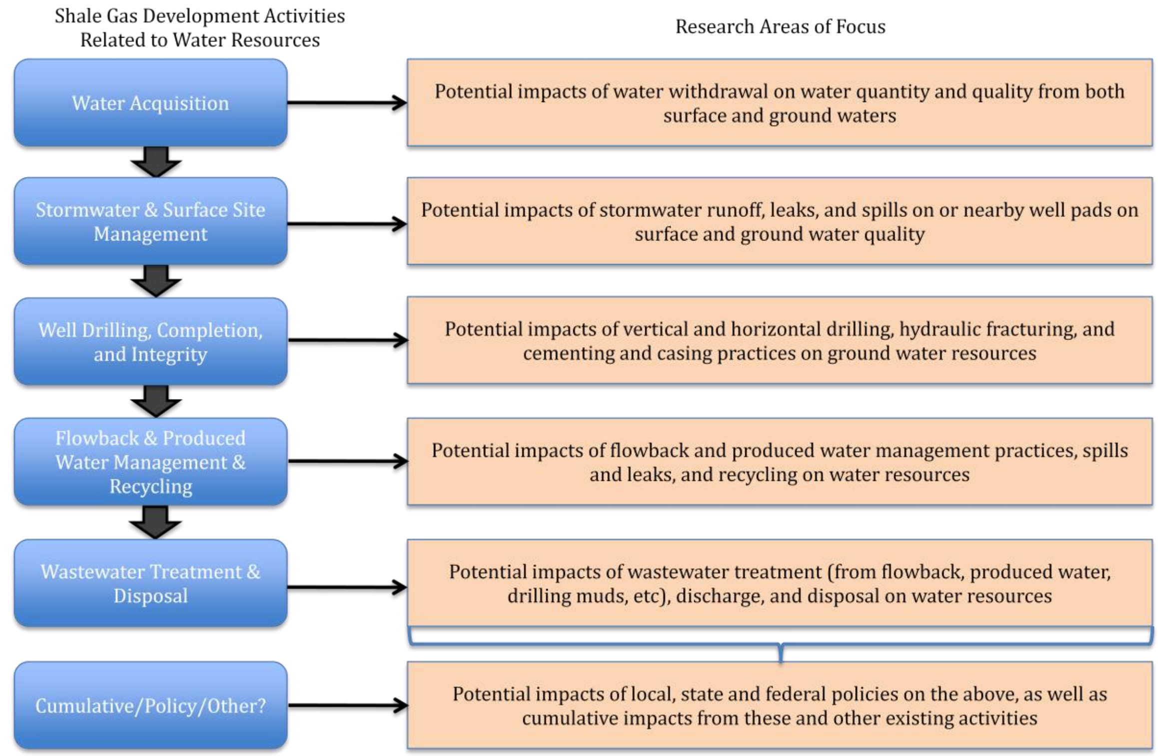
1. *What data sources are currently available for collecting information on water and air systems in the Northeast, are those data sources credible, compatible, and sufficient?*
2. *Where are the data gaps that would need to be filled in order to address important research questions, and what would effective data collection look like?*
3. *How can we integrate our work to generate a deeper understanding of such an interdisciplinary system?*
4. *How can research be used to affect policy and behavior?*

Unifying research themes that encompass multiple issues, and that should be employed to address environmental issues in general, include:

- Risk assessments using high quality data that can identify critical environmental concerns and prioritize relevant data needs
- The role of pace and scale in environmental water and air quality issues – e.g. air pollutants are emitted locally, but are transported quickly at the regional scale; aggregation of emissions from multiple sources in the same locale.
- Acknowledge need for multi-disciplinary research teams
- Use experience from other shale plays (esp Barnett) and conventional oil & gas development
- Must think in terms of best management practices in order to communicate with industry; develop strategies for addressing well sites with multiple service companies, actors, and responsible parties
- Establish coalitions and coordinated research teams that can build credibility and relationships with industry and government to conduct well-funded research
- Establish funding sources that promote unbiased research
- Generation of high quality databases that can be accessed by researchers
- Assist in the creation of national, regional, state, and local energy policies
- The importance of baseline measurements, particularly for groundwater, surface water and air quality in rural basins
- The role of industry data, and the kind of language and framing researchers need to adopt in order to use it objectively

[1]Prepared by BG Rahm & SJ Riha (NYS Water Resources Institute), D Yoxtheimer (Penn State Marcellus Center for Outreach and Research), E Boyer (PA Water Resources Research Center), D Carder (WVU Center for Alternative Fuels, Engines, and Emissions), K Davis & S Belmecheri (Penn State University)

Environmental Water Quality



Adapted from the EPA Plan to Study the Potential Impacts of Hydraulic Fracturing on Drinking Water Resources

Water Acquisition

What is it - During hydraulic fracturing of a typical Marcellus shale gas well millions of gallons of water are required over a multi-day period. This water is predominantly acquired from permitted surface water sources.

What are the issues - Although significant water recycling from previous fracturing operations occurs, large water withdrawals continue to raise concerns about environmental water availability and quality for both human and ecological needs. Large water sources, such as the Susquehanna River, represent abundant supplies that can accommodate multiple withdrawals. Smaller streams may be more sensitive to water volume loss and seasonal flow alterations, and are thus more at risk to improperly managed withdrawals.

Areas of research **(research suggestions in bold highlight potential priorities)**:

- **Development of ecologically appropriate passby flow methodologies**
- **Cumulative withdrawal impacts and protective water acquisition strategies & regulations**
- **Opportunities for alternative water sources (eg. municipal effluent, AMD from coal mines)**
- **Use of alternative fluids (eg. propane/carbon dioxide/nitrogen) or lesser volumes during fracturing**
- Water withdrawal impacts on water quality
- Type & extent of monitoring required

Additional research areas discussed at the meeting:

- Use of pipelines for water delivery in place of heavy duty vehicles
- **Role of citizen monitoring of water levels**
- Adequacy of existing monitoring regulations and locations

Stormwater & Surface Site Management

What is it – Shale gas development entails clearing land for well pad construction, access roads and collection pipelines. These construction-like activities take place outdoors and are exposed to precipitation. Well pads also act as industrial storage sites for fuel, fluids and chemical additives needed for drilling and hydraulic fracturing.

What are the issues – Improperly managed stormwater runoff can erode sediments and lead to impairment and contamination of nearby surface waters. If fuels, chemicals, and fluids are not stored and handled properly, there is increased likelihood of spills and leaks, potentially threatening groundwater quality. During a storm event, these contaminants can be transported to surface waters along with sediments.

<u>Areas of research:</u>

- Stormwater BMP's and their effect on surface water quality
- Chemical storage and handling accidents – preventative regulations and management
- **Alternative, non-toxic chemicals**

<u>Additional research areas discussed at the meeting</u>:

- **Use of planning and co-localized development to minimize surface disturbances and infrastructure need**
- **Impervious surface creation in general and its impact on surface water quality and increased peak flows**
- Reclamation & restoration: how & when it is done, what plants to choose for re-vegetation?
- Scientific basis for setback distances from well pads to surface water bodies, homes, wetlands, etc.
- Channelization of runoff around pads even when pads are constructed to specification

Well Drilling, Completion, and Integrity

What is it – Like all wells, Marcellus shale gas wells begin with vertical drilling through surface layers and near-surface groundwater zones. Wells are then cased and cemented to prevent contact between near-surface groundwater and fluids inside the well bore. When the target formation is reached, horizontal laterals may be drilled. These laterals are then fractured using high hydraulic pressure.

What are the issues – Drilling through near-surface groundwater zones entails risks associated with disturbing or contaminating potable groundwater. Drilling can alter groundwater redox conditions and pressure gradients, and poor casing and/or cementing can lead to migration of fluids (usually methane) from near the well out into the surrounding groundwater area. Improper management of well pressure can lead to blowouts at the surface.

<u>Areas of research:</u>

- Release or migration of drilling fluids to groundwater
- **Cementing and casing practices prior to completion, and longevity of integrity**
- Predicting groundwater impacts due to pressure and redox alterations
- Displacement of formation fluids
- Well abandonment procedures & technologies

<u>Additional research areas discussed at the meeting</u>:

- **Using microseismic techniques to evaluate fluid migration & fracture propagation**
- **Assess role of orphaned wells in subsurface risk**
- Refine use of isotopes in methane fingerprinting
- Explore parallel issues related to carbon sequestration and geothermal research
- Optimized fracturing technologies with less fluids and waste

Drilling Fluids, Flowback and Produced Water Management & Recycling

What is it – Water based fluids are used during the drilling phase of well development and can contain metal salts, clay, and other particles that can be recycled and or treated and disposed. Flowback is fluid that returns to the surface in relatively high volumes immediately following hydraulic fracturing. This fluid contains naturally occurring compounds associated with the shale reservoir, as well as chemical additives used to enhance the hydraulic fracturing process. Flowback is either stored in lined pits, or can be directed to tanks where it is stored for treatment, reuse, or disposal. Produced water continues to return to the surface in diminishing volumes during the active life of the well and, over time, generally contains increasing concentrations of formation-associated constituents, primarily salts, metals, and radionuclides. This produced water is generally captured in containers (tanks) and then either blended with other water for treatment and reuse, or stored for disposal. Treatment can occur off-site, usually at an industrial physical/chemical plant, however on-site treatment of fluids and subsequent reuse is becoming more widely utilized. Wastewater disposal typically occurs at underground injection control wells, primarily in Ohio.

What are the issues – Lined pits for the storage of flowback may rip or overflow, leading to potential groundwater or surface wate r impacts. Off-site and on-site treatment of waste fluids is occurring, but treatment technologies must meet operator needs for reuse. High volumes of these wastes may also lead to issues with infrastructure capacity. Disposal wells can be scarce and/or located long distances from the site of waste generation, and have been linked to induced seismicity in several states.

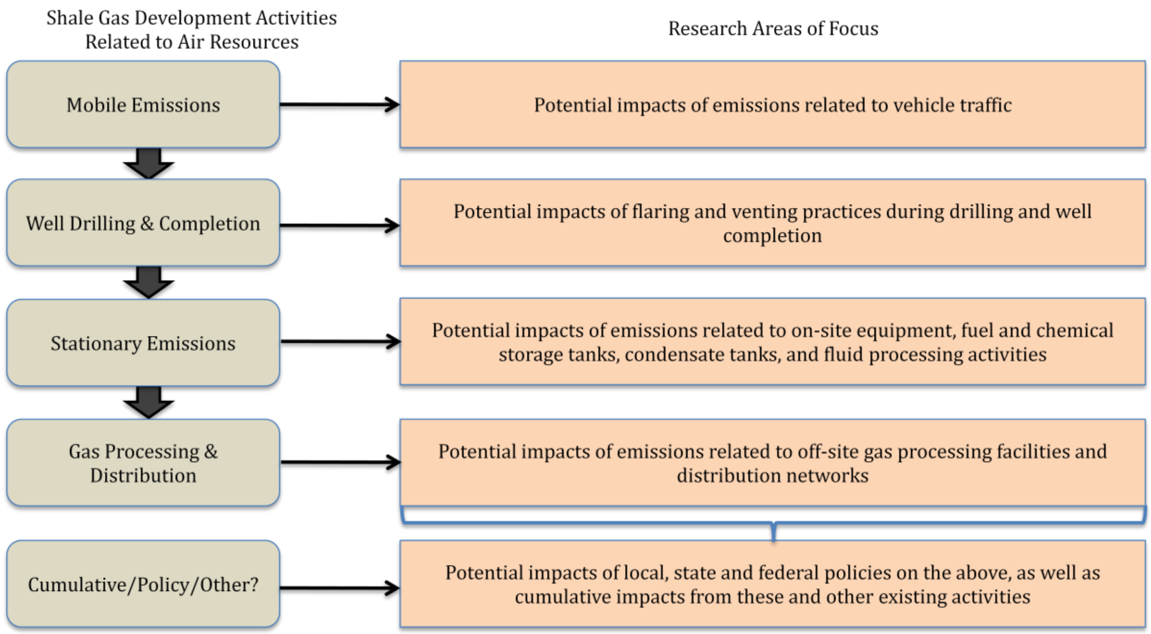
Areas of research:

- On-site recycling of waste fluids and appropriate treatment technologies
- Spills and leaks from pits and their effect on water resources
- Advantages and disadvantages of closed-loop systems
- Downhole scaling issues: real or perceived
- Waste minimization technologies
- Wastewater characterization and the treatment of waste fluids for eventual discharge
- Disposal of solids and concentrated liquid residues
- **Long-term capacity and safety of underground injection as a disposal option**

Additional research areas discussed at the meeting:

- Evaluate adequacy of current disclosure laws for making toxicity assessments
- Assessing fate and transport scenarios, and evaluating potential exposure pathways
- Develop reuse treatment standards
- Possible impacts of discharged effluent on ecosystems – BMI and other tools
- **Analysis of salt solids loadings, their origin, treatment and disposal options**
- Beneficial reuse of salts and other waste materials

Environmental Air Quality



Adapted from the EPA Plan to Study the Potential Impacts of Hydraulic Fracturing on Drinking Water Resources

Mobile Emissions

What is it – Heavy-duty vehicles are used to transport equipment and raw materials (especially water) to and from the well pad. Increased traffic of diesel engine-powered vehicles leads to emissions of pollutants that impact local and regional air quality.

What are the issues – Emissions of NOx and VOCs associated with combustion of diesel fuel can lead to photochemical production of ozone (O_3), an oxidant that irritates the respiratory passages and damages many plants. Direct emission of CO may also present local air quality issues, however CO emissions for modern diesel engines (primarily post-2007 model year) are quite low as a result of the industry-wide use of diesel oxidation catalysts. Both CO and O_3 have atmospheric lifetimes of many weeks, thus local pollution could possibly be transported over long distances.

In addition to O_3 and CO, toxic gases including benzene, toluene, ethyl benzene and xylene (commonly referred to collectively as BTEX). BTEX is classified as a potent carcinogen that poses significant risk upon ingestion. A report by the USEPA suggests 68% of the total national benzene inventory is contributed by mobile source and 19% from non-road applications. 1, 3 butadiene is another compound of interest, which has a very short atmospheric life, but ranks high on carcinogenic potential. Particulate matter emissions from heavy-duty diesel engines have been a widely targeted pollutant, due to their adverse health effects. Particulate matter emissions can be viewed as solid and volatile sub-micron particles that are formed as a result of diesel combustion. Particles emitted by diesel engines have capabilities to reach the gas diffusion regions of the human lungs, thereby increasing the potency towards respiratory and cardiovascular diseases. This has been one of the driving forces in promoting diesel fumes as a “potent carcinogen” from its existing status since 1989 as a “probable carcinogen”. On June 12, 2012, the World Health Organization classified diesel engine exhaust as carcinogenic to humans. As natural gas utilization rises, penetration into the internal combustion fuels market (as LNG and CNG) will result in release of methane, as an unburned product of incomplete combustion, as well as fugitive emissions from vehicle storage tanks, fueling station tanks (primarily LNG) and emissions released during vehicle filling operations. Exhaust after-treatment strategies, such as three-way oxidation catalysts and selective catalytic reduction, used for diesel and natural gas powered vehicles, have been reported to produce emissions of nitrous oxide (N_2O), nitrogen dioxide (NO_2) and ammonia (NH_3). N_2O has a GWP of 298, over a 100 year period, NO_2 is a toxic inhalant, and NH_3 is being increasingly targeted as a primary component of secondary PM formation, where it can eventually form NH_4NO_3(ammonium nitrate), that has been established as having a direct correlation with premature birth of infants.

Areas of research:

- Heavy-duty vehicle traffic and its influence on air quality
- Type & extent of monitoring required
- **Quantification of BTEX, VOC, GHG, and particulate emissions**
- Natural gas powered vehicles and their effect on emissions

Well Drilling & Completion

What is it – Vertical drilling operations, prior to the horizontal kick-off point, predominantly use air as the drilling fluid for hole cleaning. Horizontal drilling uses "mud", a viscous mixture of water (or oil/synthetic oil), weighting agents, bentonite clay and other salts, inert solids and organic additives to remove cuttings, cool the cutting head, and stabilize and lubricate the bore hole for pipe installation. This mud is recycled, with solids and cutting materials being separated. A variety of components can be included as shavings, including radioactive material. For air drilling operations, these cuttings are directly released at the surface, creating probable air quality issues from the resulting aerosol release. At well completion, some of the extracted gases (methane, ethane, sulfur dioxide and other hydrocarbon compounds found in smaller quantities) may be released to the atmosphere until the well can be connected to the distribution system. Usually this release results from flaring, a controlled combustion of methane and other hydrocarbon compounds. The complex hydrocarbons released may be toxic (BTEX) or ozone precursors (methane, VOCs); sulfur dioxide is a precursor to particulates and acid rain; NOx and CO_2 would be released; and, as mentioned above, methane and ethane are potent greenhouse gases (GHGs). While natural gas combustion processes are generally thought to be more environmentally friendly than most other fossil fuels, releasing fewer GHGs per unit energy generated, the leakage rates associated with gas production and use, particularly at well completion, are highly uncertain. Large leakage rates would essentially negate or even possibly reverse the potential benefit of replacing other fossil fuels with natural gas. In addition, abandoned wells are possible sources of fugitive methane emissions, and could provide inadvertent pathways for methane release from new horizontal well pads, depending upon specific geological formation, fracture zone development, and location of new and abandoned sites.

What are the issues – The diffusion of gas from geologic formations to the well bore, and then up toward the surface, leads to pressures that must be managed. These pressures can be managed via flaring or venting. Likewise, when a well is fractured the gas moves towards the surface. The quantities of gases that are released to the atmosphere during drilling and completion of wells are not well known. Aerosols that include drill cuttings are not well characterized or quantified. Similarly, estimates of the impact of flaring or venting activities are not fully substantiated.

Areas of research:

- Quantification of BTEX, VOC and GHG emissions during drilling and completion of wells
- Understanding leakage/emission rates as a function of drilling and completion practices
- Life cycle analysis of the GHG impact of natural gas drilling vs. other energy sources

Additional research areas discussed at the meeting:

- **Emission factor research by region**
- Impact of aerosol release for air drilling operations

Stationary Emissions

What is it – Industrial equipment used during shale gas development requires fuel. Hydraulic fracturing requires the use of many compressors. Storage of waste fluids and processing of raw waste/gas streams utilizes condensate tanks, mud-gas separators, dehydrators, etc. These industrial practices can also lead to atmospheric emissions that have an impact on local to regional air quality.

What are the issues – During drilling and fracturing the operation of the various internal combustion engines pose similar air quality issues as those discussed for mobile sources. Emissions of BTEX, VOC, GHG, NOx, and particulate matter would constitute probable air quality concerns. Permitting is largely based on fuel consumption per localized unit area. As multiple operations occur in a given region, aggregation of emissions has been targeted as an air quality concern, highlighting the need for revised permitting requirements. Fugitive VOC (and possibly BTYEX) emissions from fuel tanks and wastewaters are also a concern.

Areas of research:
- Industrial equipment operations, BATs, and impacts on air quality
- **Type & extent of monitoring required**
- Wet gas vs. dry gas emissions
- Use of NG/CNG/LNG vehicles/drilling rigs/equipment

Additional research areas discussed at the meeting:
- Potential for silicosis resulting from poorly managed proppant supply
- Emission factor research by region to account for aggregation

Gas Processing & Distribution

What is it – Shale gas is not always ready for distribution and consumption directly from the well. It often needs to be processed prior to distribution. Along the way it is transported through collection pipelines, processed, and ultimately delivered to market through distribution pipelines.

What are the issues – Pipelines are not always air-tight. Compressor stations are needed along the way to maintain pressure in the line. These facilities and pipelines can emit methane, and the internal combustion engines used for compression produce emissions that are probable concerns for air quality (similar to stationary and mobile source concerns above). Processing may lead to the emission of more complex hydrocarbons (VOCs). These emissions lead to the same climate change and regional air quality concerns raised above.

Areas of research:
- Quantification of BTEX, VOC and GHG emissions during gas processing and distribution
- **Understanding of leakage/emission rates as a function of processing and distribution practices and facilities**
- Leak detection technologies
- Life cycle analysis of the GHG impact of natural gas drilling vs. other energy sources

Cumulative Impacts, the Role of Policy, Etc. (Same for both water and air issues)

What is it – Cumulative impacts are the result of a combination of activities – those related and unrelated to shale gas development – that occur over time and across space. Policy is important in shaping industry activity, providing infrastructure, and guiding planning processes.

What are the issues – Cumulative impacts are difficult to predict. Rapid growth of shale gas development in the Marcellus and its impacts on a wide range of environmental and social systems indicates that complex interactions and effects should be expected. Policy is worth examination, as it is often the tool by which society attempts to manage, mitigate or prevent environmental impacts. Even when those impacts are well understood, effective policy may still be a challenge.

Areas of research:
- **Cumulative impact assessment frameworks**
- Effective regulations at various governmental levels

Additional research areas discussed at the meeting:
- Creating policy that acknowledges local actions that have regional impacts
- Evaluate policies for ability to capture relevant emissions
- Ensure that policies based on theoretical emissions are appropriate for current practices & technologies

A Sample of Resources Associated with Group Attendees

Creek Connections
http://creekconnections.allegheny.edu/
- Watershed outreach & research in Northwest PA

DOE NETL Regional University Alliance
http://www.netl.doe.gov/rua/index.html
- Applied research collaboration with a focus on fossil fuels

The Institute for Energy & Environmental Research for Northeastern Pennsylvania
http://energy.wilkes.edu/pages/1.asp
- Marcellus Shale information clearinghouse

Marcellus Center for Outreach & Research at Penn State University
http://www.marcellus.psu.edu/
- Research and Information on Marcellus Shale with a PA focus

NY State Water Resources Institute at Cornell University
http://wri.eas.cornell.edu/
- Research and Information on water resource impacts with a NY focus

OSU Subsurface Imaging Group
http://www.geology.ohio-state.edu/~jeff/research1.htm
- Modeling and imaging subsurface features

Paleontological Research Institute & Museum of the Earth
http://www.museumoftheearth.org/outreach.php?page=92387
- Marcellus Shale education outreach

Shale Network
http://www.shalenetwork.org/
- Database of water quality research in the Marcellus region

WVU Center for Alternative Fuels, Engines, and Emissions
http://cafee.wvu.edu/
- Air quality and emission research in transportation and power systems

Selected Annotated Reference List

General Reports & Analyses

Revised Draft Supplemental Generic Environmental Impact Statement (2011) NYSDEC
http://www.dec.ny.gov/energy/75370.html

- A review of shale gas drilling in New York State and a collection of data and consultant-supplied analyses

Addressing the Environmental Risks from Shale Gas Development (2010) Worldwatch Institute
http://www.worldwatch.org/node/6421

- An analysis of environmental risks along with general suggestions for ways to address these risks

How Energy Choices Affect Fresh Water Supplies: A Comparison of US Coal and Natural Gas (2010) Worldwatch Institute
http://www.worldwatch.org/system/files/NGSEI-BriefingPaper2.pdf

- A good lifecycle assessment of water resource impacts associated with coal and natural gas, with a thoughtful discussion

Plan to Study the Potential Impacts of Hydraulic Fracturing on Drinking Water Resources (2011) USEPA
http://water.epa.gov/type/groundwater/uic/class2/hydraulicfracturing/upload/FINAL-STUDY-PLAN-HF_Web_2.pdf

- Review and outline of the approach the EPA will take on their multi-year study of hydraulic fracturing and drinking water; note that environmental/ecological issues will not be covered, except as they pertain to drinking water

Natural Gas Plays in the Marcellus Shale: Challenges & Potential Opportunities (2010) Kargbo, D.M.; Wilhelm, R.G.; Campbell, D.J., *Environ. Sci. & Technol.*
http://pubs.acs.org/doi/abs/10.1021/es903811p

- A feature piece by EPA representatives that reviews some of the challenges and opportunities associated with Marcellus shale gas development

Challenges Facing Developers of the Marcellus Shale in the Appalachian Basin (2010) NETL
http://www.netl.doe.gov/technologies/oil-gas/ReferenceShelf/epfocus.html

- A newsletter containing a snapshot of development, as well as a list and description of research projects currently underway related to Marcellus and water resources issues

Subsurface Water Quality

The Impact of Marcellus Gas Drilling on Rural Drinking Water Supplies (2011) Boyer, et al. The Center for Rural Pennsylvania
http://www.rural.palegislature.us/documents/reports/Marcellus_and_drinking_water_2011_rev.pdf

- A carefully presented study of water quality in drinking water wells in close proximity to shale gas wells in PA

Natural Gases in Ground Water near Tioga Junction, Tioga County, North-Central Pennsylvania – Occurrence and Use of Isotopes to Determine Origins, 2005 (2007) Breen, et. al. *USGS Scientific Investigations Report 2207-5085*
http://pubs.usgs.gov/sir/2007/5085/

- A monitoring study in response to complaints of methane in private water wells in PA; shows the uses of stable isotopes ; also demonstrates limitations and difficulties associated with monitoring

Evaluating system for ground-water contamination hazards due to gas-well drilling on the glaciated Appalachian plateau (1983) Harrison, S.S., *Ground Water*
http://onlinelibrary.wiley.com/doi/10.1111/j.1745-6584.1983.tb01940.x/abstract

- Provides a nice, though somewhat outdated, assessment of gas well drilling related hazards to ground, surface, and well waters using specific knowledge of geology in northwest PA

Contamination of Aquifers by Overpressuring the Annulus of Oil and Gas Wells (1985) Harrison, S.S., *Ground Water*
http://onlinelibrary.wiley.com/doi/10.1111/j.1745-6584.1985.tb00775.x/abstract

- Explains the danger that pressure build up within the well annulus can pose to ground water resources

Evaluation of Well Logs for Determining the Presence of Freshwater, Saltwater, and Gas above the Marcellus Shale in Chemung, Tioga, and Broome Counties, New York (2010) Williams, J., USGS Scientific Investigations Report 2010-5224

- Reviews water and gas well data from various sources, and discusses the need for a more comprehensive and well-managed database on well water quality

Chemical and isotopic tracers of the contribution of microbial gas in Devonian organic-rich shales and reservoir sandstones, northern Appalachian Basin (2010) Osborn & McIntosh. *Appl. Geochem.*

- Gives evidence from both gas and liquid phase analysis for the thermogenic origin of methane in Devonian shales of Appalachia

Surface Water Quality

Trihalomethane Speciation and the Relationship to Elevated Total Dissolved Solid Concentrations Affecting Drinking Water Quality at Systems Utilizing the Monongahela River as a Primary Source During the 3rd and 4th Quarters of 2008 PADEP

- Study of the correlation between DBP formation, TDS, and stream flow in PA during a period of impaired water quality during 2008

Water Withdrawals for Development of Marcellus Shale Gas in Pennsylvania (2010) Abdalla, C.W., *PSU Marcellus Education Fact Sheet UA460*
http://pubs.cas.psu.edu/freepubs/pdfs/ua460.pdf

- An update on water related issues in PA, with a focus on recent changes and remaining challenges

Water & Wastewater Management

Toward Strategic Management of Shale Gas Development: Regional, Collective Impacts on Water Resources (2012) Rahm, B.G.; Riha, S.J., *Environ Sci & Policy*

- An analysis of potential water withdrawal and wastewater treatment issues in southern NY, with an emphasis on the relationship between environmental impacts and regional governance and infrastructure

Evaluating the Acceptability of Gas Well Development and Production-Related Wastewater at New York Wastewater Treatment Plants (2011) New York Water Environment Association
http://nywea.org/gac/HFSCEvaluatingAcceptability.pdf

- Discusses challenges facing wastewater treatment plants in NY and provides recommendations for plant operators and policy makers

Water Management Technologies Used by Marcellus Shale Gas Producers (2010) Veil, J.A., Argonne National Lab
http://www.evs.anl.gov/pub/dsp_detail.cfm?PubID=2537

- Discusses water management in general and provides results on a survey of current practices by operators in PA, as well as information on the capacity of treatment facilities to handle wastewaters

Air Quality - Climate Change

Life-cycle greenhouse gas emissions of shale gas, natural gas, coal, and petroleum (2011) Burnham A, Han J, Clark CE, Wang M, Dunn JB, and Rivera IP, *Environ Sci Technol.*
http://pubs.acs.org/doi/abs/10.1021/es201942m

The greenhouse impact of unconventional gas for electricity generation (2011) Hultman N, Rebois D, Scholten M, and Ramig C., *Environ. Res. Lett.* 6: 044008, doi:10.1088/1748-9326/6/4/044008.
http://iopscience.iop.org/1748-9326/6/4/044008/

Uncertainty in life cycle greenhouse gas emissions from United States natural gas end users and its effects on policy (2011) Venkatesh A, Jaramillo P, Griffin WM, and Matthews HS, *Environ. Sci. Technol.*, 45, 8182-8189.
http://pubs.acs.org/doi/abs/10.1021/es200930h

Life Cycle Greenhouse Gas Emissions of Marcellus Shale Gas (2011) Jiang, M., et al
http://iopscience.iop.org/1748-9326/6/3/034014/

Methane and the greenhouse gas footprint of natural gas from shale formations (2011) Howarth RW, Santoro R, and Ingraffea A, *Climatic Change Letters*, doi: 10.1007/s10584-011-0061-5.
http://www.springerlink.com/content/e384226wr4160653/

A commentary of "The greenhouse-gas footprint of natural gas in shale formations" by RW Howarth, R. Santoro, and A Ingraffea (2012) Cathles LM, Brown L, Taam M, and Hunter A, *Climatic Change*, DOI 10.1007/s10584-011-0333-0.
http://www.springerlink.com/content/x001g12t2332462p/

Substitution of natural gas for coal: climatic effects of utility sector emissions (2002) Hayhoe K, Kheshgi HS, Jain AK, Wuebbles DJ, *Clim Chang* 54:107–139

Greenhouse Gas Emissions Reporting from the Petroleum and Natural Gas Industry (2010) USEPA
http://www.epa.gov/climatechange/emissions/downloads10/Subpart-W_TSD.pdf

- An EPA update of GHG emissions from oil & gas industries, showing dramatically increased estimates for several emission factors, particularly those for unconventional gas well completions and compressor stations

Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2009 (2011) USEPA
http://epa.gov/climatechange/emissions/usinventor-yreport.html

Climate Change – Regulatory Initiatives (2011) USEPA
http://www.epa.gov/climatechange/emissions/ghgrulemaking.html

Air Quality - Other

Regulatory Impact Analysis: Proposed New Source Performance Standards and Amendments to the National Emissions Standards for Hazardous Air Pollutants for the Oil and Gas Industry (2011) USEPA

Oil and natural gas sector: standards of performance for crude oil and natural gas production, transmission, and distribution (2011) USEPA

Proposed Amendments to Air Regulations for the Oil and Gas Industry (2011) USEPA Fact Sheet
http://www.epa.gov/airquality/oilandgas/pdfs/20110728factsheet.pdf

Hydrocarbon Emissions Characterization in the Colorado Front Range – A Pilot Study (2012 – in press) Petron G, et al., *Journal of Geophysical Research*, doi:10.1029/2011JD016360.

Northeastern Pennsylvania Marcellus Shale Short-Term Ambient Air Sampling Report (2011) PADEP
http://www.dep.state.pa.us/dep/deputate/airwaste/aq/aqm/docs/Marcellus_NE_01-12-11.pdf

- Brief, preliminary study of ambient air quality in the vicinity of shale gas operations; evidence for elevated levels of some VOC's, though no exceedance of health standards found

Southwestern Pennsylvania Marcellus Shale Short-Term Ambient Air Sampling Report (2010) PADEP
http://www.dep.state.pa.us/dep/deputate/airwaste/aq/aqm/docs/Marcellus_SW_11-01-10.pdf

Legal Information, Government Regulations, and Industry Guidelines

HVHF Proposed Regulations (New York) (2011) NYSDEC
http://www.dec.ny.gov/regulations/77353.html

Hydraulic Fracturing and Safe Drinking Water Act Issues (2011) Tiemann & Vann, Congressional Research Service
http://www.arcticgas.gov/node/529

- Discusses the evolution of policy and legal precedence regarding the coverage of hydraulic fracturing under major federal legislation

Notice of Final Rulemaking: Wastewater Treatment Requirements (2010) 25 PA Code 95
http://www.pacode.com/secure/data/025/chapter95/s95.10.html

- Revised rules in PA limiting the effluent concentrations of various substances in shale gas wastewater discharges

Reasonable & Prudent Practices for Stabilization (RAPPS) of Oil & Gas Construction Sites (2009) IPAA
http://www.ipaa.org/news/docs/RAPPS_Guidance_Document_10-6-9.pdf

- Guidance based on USDA RUSLE2 model providing decision trees and BMP lists for stormwater and erosion control

Hydraulic Fracturing Operations - Well Construction & Integrity Guidelines (2009) API HF1
http://www.api.org/Standards/epstandards/index.cfm

Water Management Associated with Hydraulic Fracturing (2010) API HF2
http://www.api.org/Standards/epstandards/index.cfm

Data & Information Sources

New York State Department of Environmental Conservation
http://www.dec.ny.gov/energy/205.html

Pennsylvania Department of Environmental Protection
http://www.dep.state.pa.us/dep/deputate/minres/oilgas/reports.htm

Susquehanna River Basin Commission
http://www.srbc.net/wrp/

Delaware River Basin Commission
http://www.state.nj.us/drbc/

FracFocus
http://fracfocus.org/

Environmentally Friendly Drilling Systems
http://www.efdsystems.org/

Intermountain Oil & Gas BMP Project
http://www.oilandgasbmps.org/resources/gis.php#gis