Anthony R. Ingraffea, Ph.D., P. E.
Consulting Engineer

Expert Report

by
Anthony R. Ingraffea, Ph.D., P.E.

In the matter of:

Substantive Validity Challenge to Penn Township Zoning Ordinance, *Protect PT v. Penn Township Zoning Hearing Board v. Huntley & Huntley Energy Exploration, LLC and Apex Energy (PA), LLC*, Case No. 3499 of 2017, Westmoreland County Court of Common Pleas

Prepared for
Hamilton Law, LLC
PO Box 40257
Pittsburgh, PA 15201

October 20, 2017

1.0 Personal Background

I am the Dwight C. Baum Professor of Civil and Environmental Engineering, Emeritus, at Cornell University. I hold a PhD in Civil Engineering from the University of Colorado, Boulder, an MS in Civil Engineering from the New York University Polytechnic School of Engineering, and a BS in Aerospace Engineering from the University of Notre Dame. I am a licensed Professional Engineer in the states of Texas, Colorado, and New York.

I have expertise in rock mechanics, rock fracture, hydraulic fracturing for well stimulation, design of high pressure gas pipelines, computational mechanics, experimental rock mechanics, oil/gas well drilling and cementing, and oil/gas well integrity. During the period from 1977-2004, I performed paid consultancy and sponsored research for the oil/gas industry and the federal government, including EXXON, Amoco, Schlumberger, the Gas Technology Institute, the New York Gas Group, and the U.S. Department of Energy.

I have published more than 315 technical journal articles, proceedings papers, and reports during my career. I have written 5 book chapters on computational and experimental geomechanics and hydraulic fracturing. Since 2006, I have been the Co-Editor-in-Chief of *Engineering Fracture Mechanics*, the premier journal in the field of fracture mechanics, which publishes many papers on hydraulic fracturing and rock fracture mechanics. I have won the highest American honor for fracture mechanics, the George Irwin Medal of the American Society for Testing and materials:

> "The award, given by ASTM Committee E08 on Fatigue and Fracture, honors Ingraffea's pioneering and outstanding contributions to the advanced computational simulation of fatigue and fracture processes and the resulting improved understanding necessary for practical applications of fracture mechanics to the assessment of integrity in engineering structures."

I have also twice (1978, 1991) won the National Research Council/U.S. National Committee for Rock Mechanics award for outstanding research in rock mechanics, the latter specifically for research into hydraulic fracturing.

My professional résumé is attached as Appendix A. My deposition and trial testimony is summarized in Appendix B. Selected references are attached as Appendix C.

2.0 Retention

In July 2017, I was retained by Fair Shake Environmental Legal Services to provide expert consulting services in this matter (NOTE: Case assigned to Hamilton Law, LLC on September 28, 2017). I was asked to review and analyze the following materials relevant to this issue:

- Notice of Substantive Validity Challenge to the Penn Township Zoning Ordinance Number 912-2016 Chapter 190, including the Mineral Extraction Overlay District, as amended and adopted on September 19, 2016
- Penn Township Mineral Extraction Overlay District Map 08.2016

I have been asked to provide:

- Written opinions concerning the processes, equipment, and timelines typically utilized in developing an unconventional natural gas well pad in the Marcellus Shale regions of southwestern Pennsylvania.
- Live testimony based on the written expert opinion provided to Fair Shake on a date to be determined, with advance confirmation of availability from Expert. Such testimony will be given during a hearing conducted by the Westmoreland County Court of Common Pleas at 2 North Main Street, Greensburg, PA 15601.

3.0 Opinions

This matter involves an amendment to a Penn Township Zoning Ordinance that would permit development of hydrocarbon fluids from shale wells in the entire Rural Resource District and the entire Industrial Commerce District of Penn Township.

On the basis of the following discussions in this report, the documents and publications I reviewed, my education, experience, and training, I provide my opinions as follows. I reserve the right to prepare additional reports should additional information become available as this matter proceeds.

OPINION 1:

To a reasonable degree of engineering certainty, I conclude that unconventional development of hydrocarbon liquids and gases from the Marcellus formation beneath Penn Township is a heavy industrial activity.

OPINION 2:

To a reasonable degree of scientific certainty, I conclude that unconventional development of hydrocarbon liquids and gases from the Marcellus formation beneath Penn Township would cause undesirable impacts on public health and the environment in the Rural Resource District.

4.0 Unconventional Shale Gas Development Is a Heavy Industry: Root Cause

There is a root cause for why the unconventional development of shale gas is a heavy industry: ultra-low permeability of shale rock. Unlike conventional mineral formations containing natural gas, shale rock has permeability, the ability for fluids to move through the rock, of typically less than 10 nano-darcies (Sakhaee-Pour and Bryant, 2012). This is about a thousand times less permeable than gas-bearing sandstones. If shale is so stingy with its hydrocarbons, how can they be produced?

Although some shale formations contain large amounts of shale gas and other hydrocarbons trapped in the *shale rock* itself, such formations can be made to produce these hydrocarbons if they have migrated into naturally existing cracks, joints, bedding planes and faults, discontinuities, in the *shale rock mass*. For example, Figure 1 shows a surface exposure of a shale rock formation. Note the many such discontinuities in the rock mass. Over many millions of years, the hydrocarbons actually being produced in the shale though bio-thermo-mechanical processes can migrate from within the shale rock and occupy these discontinuities. This process and its timeline are depicted in Figure 2.

Figure 1. A surface exposure of a typical naturally fractured shale rock mass.

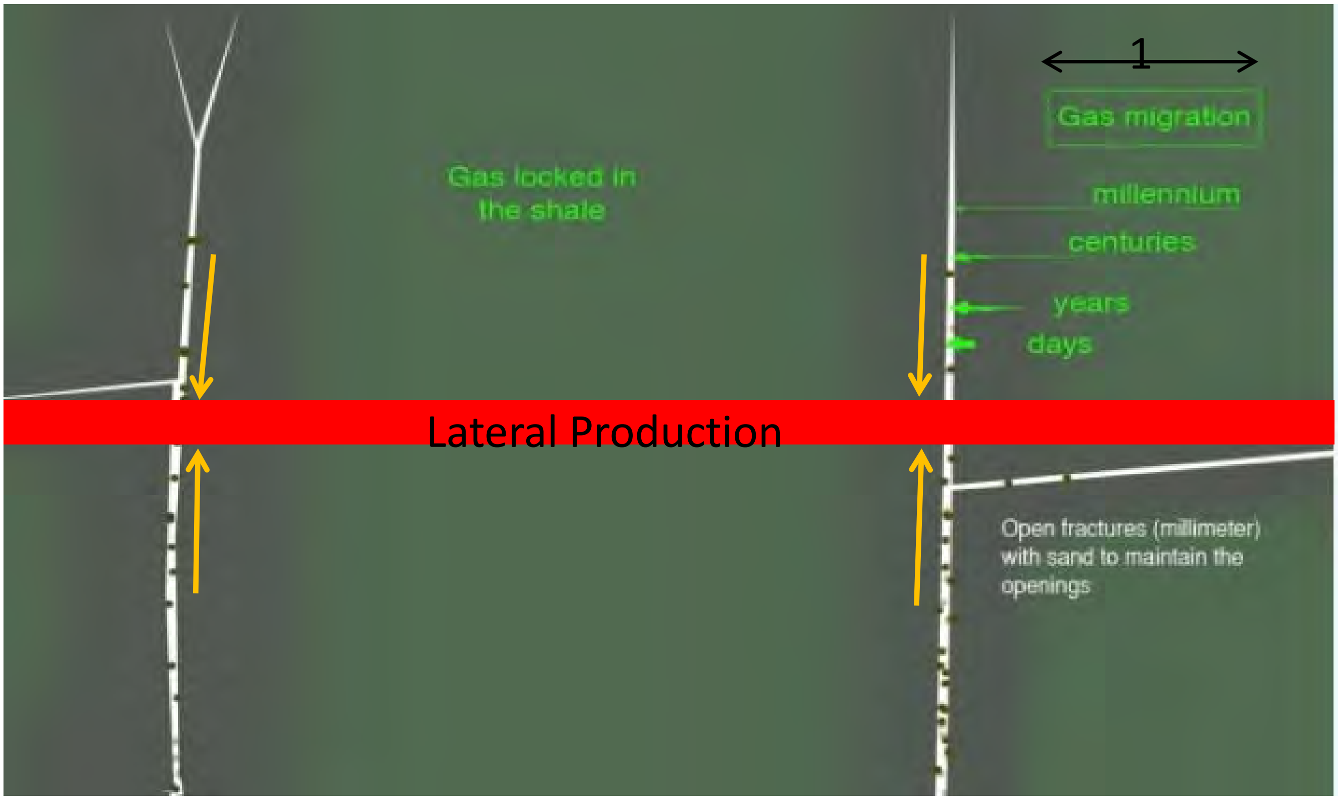

Figure 2. Depiction of how gas can be accessed in a shale rock mass through migration. Courtesy of Prof. Marc Durand.

To extract natural gas and other hydrocarbons trapped in the shale, unconventional, heavy industrial methods, in this instance vertical/horizontal drilling, clustered multi-well pads, and high- volume "hydraulic fracturing", must be employed to access as many of the discontinuities in the shale rock mass so that gas and oil will flow from the rock mass to the well. It is a misnomer to use "hydraulic fracturing" as a description of this process, since little actual new fracturing is done. Rather, the purpose of "hydraulic fracturing" in this instance is merely to widen, interconnect, and prop open as many pre-existing discontinuities as feasible.

Proof that shale wells initially access the readily available hydrocarbons stored in the natural discontinuities, and then quickly decline in production as implied by Figure 2, is shown in Figure 3. Such steep declines require that many wells be continuously developed to maintain contracted supplies of the targeted hydrocarbon. This overall approach which accounts for near-impermeability and the need to access as many natural discontinuities as feasible, is depicted

in Figure 4. This figure shows a clustered, multi-well pad arrangement of wells with both vertical and lateral segments, and closely spaced long laterals stimulated by high-volumes of injected fluid and proppant.

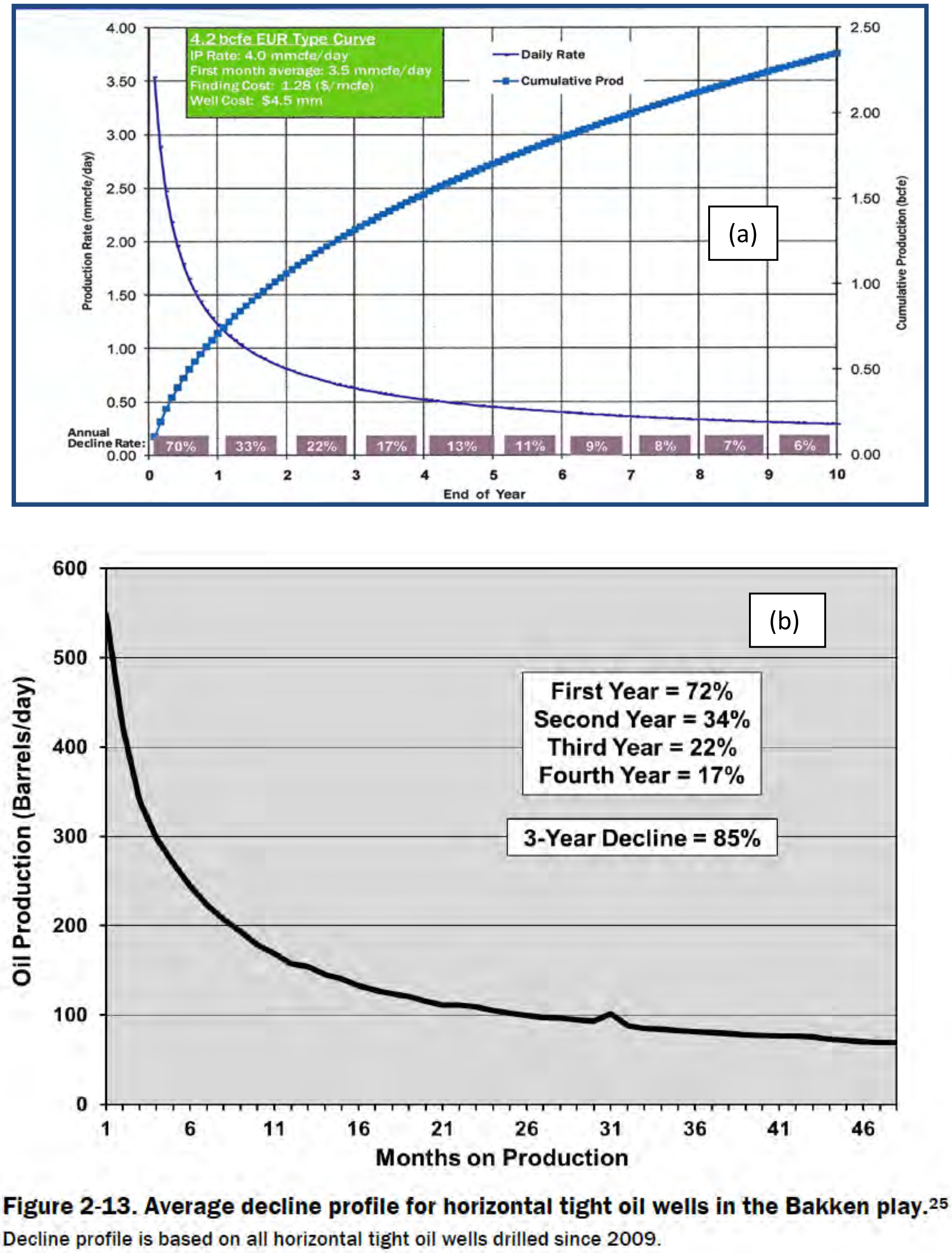

Figure 3. (a) Typical decline curve for shale gas. From: Chesapeake Energy (CHK) published pro forma data. (b) Typical decline curve for shale oil. Data from DRILLING INFO; Hughes, http://shalebubble.org/drilling-deeper/

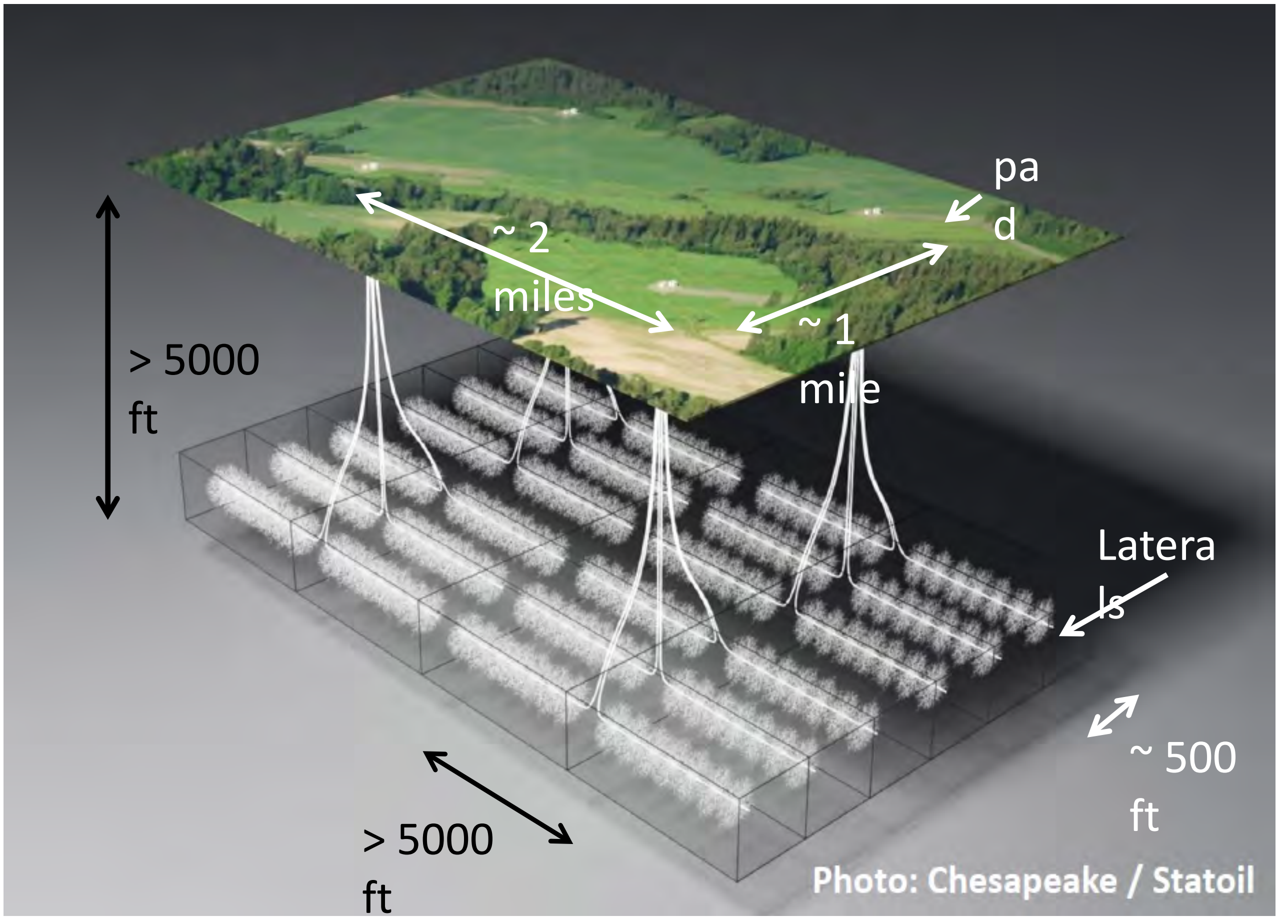

Figure 4. Depiction of overall shale hydrocarbon development approach. (Not to Scale)

In effect, getting hydrocarbons out of a shale formation requires a massive "scaling-up" of industrial operations: more wells, longer wells, more stimulation fluids, more solid and liquid waste, more traffic, more attendant infrastructure, and longer timelines. As will be described in the next section, this "state-of-the-practice" approach requires a myriad of operations typical of heavy industry.

5.0 Unconventional Shale Gas Development Is a Heavy Industry: Operations Typical of a Heavy Industry

The process of producing natural gas from shale involves a series of operations before and after stimulation, "hydraulic fracturing", all of which are industrial in nature, many of which have the potential to impact public health and the environment. The following are the principal operations and some of their associated impacts:

1. The initial phase of shale gas development involves construction of access roads and well pads in an arrangement like that shown in Figure 4. A well pad must provide a stable base for large rigs, trucks, pumps, diesel engines, storage tanks, separation units and other equipment needed to drill, complete and operate the well. The size of a well pad depends on the number of wells that will be put on the pad. Figure 5 shows most recent data on the number of wells per pad in Pennsylvania. Westmoreland County is averaging about 5 wells per pad. Statewide data show a trend towards an ever-increasing number of wells per pad, so one can expect that the numbers shown in Figure 5 are low-end snapshots in time.

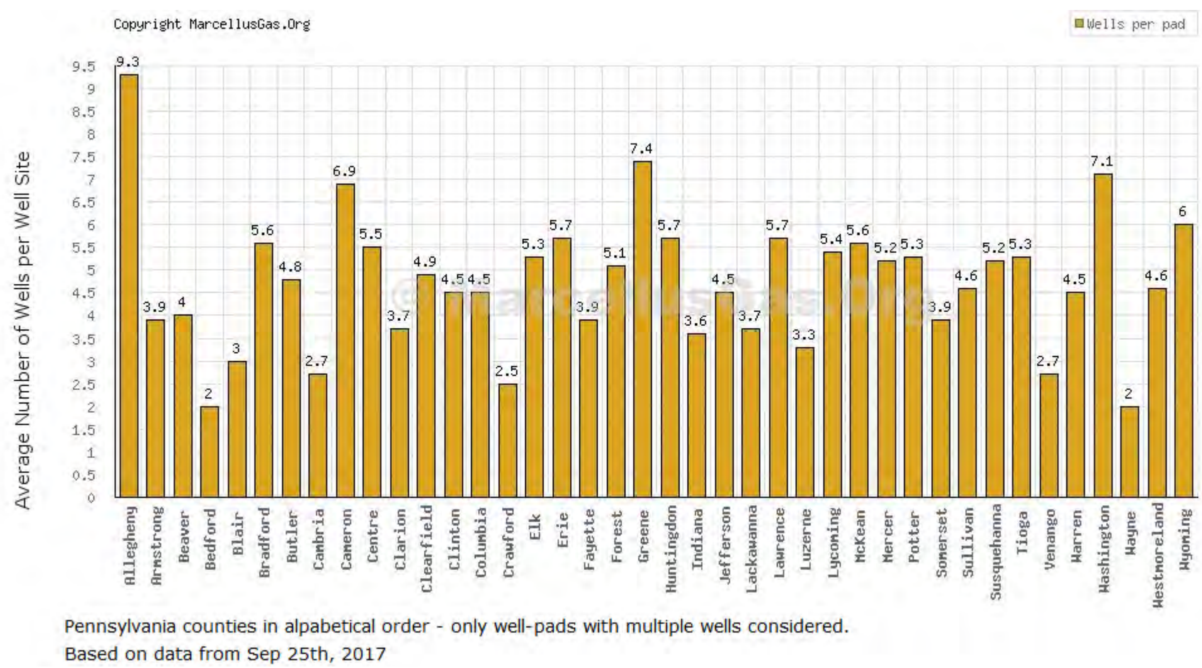

Figure 5. Average number of wells per pad in Pennsylvania by county. Data from https://www.marcellusgas.org/graphs/PA#avgpad

2. Construction of the access road and well pad involves the operation of large, heavy machinery to excavate/backfill, grade and compact the site, transport and place large quantities of gravel on the ground, install an impermeable barrier, and potentially construct a large, lined impoundment for storage of water to be used in hydraulic fracturing. See Figure 6 for examples of pad construction activities. Each well pad, with associated roads and impoundments, consumes about five to fifteen acres of land.

3. Once the site has been prepared, equipment must be transported to the site and unloaded. Before the horizontal drill rig is assembled and powered up, another smaller rig will be brought on site to drill the starter hole and vertical section of the well, anywhere from 5,000 to 9,000 feet in depth. Rigs are transported using specialized heavy trucks. Portions of the vertical well section may be drilled using air, while other portions will be drilled using fluids or mud. The mud may be water-based, oil-based or synthetic based fluids, all of which must be stored on site. Drilling the vertical well produces at least 750 tons of drill cuttings per hole. Depending on the drilling technique and depth of wellbore, the cuttings may contain contaminants such as pyrite, which with air and water generate acid mine drainage, high concentrations of chlorides, and other toxic constituents associated with the drilling mud. Drill cuttings must be processed (solids separated from liquids), stored, transported away from the site by heavy truck, and managed as a residual waste. Figure 6(a) shows a multi-well pad in southwest Pennsylvania during the drilling operation.

4. Thousands of feet of steel pipe, some as drill string others as casing, must be transported, again using heavy trucks, onto the site to drill and line the well. A typical Marcellus shale gas well will need about 20,000 feet of drill string, and 25,000 feet of casing or different diameters.

5. Cementing operations are used on-site to fill the annulus after a casing string has been run, to seal a lost circulation zone, or set a plug before directional tools are used to push off from the vertical section of the well. A cementing crew uses special trucks, mixers and large hydraulic pumps to displace drilling fluids and place cement in the wellbore. Dry materials are ordinarily stored in silos on-site prior to mixing, see Figure 6(A).

6. The large drill rig used to construct the horizontal portion of the wellbore must be transported in pieces to the site and assembled. The horizontal drilling occurs for another 5,000 to 10,000 feet, or more, farther than the vertical portion of the well.

The major components of the rig include mud tanks and pumps, the derrick, drawbacks, the rotary table, the drill string, power generation equipment -large electric, diesel or gas powered engines that drive turbines - and a variety of auxiliary equipment. During drilling of the horizontal section another 750 to 1,000 tons of drill cuttings will be generated, depending on the length of the borehole. Drill cuttings from the horizontal section of the well contain various toxic contaminants, including benzene and naturally occurring radioactive materials such as R-226 and R-228. The drill cuttings must be stored, transported using heavy trucking, and managed as a residual waste.

Figure 6. (A) Typical Marcellus shale gas multi-well pad during drilling operation. (a) Drill rig; (b) Unlit but venting flare stack; (c) Air compressors; (d) Main high-pressure

air line; (e) Flow line; (f) Separator unit; (g) Water tanks. (B) Typical Marcellus shale gas multi-well pad during stimulation operation.

7. Well completion refers to the process of perforating the horizontal portion of the well casing, cement and rock with shaped charges to create communication between the discontinuities in the formation and the wellbore, and stimulation of the reservoir to create high permeability pathways for the gas and oil to flow into the wellbore, as described in Section 4.0, above.

8. Stimulation via "hydraulic fracturing" requires large volumes of liquids – on average 4.5 million gallons per well in Pennsylvania - to be transported to the well pad either by custom-constructed pipeline, or by using 18-wheel, 8,000 gallon tanker trucks. The fracking liquid is pumped down the well under high pressure in order to increase the "effective permeability of the shale rock mass". *The scale-up required for shale gas wells is readily seen when one considers that the volume of stimulating liquid needed is about 100-times more in an unconventional shale gas well than in a typical non-shale well.* Use of all this water and the concomitant large volume of liquid waste-water has documented environmental and health impacts. An exhaustive compilation (currently 35 publications) of the peer-reviewed publications concerning water use and quality impacts from shale development can be found at: https://www.zotero.org/groups/248773/pse_study_citation_database/items/collectionKey/Q7GFAPNU

9. During stimulation, dozens of pump trucks and containers must be brought onto the well pad. The water is mixed with proppant, either sand or ceramic beads, and a suite of chemicals before being injected into the well. The proppant and chemicals must be brought to, and stored on, the well pad. *Typically, about 1,000 pounds of proppant are used for each 1 foot of stimulated lateral.* Therefore a typical Marcellus well with a 5,000 foot long lateral will require about 2,500 tons of proppant to be transported to each well. On a 5-well pad, that would be about 12,500 tons of proppant delivered by truck. Figure 6(B) shows a multi-well pad in southwest Pennsylvania during the stimulation operation.

10. Once stimulation is completed, the internal pressure of the rock formation causes fluid to return to the surface through the wellbore, which is known as "flowback" or "produced water." This cleans the well bore and formation of debris and stimulation fluid. The flowback contains the injected chemicals and naturally occurring materials, including brines, metals, hydrocarbons and radionuclides. Additional equipment such as separators, sand traps and tanks are used to capture and process the gas and condensate. The flowback, typically a few million gallons, must be initially stored on-site and then taken off-site using heavy 18-wheel, 8,000-gallon tanker trucks for management as a residual waste.

11. When drilling and completion are complete, drilling and stimulation equipment is removed from the site. There remains equipment needed for production such as separator units and condensate tanks, both of which emit GHG’s. Maintenance vehicles must visit the site, and drill rigs will return to add new wells to the pad, or to re-fracture existing wells. The existing wells must be tied into pipelines and other infrastructure to convey the gas to market. This infrastructure includes compressor stations, processing plants, and heavy equipment depots. These all require additional land use, and compressor stations and processing plants are point-source emitters of air/noise/light pollution.

12. Shale gas development causes noise pollution for persons residing near the well and along the truck routes that service the well pad. The most intensive noise from well pads will last about a month per well, and will recur when new wells are added, or when wells are reworked. The increased truck traffic associated with well development will impact residents throughout the township. Increased noise pollution can contribute to stress and result in physical effects associated with excess stress such as annoyance, irritation, fatigue, headache, unease, and disturbed sleep.

A number of recent peer-reviewed papers have addressed the issue of noise from shale gas development activities. Figure 7, taken from Hays *et al.* (2017), depicts the potential non-auditory health outcomes of environmental noise exposure.

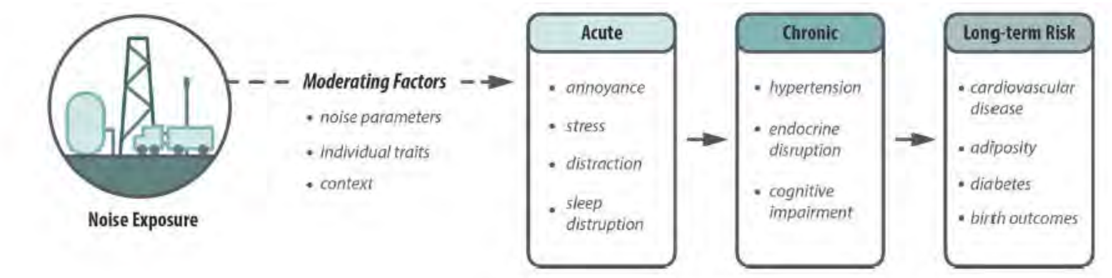

Figure 7. Potential non-auditory health outcomes of environmental noise exposure. This figure is adapted from Shepherd *et al.* (2010) and depicts the relationships between exposure to noise and primary and secondary health effects. Non-physical effects of noise are also mediated by psychological and psycho-physiological processes (Shepherd *et al.*, 2010). The dashed lines indicate the physical effects of noise and the solid lines indicate the non-physical effects. Annoyance and sleep disturbance act as mediators between predisposing factors and secondary health effects, such as quality of life or cardiovascular disease.

Hays *et al*. evaluate the available literature specific to noise from unconventional oil/gas development (UOGD) and conclude the following:

> "…both the nature and duration of noise are relevant to potential health outcomes. Many of the noise levels associated with UOGD are transient in nature and only occur during certain development activities. For instance, some activities, such as well pad preparation, drilling, and hydraulic fracturing will only be encountered prior to the completion of a well. Certain adverse health outcomes usually only result from long-term noise exposure and may be less of a concern with most development activities. On the other hand, some sources, such as compressor stations, produce chronic noise that will continue for years after wells are put out of production. *Although noise levels may fall under municipal and industrial noise limits, data indicate these limits may not be low enough to protect public health."*

13. Shale gas development causes air pollution of various types from many sources. Development of a shale gas well typically requires 1,000 to 1,500 heavy diesel truck trips per well installed, which damages roads, and impacts the health of residents, especially in highly populated areas. Trucks typically run on diesel engines, as do the

engines that provide electricity to the drill rig and other auxiliary equipment. Diesel-powered vehicles and equipment account for nearly half of all nitrogen oxides (NOx) and more than two-thirds of all particulate matter (PM) emissions from United States transportation sources. PM is comprised of hundreds of chemical elements, including sulfates, ammonium, nitrates, elemental carbon, condensed organic compounds, and carcinogenic compounds and heavy metals such as arsenic, selenium, cadmium and zinc.

A recent peer-reviewed journal article (Anirban and Adams, 2016) evaluated air pollution impacts form shale gas development in Pennsylvania, both retrospectively and prospectively. Its approach and principal findings were (***emphases mine***):

> "This paper describes an air emissions inventory for the development, production, and processing of natural gas in the Marcellus Shale region for 2009 and 2020. It includes estimates of the emissions of oxides of nitrogen (NOx), volatile organic compounds (VOCs), and primary fine particulate matter (≤2.5 μm aerodynamic diameter; PM2.5) from major activities such as drilling, hydraulic fracturing, compressor stations, and completion venting. The inventory is constructed using a process-level approach; a Monte Carlo analysis is used to explicitly account for the uncertainty. Emissions were estimated for 2009 and projected to 2020, accounting for the effects of existing and potential additional regulations***. In 2020, Marcellus activities are predicted to contribute 6–18% (95% confidence interval) of the NOx emissions in the Marcellus region, with an average contribution of 12% (129 tons/day). In 2020, the predicted contribution of Marcellus activities to the regional anthropogenic VOC emissions ranged between 7% and 28% (95% confidence interval), with an average contribution of 12% (100 tons/day).*** …The development and production of this gas may emit substantial amounts of oxides of nitrogen and volatile organic compounds. These emissions may have special significance because Marcellus development is occurring close to areas that have been designated nonattainment for the ozone standard. Control technologies exist to substantially reduce these impacts. PM2.5 emissions are predicted to be negligible in a regional context, but ***elemental***

carbon emissions from diesel powered equipment may be important."

Particulate matter irritates the eyes, nose, throat, and lungs, contributing to respiratory and cardiovascular illnesses and even premature death. Diesel exhaust has been classified a potential human carcinogen by the U.S. Environmental Protection Agency (EPA) and the International Agency for Research on Cancer. Diesel emissions of nitrogen oxides contribute to the formation of ground level ozone, which irritates the respiratory system, causing coughing, choking, and reduced lung capacity. An exhaustive compilation (currently 93 publications) of the peer-reviewed publications concerning air pollution from shale and tight gas development can be found at: https://www.zotero.org/groups/248773/pse_study_citation_database/items/collectionKey/FX6WTII3

14. Shale gas development causes light pollution, see Figure 8. As with excess noise, the constant illumination of shale gas pads can contribute to stress among those living in areas exposed to constant artificial light from the well pad.

15. Increased heavy traffic caused by shale gas development will have both local and cumulative impacts because of the multiple projects that will be ongoing in the zoned districts, all of which will contribute to traffic due to construction, drilling, transport of wastewater, transport associated with hydraulic fracturing, as well as an overlap of development phases on different well pads.

16. Shale gas development may cause surface and groundwater contamination. Numerous polluting substances are transported to and from well pads, stored on well pads, and used in association with shale gas development. The mismanagement of these substances would result in surface or groundwater contamination from spills, leaks or accidents. To date, the Pennsylvania Department of Environmental Protection (PADEP) has received over 4,000 formal complaints concerning potential water impacts from shale gas development in the state. In the last year, the PADEP

has received about one new complaint for each new shale gas well drilled in the state (PublicHerald, 2017). The PADEP has determined that, to date, 293 incidents have been proven to be attributed to shale gas development (PADEP, 2017). An exhaustive compilation (currently 184 publications) of the peer-reviewed publications concerning water pollution from shale and tight gas development can be found at: https://www.zotero.org/groups/248773/pse_study_citation_database/items/collectionKey/DCS54HV7

Figure 8. Flaring at night near a home in southwest Pennsylvania.

17. Faulty well construction, such as a bad cement job, can cause groundwater contamination that will affect private water wells, such as that experienced by the residents of Dimock, Pennsylvania. In a comprehensive evaluation of PADEP inspection and violations records for over 41,000 gas and oil wells drilled between 2000 and 2012, Ingraffea et al. (2014) found that risk of faulty well construction was about 50% higher in unconventional wells. They also found that loss of well integrity occurred in over 6% of the unconventional wells developed in the state during that time period.

18. In addition to well-pads, compressor stations and natural gas processing stations are major industrial operations needed to accompany shale hydrocarbon development. Figure 9 shows a typical compressor station and a typical processing plant operating in southwest Pennsylvania. Air, noise, and light pollution and their impacts on human health accompany the continuous operation of such infrastructure.

Compressor stations consist of large reciprocating engines, operating at thousands of horsepower, which compress gas in order to transport it through transmission pipelines. Compressor station engines emit nitrogen oxides, volatile organic compounds, particulate matter, carbon monoxide, and other pollutants. When vented, compressor stations emit volatile organic compounds and methane.

Gas processing plants separate natural gas from other longer-chained hydrocarbons and contaminants produced from shale gas wells so that the natural gas complies with pipeline specifications, and the higher order hydrocarbons can be marketed. Processing plants may include fractionators and de-ethanators. Shale gas processing emits greenhouse gases, as well as toxic air pollutants such as benzene, formaldehyde and hexane. Shale gas wells, compressor stations, and processing facilities have a greater impact on more vulnerable populations, such as school-aged children. Air pollutants from all forms of shale gas development may interfere with brain development of children and more easily accumulate in their bodies as children cannot metabolize toxins at the same rate as adults. Pollutants and impacts from shale gas development may also lead to an increased rate of development of asthma and other respiratory diseases in children. An exhaustive compilation (currently 120 publications) of the peer-reviewed publications concerning human health impacts from shale and tight gas development can be found at: https://www.zotero.org/groups/248773/pse_study_citation_database/items/collectionKey/FX6WTII3

Unlike the noise and light emissions from pads, air pollution from compressor stations and processing plants are continuous for as long as such are in operation. Planned and un-planned "blowdowns" and "burnoffs" from such facilities can be dramatic and require emergency evacuations from residences near these heavy industrial sites, Figure 10.

Figure 9. (a) Three Brothers Compressor station in Smith Township. Lat 40;19;40.698. Long 80;23;25.236 (b) New processing plant under construction in Smith Township. Lat 40;25;3.402. Long 80;20;44.951 Photos courtesy of Bob Donnan.

Figure 10. (a) Burnoff at Mark West processing plant, Houston, Pa. Photo courtesy of Bob Donnan. (b) Blowdown at Teel compressor station, Dimock, Pa. Video courtesy of Ron Teel.

6.0 Conclusion

Unconventional development of shale hydrocarbons, anywhere in the world, is a heavy industry that should not be permitted in areas like Penn Township's Rural Resource District which is designated as primarily a residential community. As described herein, such development has all the characteristics of a heavy industry. Moreover, the impacts to human health and the environment, which have now been thoroughly documented in over 1,200 peer-reviewed publications, are occurring precisely because this industry has been free to operate outside of industrial zones.

7.0 REFERENCES (enclosed as Appendix C)

Anirban R, Adams P, Robinson A. Air pollutant emissions from the development, production, and processing of Marcellus Shale natural gas. *J. Air & Waste Management Association*, 64, 2016.

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Sakhaee-Pour A, Bryant S. Gas Permeability of Shale. *SPE Reservoir Evaluation & Engineering 15(04),* August, 2012.

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Shepherd D, Welch D, Dirks KN, Mathews. Exploring the relationship between noise sensitivity, annoyance and health-related quality of life in a sample of adults exposed to environmental noise. *Int. J. Environ. Res. Public Health* 7, 3579–3594, 2010.

Hays J, McCawley M, Shonkoff S. Public health implications of environmental noise associated with unconventional oil and gas development. *Science of the Total Environment*, 580 (2017) 448–456.

APPENDICES

APPENDIX A – CURRICULUM VITAE

Anthony R. Ingraffea

Dwight C. Baum Professor of Engineering Emeritus

Weiss Presidential Teaching Fellow

School of Civil and Environmental Engineering

Cornell University

Ithaca, N.Y. 14853 USA

GENERAL

Born: April 4, 1947, Easton, Pennsylvania, USA

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EDUCATION

University of Notre Dame

B.S., Aerospace Engineering, *Magna Cum Laude*, June 1969.

Polytechnic Institute of New York

M.S., Civil Engineering, Grumman Masters Fellow, June 1971.

University of Colorado/Boulder

Ph.D., Civil Engineering, May 1977, University Fellow, 1974-1976.

AREAS OF EXPERTISE

Computational and Experimental Fracture Mechanics, Structural Engineering, Structural Mechanics, Microstructural Simulation of Fatigue and Fracture Mechanisms, Rock Mechanics, Numerical Methods, Engineering Education

PROFESSIONAL EXPERIENCE

June 1969 - June 1971

Grumman Aerospace Corporation. Bethpage, L.I., N.Y.

Rotating traineeship in the following areas: preliminary design on Navy F - 14; loads and dynamic studies, stress analysis, and final design on NASA Space Shuttle proposal. Two in - house technical publications.

July 1971 - June 1973

Peace Corps. Bejuma, Venezuela

County Engineer. Responsible for all technical services to a county of 40,000 people. Directed surveying, design, and construction of farmers' market, tourist hotel, and cemetery. Directed urban planning resource study. Co - directed urban renewal plan and data collection for section of state capital city.

September 1973 - August 1977

University of Colorado/Boulder

Department of Civil, Environmental and Architectural Engineering

Instructor, **Teaching Assistant**, **Research Assistant**

September 1977 - June 1982

Cornell University, Department of Structural Engineering

Assistant Professor

September 1979 - July 1983

Cornell University, Department of Structural Engineering

Manager of Experimental Research

July 1982 - June 1987

Cornell University, Department of Structural Engineering

Associate Professor

August 1983 - August 1984

Lawrence Livermore National Laboratory Livermore, California

Visiting Research Engineer: Hydraulic Fracture Simulation

January 1986 - September, 1986

Cornell University, Computer Aided Design Instructional Facility,

College of Engineering

Director

September 1986 - October, 1990

Cornell University, College of Engineering

Faculty Coordinator for Instructional Computing

July 1987 - Present

Cornell University, School of Civil and Environmental Engineering

Professor

September 1987 - April 1992

Cornell University, Program of Computer Graphics

Associate Director

September 1988 - Present

Fracture Analysis Consultants, Inc.

President

October 1990 - October 1994

Cornell University

Director, **NSF-Synthesis National Engineering Education Coalition**

July 1993 - Present

Cornell University

Dwight C. Baum Professor of Engineering

October 1994 - October 1995

Cornell University

Associate Director, **NSF-Synthesis National Engineering Education Coalition**

December 1997 –August 2005

Cornell Center for Theory and Simulation in Science and Engineering

Associate Director

Coordinator, Computational Materials Institute

July 1998 – December 1999

Cornell University

Coordinator, Infrastructure Group, School of Civil and Environmental Engineering

November 2002-Present

Cornell University

Member, Graduate Fields of Mechanical and Aerospace Engineering

May 2004-May 2014

Wright Patterson Air Force Base/AFRL/Air Vehicle Directorate/Structures Division

Structural Sciences Center of Excellence

Visiting Scientist

August 2005 – July 2007

Cornell University

Acting Director, Cornell Center for Theory and Simulation in Science and Engineering

November 2005 – Present

Cornell University

Weiss Presidential Fellow

July 2006 – December 2007

Cornell University

Coordinator, Infrastructure Group, School of Civil and Environmental Engineering

August 2005 – Present

Engineering Fracture Mechanics

Co-Editor-in-Chief

August 2010 – Present

Physicians, Scientists, and Engineers for Sustainable and Healthy Energy, Inc.

www.psehealthyenergy.org

President (2010-2014), Treasurer (2014-2015), Senior Fellow (2015-)

August 2011 – Present

EARTHWORKS

www.earthworksaction.org

Member of the Board of Directors

AWARDS AND HONORS

National

• One of **TIME Magazine's "People That Mattered"** in 2011.

http://www.time.com/time/specials/packages/article/0,28804,2101745_2102309_2102323,00.html

"Anthony Ingraffea is an engineer at Cornell University who is willing to go anywhere to talk to audiences about the geologic risks of fracking, raising questions about the threats that shale gas drilling could pose to water supplies."

- **Fellow, American Society of Civil Engineers**, 1991

- **Presidential Young Investigator Award**, National Science Foundation, 1984 - 1989

Research

- National Research Council/U.S. National Committee for Rock Mechanics **1978 Award for Outstanding Research in Rock Mechanics at the Doctoral Level**

- National Research Council/U. S. National Committee for Rock Mechanics **1991 Award for Applied Research** for the paper, "Simulation of Hydraulic Fracture Propagation in Poroelastic Rock with Application to Stress Measurement Techniques", co-authored by T. J. Boone, *Int. J. Rock Mech. Min. Sci. & Geomech. Abstr.*, 28, 1, 1-14, 1991.

- International Association for Computer Methods and Advances in Geomechanics **1994 Significant Paper Award**: One of Five Significant Papers in the category of Computational/Analytical Applications in the past 20 years, "A Numerical Procedure for Simulation of Hydraulically-driven Fracture Propagation in Poroelastic Media", co-authored with T. J. Boone, *Int. J. Num. Analyt. Meth. in Geomech.,* 14, 1, 1990.

- The **NASA Group Achievement Award** for contributions, with former students Drs. Paul Wawrzynek and David Potyondy, to the Fuselage Structural Integrity Analysis Team, NASA Langley Research Center, 1996.

- **Aviation Safety Turning Goals into Reality Award**, NASA Airframe Structural Integrity Program Team, NASA Langley Research Center, with Dr. Paul Wawrzynek, 1999.

- **George R. Irwin Medal**, American Society for Testing and Materials, 2006.

  "The award, given by ASTM Committee E08 on Fatigue and Fracture, honors Ingraffea's pioneering and outstanding contributions to the advanced computational simulation of fatigue and fracture processes and the resulting improved understanding necessary for practical applications of fracture mechanics to the assessment of integrity in engineering structures."

- **Fellow, International Congress on Fracture,** 2009.

Teaching

- Cornell College of Engineering "**Professor of the Year**," 1978 - 79

- Cornell School of Civil Engineering "**Professor of the Year**," 1981 - 82

- **Dean's Prize for Innovation in Teaching**, Cornell College of Engineering, 1989.

- **Dean's Prize for Innovation in Teaching**, Cornell College of Engineering, 1991.

- The First **Society of Women Engineer's Professor of the Year Award**, Cornell College of Engineering, 1997.

- **J. P. and Mary Barger '50 Excellence in Teaching Award**, Cornell College of Engineering, 1997.

- **Daniel Luzar '29 Excellence in Teaching Award**, Cornell College of Engineering, 2001.

• **Weiss Presidential Teaching Fellow,** Cornell University, 2005.

Academic

• **3 - M Corporation Scholarship**, 1965 - 1969

• **Grumman Masters Fellowship**, 1969 - 1971

• University of Colorado **Graduate Fellowships**, 1974 - 1976

• The **MTS Visiting Professor Chair**, Department of Civil Engineering, University of Minnesota, 1998.

• **Honor Award, University of Notre Dame,** College of Engineering, for "Significant Contributions to the Advancement of Engineering", 2002.

Outreach

• **1999 Premier Award for Educational Software** for "Cracking Dams-HTTP://www.simscience.org", with Megann Polaha

• **Richard J. Almeida Award, Project High Jump,** given each year to an individual whose dedication and contribution to High Jump have been extraordinary, 2008. highjumpchicago.org/

HONORARY/PROFESSIONAL SOCIETY MEMBERSHIP

Tau Beta Pi (1967 -

Chi Epsilon (1974 -

Sigma Xi (1977 -

American Academy of Mechanics (1988 -

American Society of Civil Engineers

Chairman, Committee on Properties of Materials (1983 - 1985)

Member, Committee on Finite Element Analysis of Reinforced Concrete

Member, Committee on Computer Applications and Numerical Methods

International Society for Boundary Elements

International Society for Rock Mechanics

Society for Experimental Mechanics

American Society for Testing and Materials

Committee E - 8 on Fracture and Fatigue

Committee D - 18 on Soil and Rock for Engineering Purposes

Committee C - 9 on Concrete

American Concrete Institute

Committee 446 on Fracture Mechanics

RILEM

Committee 90 - FMA on Fracture Mechanics Applications

Member, Committee 89 - FMT on Fracture Mechanics Testing

American Rock Mechanics Association/Foundation

Founding Member

Member of the Board, 1999-2003

PROFESSIONAL REGISTRATION

Colorado	PE No. 14837
New York	PE No. 081309-0
Texas	PE No. 120758
Alaska	Professional Fishing Guide

UNITED STATES PATENT

Number 481,826, Hand - held, direct reading, fully mechanical fracture loading device for short-rod/bar specimens

PROFESSIONAL JOURNAL EDITORSHIPS AND ADVISORY BOARDS

Co-Editor-in-Chief:

Engineering Fracture Mechanics, August, 2005-present

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Boundary Element Communications

Engineering with Computers

Engineering Computations

International Journal for Multiscale Computational Engineering

PUBLICATIONS

TEXTS EDITED

1. **Fracture Mechanics of Concrete: Material Characterization and Testing**, co - edited with A. Carpinteri, Martinus Nijhoff Publishers, 1984.

PUBLISHED IN TEXTS

1. Ingraffea, A R (co - author). Modelling of Reinforcement and Representation of Bond. Chapter 3 in **Finite Element Analysis of Reinforced Concrete,** State - of - the - Art report prepared by the Task Committee on Finite Element Analysis of Reinforced Concrete Structures, Structural Division, ASCE, 1982, pp. 149 - 203.

2. Ingraffea A R (co - author). Concrete Cracking. Chapter 4 in **Finite Element Analysis of Reinforced Concrete**. State-of-the-Art report prepared by the Task Committee on Finite Element Analysis of Reinforced Concrete Structures, Structural Division, ASCE, 1982, pp. 204 - 233.

3. Ingraffea A R. Numerical Modelling of Fracture Propagation. Chapter 4 in **Rock Fracture Mechanics**, H. P. Rossmanith, editor, CISM Courses and lectures No. 275, International Center for Mechanical Sciences, Udine, Italy, Springer - Verlag, Wien - New York, 1983, pp. 151 - 208.

4. Ingraffea A R, Saouma V. Numerical Modeling of Discrete Crack Propagation in Reinforced and Plain Concrete. Chapter 4 in **Application of Fracture Mechanics to Concrete Structures: Structural Application and Numerical Calculation,** G. C. Sih and A. DiTommaso, editors, Martinus Nijhoff Publishers, 1984.

5. Ingraffea A R, Gerstle W. Non - Linear Fracture Models for Discrete Crack Propagation. **Application of Fracture Mechanics to Cementitious Composites,** S. P. Shah, editor, Martinus Nijhoff Publishers, 1985, pp. 171 - 209.

6. Ingraffea A R. Fracture Propagation in Rock. Chapter 12 in **Mechanics of Geomaterials,** Z. P. Bazant, editor, John Wiley & Sons, Limited, 1985.

7. Ingraffea A R. Theory of Crack Initiation and Propagation in Rock. Chapter 3 in **Rock Fracture Mechanics**, B. Atkinson, editor, Academic Press, Inc., 1987.

8. Ingraffea A R, Gerstle W H, Perucchio R. Fracture Analysis with Interactive Computer Graphics. **Boundary Element Methods in Structural Analysis**, D. E. Beskos, Editor, ASCE, 1989, pp. 235 - 271.

9. Ingraffea A R, Sections 9.3, 12.3, 13.4, and 15.2, of **Fracture Mechanics of Concrete Structures: From Theory to Applications**, L. Elfgren, Editor, Chapman and Hall, London, 1989.

10. Ingraffea A R, Boone T J, Swenson D V. Computer Simulation of Fracture Processes. Chapter 22 in **Comprehensive Rock Engineering,** J. Hudson, Editor-in-Chief, Pergamon Press, Oxford, 1993.

11. Carter B J, Desroches J, Ingraffea A R, Wawrzynek P A. Simulating Fully 3D Hydraulic Fracturing. In **Modeling in Geomechanics**, Ed. Zaman, Booker, and Gioda, Wiley Publishers, pp 525-557, 2000.

12. Ingraffea A R, Wawrzynek P A. Crack Propagation. In the **Encyclopedia of Materials: Science and Technology**, Elsevier Science, 2001.

13. Ingraffea A R, Wawrzynek P A. Finite Element Methods for Linear Elastic Fracture Mechanics. Chapter 3.1 in **Comprehensive Structural Integrity**, R. de Borst and H. Mang (eds), Elsevier Science Ltd., Oxford, England, 2003.

14. Ingraffea A R. Computational Fracture Mechanics. Volume 2, Chapter 11, **Encyclopedia of Computational Mechanics**, E. Stein, R. de Borst, T. Hughes (eds.) John Wiley and Sons, 2004, 2nd Edition 2008.

15. Emery J, Ingraffea A R. DDSim: Framework for Multiscale Structural Prognosis, Chapter 13 in **Computational Methods for Microstructure-Property Relationships,** S Ghosh and D Dimiduk (eds), Springer Science, 2011.

PUBLISHED IN PEER-REVIEWED JOURNALS

1. Ingraffea AR. Nodal Grafting for Crack Propagation Studies. *Int. J. Num. Meth. Eng.,* **11**, 7, 1977, 1185 - 1187.

2. Lynn PP, Ingraffea AR. Transition Element to be Used With Quarter - Point Crack Tip Elements. *Int. J. Num. Meth. Eng.,* **12**, 6, 1978, 1031 - 1036.

3. Ingraffea AR, Heuze FE. Finite Element Models for Rock Fracture Mechanics. *Int. J. Num. Analyt. Meth. Geomech.,* **4**, 1980, 25 - 43.

4. Ingraffea AR, Manu C. Stress - Intensity Factor Computation in Three Dimensions With Quarter - Point Elements. *Int. J. Num. Meth. Eng.,* **15**, 10, 1980, 1427 - 1445.

5. Blandford G, Ingraffea AR, Liggett JA. Two-Dimensional Stress Intensity Factor Calculations Using the Boundary Element Method. *Int. J. Num. Meth. Eng*., **17**, 1981, 387 - 404.

6. Beech J, Ingraffea, AR. Three - Dimensional Finite Element Stress Intensity Factor Calibration of the Short Rod Specimen. *Int. J. Fracture*, **18**, 3, 1982, 217 - 229.

7. Perucchio R, Ingraffea AR, Abel JF. Interactive Computer Graphic Preprocessing for Three - Dimensional Finite Element Analysis. *Int. J. Num. Meth. Eng.,* **18**, 6, 1982, 909 - 926.

8. Saouma V, Ingraffea AR, Catalano D. Fracture Toughness of Concrete: K_{Ic} Revisited. *J. Eng. Mech. Div.*, ASCE, **108**, No. EM6, 1982, 1152 - 1166.

9. Perucchio R, Ingraffea AR. Interactive Computer Graphics Preprocessing for Three - Dimensional Boundary Integral Element Analysis. *J. Computers Structures*, **16**, 1 - 4, 1983, 153 - 166.

10. Ingraffea AR, Blandford G, Liggett JA. Automatic Modelling of Mixed - Mode Fatigue and Quasi - Static Crack Propagation Using the Boundary Element Method. *ASTM STP **791**: Proc. of the 14th National Symposium on Fracture Mechanics*, June, 1983, I - 407 - I - 426.

11. Ingraffea AR, Gunsallus KL, Beech JF, Nelson PP. A Short - Rod Based System for Fracture Toughness Testing of Rock. *ASTM STP **855**: Chevron - Notched Specimens: Testing and Stress Analysis*, 1984, 152 - 166.

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13. Manu C, Ingraffea AR. Numerical Evaluation of the Growth Rate Material Parameters in Fatigue Propagation of Surface Flaws. *Nucl. Eng. Design,* **77**, 2, March, 1984, 131 - 138.

14. Ingraffea AR, Gerstle W, Gergely P, Saouma V. Fracture Mechanics of Bond in Reinforced Concrete. *J. Structural Division,* ASCE, **110**, 4, 1984, 871 - 890.

15. Perucchio R, Ingraffea AR. An Integrated Boundary Element Analysis System with Interactive Computer Graphics for Three Dimensional Linear - Elastic Fracture Mechanics. *J. Comp. Structures*, **20**, 1985, 157 - 171.

16. Nelson PP, Ingraffea AR, O'Rourke TD. TBM Performance Prediction with Rock Fracture Parameters. *Int. J. Rock Mech. Mining Sciences*, **22**, 3, June, 1985, 189 - 192.

17. Elices M, Llorca J, Ingraffea AR. Fractura del Hormigon en Regimen Elastico y Lineal. Un Ejemplo: La Presa de Fontana (in Spanish), *Informes de la Construccion.* **37**, 372, July, 1985, 19 - 33.

18. Ingraffea AR, Gerstle WH, Mettam K, Wawrzynek P, Hellier AK. Cracking of Welded Crane Runway Girders: Physical Testing and Computer Simulation. *Iron and Steel Engineer,* **62**, 12, 1985, 46 - 52.

19. Boone TJ, Wawrzynek P, Ingraffea AR. Simulation of the Fracture Process in Rock with Application to Hydro-fracturing. *Int. J. Rock Mech. Mining Sciences*, **23**, 3, 1986, 255 - 265.

20. Abel JF, Ingraffea AR, McGuire W, Greenberg DP. Interactive Color Graphical Postprocessing as a Unifying Influence in Numerical Analysis Research. *Finite Elements in Analysis and Design*, **2**, 1986, 1 - 17.

21. Boone TJ, Wawrzynek P, Ingraffea, AR. Finite Element Modeling of Fracture Propagation in Orthotropic Materials. *Eng. Fract. Mech.,* **26**, 2, 1987, 185 - 201.

22. Gerstle WH, Martha L, Ingraffea AR. Finite and Boundary Element Modeling of Crack Propagation in Two - and Three – Dimensions. *Eng. with Computers*. **2**, 1987, 167 - 183.

23. Hellier AK, Sansalone M, Ingraffea AR, Carino NJ, Stone, C. Finite Element Analysis of the Pullout Test Using a Nonlinear Discrete Cracking Approach. *Cement, Concrete and Aggregates*, **9**, 1, Summer 1987, 20 - 29.

24. Wawrzynek P, Ingraffea AR. Interactive Finite Element Analysis of Fracture Processes: An Integrated Approach. *Theor. Appld. Fract. Mech*. **8**, 1987, 137 - 150.

25. Wawrzynek P, Ingraffea AR. An Edge - Based Data Structure for Two-Dimensional Finite Element Analysis. *Eng. with Computers*, **3**, 1987, 13 - 20.

26. Llorca J, Elices M, Ingraffea AR. Analisis Lineal Y No Lineal De Propagacion De Fisuras En Hormigon," (In Spanish), *Revista Internacional de Metodos Numericos para Calculo y Diseno en Ingenieria*, **3**, 3, 1987, 309 - 333.

27. Swenson DV, Ingraffea AR. Using Combined Experiments and Analysis to Generate Dynamic Critical Stress Intensity Data. *ASTM STP **969**: Fracture Mechanics: 19th Symposium*, T. A. Cruse, Ed., American Society for Testing and Materials, Phila., 1988, 405 - 426.

28. Gerstle WH, Ingraffea AR, Perucchio R. Three-Dimensional Fatigue Crack Propagation Analysis Using the Boundary Element Method. *Int.J. Fatigue*, **10**, 3, 1988, 187 - 192.

29. Swenson DV, Ingraffea AR. Modelling Mixed-Mode Dynamic Crack Propagation Using Finite Elements: Theory and Applications. *Computational Mech.,* **3**, 1988, 187-192.

30. Linsbauer HN, Ingraffea AR, Rossmanith H P, Wawrzynek PA. Simulation of Cracking in a Large Arch Dam: Part I. *J. Structural Eng.,* **115**, 7, July 1989, 1599 - 1615.

31. Linsbauer HN, Ingraffea AR, Rossmanith HP, Wawrzynek PA. Simulation of Cracking in a Large Arch Dam: Part II. *J. Structural Eng.,* **115**, 7, July, 1989, 1616 - 1630.

32. Ingraffea AR. Case Studies of Simulation of Fracture in Concrete Dams. *Eng. Fracture Mech.*, **35**, 1/2/3, 1990, 553-564.

33. Vossoughi H, Soudki K, White RN, Ingraffea AR, Sansalone M. Fatigue of Thick Steel Plates Bent to a Low R/t Ratio. *J. Pressure Vessel Tech.,* **111**, August 1989, 259 - 265.

34. Boone TJ, Ingraffea AR. A Numerical Procedure for Simulation of Hydraulically - Driven Fracture Propagation in Poroelastic Media. *Int. J. Num. Analyt. Meth. Geomech.,* **14**, 1990, 27-47.

35. Grigoriu M, Saif M, El Borgi S, Ingraffea AR. Mixed - Mode Fracture Initiation and Trajectory Prediction Under Random Stresses. *Int. J. Fracture*, **45**, 1990, 19-34.

36. Boone TJ, Ingraffea AR, Roegiers J - C. Visualization of Hydraulically - Driven Fracture Propagation in Poroelastic Media Using a Super – Workstation. *J. Petroleum Tech*, June 1989, 574 - 580.

37. Wawrzynek PA, Ingraffea AR. An Interactive Approach to Local Remeshing Around a Propagating Crack. *Finite Elem. in Analys. and Design*, **5**, 1989, 87 - 96.

38. Ingraffea AR, Barry A. Analytical Study of Transmission, Distribution Lines under Railroads. *Pipe Line Industry,* October 1989, 34 - 39.

39. Gray LJ, Martha LF, Ingraffea AR. Hypersingular Integrals in Boundary Element Fracture Analysis. *Int. J. Num. Meth. Eng.,* **29**, 1990, 1135-1158.

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42. Swenson DV, Ingraffea AR. The Collapse of the Schoharie Creek Bridge: A Case Study in Concrete Fracture Mechanics. *Int. J. Fracture*, **51**, 73-92, 1991.

43. Gerstle WH, Ingraffea AR. Does Bond-Slip Exist? *Concrete International*, **13**, 1, 44-48, 1991.

44. Gerstle WH, Ingraffea AR. Compliance and Stress-Intensity Factor Calibration of the CENRBB Specimen. *Int. J. Rock Mech. Mining Sci. & Geomech. Abstr.,* **28**, 1, 85-92, 1991.

45. Bittencourt TN, Barry A, Ingraffea AR. Comparison of Mixed-Mode Stress Intensity Factors Obtained Through Displacement Correlation, J-Integral Formulation, and Modified Crack-Closure Integral. *ASTM STP 1131: Fracture Mechanics: Twenty Second Symposium (Vol. II)*, Philadelphia, 69-82, 1992.

46. Boone TJ, Ingraffea AR, Roegiers JC. Simulation of Hydraulic Fracture Propagation in Poroelastic Rock with Application to Stress Measurement Techniques. *Int. J. Rock Mech. Min. Sci. & Geomech. Abstr.*, **28**, 1, 1-14, 1991.

47. Mukherjee Y X, Xie Z, Ingraffea AR. Delamination Buckling of Laminated Plates. *Int. J. Num. Meth. Eng.,* **32**, 1321-1337, 1991.

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53. Martha L, Wawrzynek P, Ingraffea AR. Arbitrary Crack Propagation Using Solid Modeling. *Engrg. with Computers*, **9**, 2, 63-82, 1993.

54. Sousa J, Carter B, Ingraffea AR. Numerical Simulation of 3D Hydraulic Fracture Using Newtonian and Power-Law Fluids. *Int. J. Rock Mech. Min. Sci. & Geomech. Abstr.*, **30**, 7, 1265-1271, 1993.

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56. Gray L, Potyondy D, Lutz E, Wawrzynek P, Martha L, Ingraffea AR. Crack Propagation Modeling. *Math. Models Meth. Applied Sci.,* **4**, 2, 179-202, 1994.

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60. Bittencourt T, Ingraffea AR. Three-Dimensional Cohesive Crack Analysis of Short-Rod Specimens. *ASTM-STP* ***1220****: Fracture Mechanics: 25th Volume*, 46-60, 1995.

61. Bittencourt T, Ingraffea AR. Um Metodo Numericao para o Modelmento de Fraturamento Coesivo em 3D (In Portugese). *Revista Internacional de Metodos Numericos para Calculo y Diseno en Ingeneria*, **11**, 4, 1-10, 1995.

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63. Shah KR, Carter BJ, Ingraffea AR. Hydraulic Fracturing Simulation in Parallel Computing Environment. *Int. J. Rock Mech. & Min. Sci.,* 34, 3-4, Paper 282, 1997.

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72. Castell M, Ingraffea AR, Irwin L. Fatigue Crack Growth in Pavements. **126:**283-290, *ASCE J. Transportation Eng.*, 2000.

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FUNDED RESEARCH PROJECTS

Structural Engineering

1. "An Investigation into Mixed - Mode Fracture Propagation in Rock," National Science Foundation Research Initiation Grant ENG78 - 05402, 4/78 - 3/80, $25,000, Principal Investigator.

2. "Finite Element Analysis of Reinforced Concrete for Cyclic Loading," National Science Foundation Grant PFR - 7900711, 4/79-3/81, $84,000, Principal Investigator. P. Gergely and R. N. White, Co - Principal Investigators.

3. "Laboratory Testing of the Crack - at - an - Interface Problem," Sandia National Laboratories Contract No. 13 - 5038, 5/79 - 5/80, $42,000, Principal Investigator.

4. "Three - Dimensional Interactive Computer Graphics in Structural and Geo - Mechanics," National Science Foundation Grant CME79 - 16818, 1/80 - 6/82, $500,000, Faculty Investigator. J. F. Abel, D. P. Greenberg, W. McGuire, Co-Principal Investigators; F. H. Kulhawy, Faculty Investigator.

5. "Interaction Between Steel and Concrete for Earthquake-Type Loadings," National Science Foundation Grant CME80 - 20925, 4/1/81 - 9/30/83, $140,000, Principal Investigator. P. Gergely, Co - Principal Investigator.

6. "Interactive Color Display of Three - Dimensional Engineering Analysis Results," National Aeronautics and Space Administration, Grant NAG3 - 395, 3/1/83 - 2/28/87, $133,285, Associate Investigator. J. F. Abel, Principal Investigator.

7. "Welded Crane Runway Girder Study," Association of Iron and Steel Engineers, 8/83 - 8/85, $234,348, Principal Investigator. W. McGuire, T. Pekoz, Co - Principal Investigators.

8. Presidential Young Investigator Award in Structural Mechanics, National Science Foundation Grant 8351914, 6/84 - 6/89, $500,000, Principal Investigator.

9. "Fatigue Behavior of Thick Steel Plates," Electric Boat Division/General Dynamics, PO# R2041 - 907, 1/86 - 12/88, $233,218, Co - Principal Investigator. R. N. White, Principal Investigator.

10. "Probabilistic Fracture Mechanics," AFOSR, 4/87 - 4/90, $269,624, Co - Principal Investigator. M. Grigoriu, Co - Principal Investigator.

11. "CISE Research Instrumentation: Computer Graphics Dynamic Simulation for Scientific Inquiry," National Science Foundation Grant CCR - 8717024, 4/1/88 - 9/30/89, $145,600, Co - Principal Investigator. M. Cohen, D. Greenberg, and J. Abel, Co - Principal Investigators.

12. "Visualization for Supercomputing: A Graphics Workstation Approach," National Science Foundation, Grant ASC - 8715478, 8/1/88 - 1/31/90, $202,532, Co - Principal Investigator. D. Greenberg, Principal Investigator. J. Abel, M. Cohen, D. Caughey, Co - Principal Investigators.

13. "Advanced Computational Fracture Mechanics," Digital Equipment Corporation, 7/89 - 7/90, $100,000, Principal Investigator.

14. “Fatigue and Damage Tolerance”, Northrop-Grumman Corporation, 6/89-12/00, $249,000, Principal Investigator.

15. "Research in Fracture Mechanics", Exxon Education Foundation, 9/89-9/92, $30,000, Principal Investigator.

16. "Crack Growth Prediction Methodology for Multi-Site Damage", NASA Langley Research Center, 9/90-9/98, $926,147, Principal Investigator.

17. “Fracture Mechanics Life Analytical Methods Verification Testing", Nichols Research Corp. /NASA MSFC, 8/91 - 8/94, $183,860, Principal Investigator.

18. "Mode I/III Fatigue Crack Growth Measurements in 2024 Aluminum Sheet", NASA Langley Research Center, 6/91-9/93, $159,836, Co-Principal Investigator. A. Zehnder, Co-Principal Investigator.

19. “A Study of Failure Mechanisms of Advanced Flex Cables”, IBM Corporation, 1/20/92-1/19/93, $25,000, Co-Principal Investigator. A. Zehnder, Co-Principal Investigator.

20. “Detecting Cracks in Concrete Dams”, U. S. Army Engineer Waterways Experiment Station, 4/1/94-1/1/95, $39,339, Co-Principal Investigator. M. Sansalone, Principal Investigator.

21. “Measurement of Fracture Toughness of Concrete Using the Short-Rod Procedure”, NSF CMS 9414243, 9/95-8/98, $203,854. Principal Investigator.

22. "Simulation of Damage Tolerance in Honeycomb Core Structure", Boeing Commercial Airplane Co., 5/96-12/98, $204,000. Principal Investigator.

23. "Simulation of Crack Growth in Spiral Bevel Gears", NASA Glenn Research Center, 12/96-12/00, $289,961. Principal Investigator.

24. "Fracture of Steel Joints", CUREe SAC Phase II Subcontract No. 28, 9/96-12/96, $23,000. Co-Principal Investigator. Prof. G. Deierlein, Principal Investigator.

25. “Multidisciplinary Center for Earthquake Engineering Research”, NSF, 10/97-9/02, $1,500,000. Associate Investigator. Prof. R. White, Co-Principal Investigator; Profs. G. Deierlein, M, Grigoriu, Associate Investigators.

26. “Simulation of Crack Propagation on Teraflop Computers”, NSF, 1/98-12/00, $1,800,000. Co-Principal Investigator. Profs. S. Vavasis and K. Pingali, Co-Principal Investigators.

27. “Probabilistic Simulation of Fatigue Crack Initiation”, AFOSR, 3/98-2/01, $600,000. Principal Investigator. Profs. M. Grigoriu, M. Miller, P. Dawson, Co-Principal Investigators.

28. “Development and Implementation of T-Stress Criterion”, NASA Langley Research Center, 8/97-3/98, $20,128. Principal Investigator.

29. “Crack Turning and Arrest Mechanisms for Integral Structures”, NASA Langley Research Center, 1/98-6/00, $103,642. Principal Investigator.

30. “Basic Research in Crack Growth Prediction Methodologies”, NASA Langley Research Center, 1/98-11/99, $185,000. Principal Investigator.

31. “Fatigue Crack Growth in Aluminum Alloys”, Alcoa Foundation, 6/97-5/98, $10,000. Principal Investigator.

32. “Multiscale Modeling of Defects in Solids”, NSF 9873214, 10/98-9/01, $1,500,000. Co-Principal Investigator. Profs. P. Dawson, and J. Sethna Co-Principal Investigators, C. Myers, Co-Principal Investigator.

33. “A Two-Tier Computation and Visualization Facility for Multiscale Problems”, NSF 9972853, 10/99-9/04, $1,500,000. Co-Principal Investigator. Profs. K. Pingali, N. Chrisochoides, C. Cruz-Neira, Guang Gao, Co-Principal Investigators.

34. “Finite Element Stress Analysis Subroutines for RAPID”, Federal Aviation Administration, 9/99-4/2000, $34,438. Principal Investigator.

35. “Finite Element/Fracture Mechanics Simulation of Trajectories During Slitting of Plastic Films”, Eastman Kodak Company, 1/1/99-12/31/01, $110,000. Principal Investigator.

36. “ITR: Adaptive Software for Field-driven Simulations”, NSF 0085969, 9/1/00-8/31/04, $5,000,000. Co-Principal Investigator. Prof. K. Pingali, PI, B. K. Soni, J. F. Thompson S. A. Vavasis, Co-PIs.

37. “Developing Technologies for Modeling Damage in Stiffened Thin Shell Structures”, NASA LaRC, 11/1/01-10/31/04, $160,107. Principal Investigator.

38. “Computational Micro-Mechanical Investigations of Crack Initiation in Metallic Polycrystals”, NASA LaRC, 2/1/02-1/31/05, $230,182. Principal Investigator.

39. “The Institute for Future Space Transport”, NASA Marshall RC University Research, Engineering and Technology Institute, 8/1/02-9/15/07, $15,616,120, Co-Principal Investigator. W. Shyy, Principal Investigator, B. Soni, B. Davidson, J. Olds, Co-Principal Investigators.

40. “Structural Integrity Prognosis System-SIPS”, DARPA, 10/1/03-8/31/08, $1,288,400, Cornell Principal Investigator. J. Madsen, Northrop Grumman Corp. Project Manager.

41. "Fracture Mechanics Analysis of MANPADS-Damaged Aircraft Structures", NASA LaRC, 5/05-9/06, $74,000. Principal Investigator.

42. "Advanced Digital Material Machine (ADMM) "AFOSR/DURIP, 2006, $300,000. Principal Investigator.

43. "Multi-Scale Simulation of Cracking Processes in Metallic Materials", NASA LaRC, NNX07AB69A, 1/07-12/10, $392,526. Principal Investigator.

44. "Constellation University Institute Project: Computational Simulation of Damage Tolerance for Composite and Metallic Structures", NASA, 10/1/07-9/30/10, $450,000, Principal Investigator.

45. "Multi-scale Simulation of Fatigue Damage", Northrop Grumman Corporation, 1/1/07-12/31/09, $55,000, Principal Investigator.

46. "Computational Methods in Physics-Based Modeling of Damaged Flight Structures", NASA LaRC NNX08AC50A, 1/1/08-12/31/2010, $299,972, Principal Investigator.

47. "Collaboration between Cornell Fracture Group and Exponent, Inc.", Exponent Inc., 3/08-12/08, $29,204, Principal Investigator.

48. "Geometrical Simulation of Complete Process of Microstructurally Small Fatigue Cracking" E DARPA, HR0011-09-1-0002, 1/09-12/09, $150,000, Principal Investigator.

49. "Parallel File Serving R&D", IBM, $20,200, 7/09-6/10, Principal Investigator.

50. "Prognosis of Long-Term Load-Bearing Capability in Aerospace Structures: Quantification of Microstructurally Short Crack Growth", Air Force Office of Scientific Research, $750,000, 5/10/5/13, Co-Principal Investigator.

51. "Research in Computational Fracture Mechanics". Northrop Grumman Corp., $50,000, 7/14-, Principal Investigator

Geotechnical Engineering

1. "TBM Performance Study," U.S. Dept. of Transportation, 3/80 - 3/82, $164,000, Associate Investigator. T. D. O'Rourke, Principal Investigator; F. H. Kulhawy, Associate Investigator.

2. "A Study of Cast Iron Gas Main Replacement," New York Gas Group, 8/81 - 12/83, $287,000, Associate Investigator. T. D. O'Rourke, Principal Investigator; F. H. Kulhawy, Associate Investigator.

3. "Uplift/Compression Transmission Line Structure Foundation Research," Electric Power Research Institute, RP1493 - 4, 1984 - 1988, $2,450,000, Associate Investigator. F. H. Kulhawy, Principal Investigator; T. D. O'Rourke, M. Grigoriu, Associate Investigators.

4. "Numerical Investigations into Crack Propagation in Rock," National Science Foundation Grant CEE - 8316730, 6/1/84 - 5/30/86, $150,000. Principal Investigator

5. "Workshop on Interactive Computer Modeling and Graphics for the Design and Optimization of Field and Laboratory Experiments in Geotechnical Engineering." National Science Foundation Grant CEE 8413471, 12/84 - 11/86, $39,681. Principal Investigator.

6. "Evaluation of Cased and Uncased Gas Distribution and Transmission Piping Under Railroads and Highways, Gas Research Institute, 11/86 - 1/94, $ 3,602,035. Co-Principal Investigator. T. D. O'Rourke and H. Stewart, Co-Principal Investigators.

7. "Influence of Perforations Upon Subsequent Hydraulic Fracturing," Digital Equipment Corp. and Dowell Schlumberger, 1/88 - 12/96, $448,000. Principal Investigator.

8. "Computational Simulation of Hydrofracturing", NSF CISE Postdoctoral Associate Award for Dr. K. Shah. 11/95-10/97, $46,200. Principal Investigator.

9. "3D Crack Initiation and Propagation in Transparent Rock Like Materials Loaded in Compression", NSF, 9/96-8/99, $148,000. Principal Investigator.

Engineering Education

1. "Study of Complementary Research and Teaching in Engineering Science - PROJECT SOCRATES," U. S. Department of Education, Fund for the Improvement of Post - Secondary Education, G 008642170, 9/15/86 - 9/14/89, $236,496, Project Director.

2. "Workstations For Instructional Computing in the College of Engineering," Digital Equipment Corporation, 5/1/88 - 4/31/90, $664,000. Project Director.

3. "Workstations for Project SOCRATES," Apollo Computer, Inc., June, 1989, $87,105. Project Director.

4. "Workstations for Project SOCRATES", Sun Microsystems, Inc., June, 1990, $89,415. Project Director.

5. "Synthesis National Engineering Education Coalition", National Science Foundation, 9/30/90 - 9/30/94, $12,278,036. Project Director.

6. "1992 Summer Institute for Computer Graphics", New York State Education Department, $56,000, 7/19/92-8/8/92, Project Co-Director. C. Mink, Director.

7. "Support for Educational Computing Equipment", Hewlett Packard, 6/92, $427,318. Project Director.

8. "Synthesis Coalition/GE Foundation Faculty Exchange Award", GE Foundation, Spring 1994 - Spring 1997, $230,000, Principal Investigator.

9. "Synthesis Coalition/Raytheon Company Student Award" Raytheon Company, 1994-1995, $24,000, Principal Investigator.

10. "Application and Infrastructure Linkage to Altoona Area School District and Manhatten Center for Science and Math High School", Synthesis Coalition/NSF/GE Foundation/Mr. A. Misciagna, 10/1/94-9/30/96, $284,000, Project Director.

11. "Integration of Information Age Networking and Parallel Supercomputer Simulations into University and General Science K-12 Curricula", NSF, 1/96-12/98, $102,000, Co-Principal Investigator. J. Sethna, Co-Principal Investigator.

12. REU Supplement to "Measurement of Fracture Toughness of Concrete Using the Short-Rod Procedure", NSF, 9/95-9/98, $10,000, Principal Investigator.

13. REU Supplements to "Integration of Information Age Networking and Parallel Supercomputer Simulations into University and General Science K-12 Curricula", NSF, 9/96-9/98, $20,000, Co-Principal Investigator with Prof. James Sethna, Physics.

14. “Tech City Exhibition”, NSF, 7/98-6/01, $639,543, Co-Principal Investigator. Dr. C. Trautmann, Principal Investigator.

15. “An Advanced Interactive Discovery Environment for Engineering Education” NASA/New York State/AT&T, 2/1/01-12/31/07, $4,300,000, Co-Principal Investigator. Prof. B. Davidson, Principal Investigator, Prof. E. Liddy, Co-PI.

16. "An IGERT Training Program In Sustainable Energy Recovery From The Earth-Education At The Intersection Of Geosciences And Engineering". July 2010-June 2015, National Science Foundation, $1,137,047. Co-Principal Investigator. Prof. Jeff Tester, Principal Investigator, Profs. Terry Jordan, Paulette Clancy, Co-PI’s.

Co-operative Research

1. "Co-operative Agreement between Cornell University and the Technical University of Delft", National Science Foundation Grant PFR-8020924, 1/81 - 12/82, $25,800, Co - Principal Investigator. P. Gergely, Principal Investigator; R. N. White, Co – Principal Investigator.

2. "Scientific Visit to Plan Co-operative Research in Hydraulic Fracturing," Catholic University of Rio de Janiero/Cornell University, National Science Foundation Grant INT - 8814466, July 1988, $2,336, Principal Investigator.

3. "Fracture Mechanics Case Studies of Concrete Dams" Technical University of Vienna, Austria/Cornell University, National Science Foundation Grant INT-8814457, 2/89 - 2/92, $8,080, Principal Investigator.

4. International Supplement to National Science Foundation Grant “ITR: Adaptive Software for Field-driven Simulations”, to collaborate with Czech Technical University, Z. Bittnar, Czech Co-PI, 7/99-8/03, $24,375, Co-Principal Investigator.

THESES DIRECTED

Master of Science

1. "A Fracture Mechanics Analysis of the Fontana Dam," John Chappell, May, 1981.

2. "Mixed-Mode Crack Propagation in Mortar and Concrete." Manrique Arrea, January 1982.

3. "The Fracture Mechanics of Bond in Reinforced Concrete," Walter Gerstle. May 1982.

4. "Concrete Fracture: A Linear Elastic Fracture Mechanics Approach," David Catalano, August, 1982.

5. "Interactive and Graphic Two - Dimensional Fatigue Crack Propagation Analysis Using Boundary Element Method," Kodwo Otsei;du, January, 1983.

6. "An Experimental Investigation of Fatigue Cracking in Welded Crane Runway Girders Due to Wheel Induced Stresses," Kirk I. Mettam, January, 1986.

7. "An Investigation of the Failure Process of the STEM - PMMA Interface in Cemented Prostheses," Leonard Daniel - Timmie Topoleski, June 1986.

8. "Interactive Finite Element Analysis of Fracture Processes: An Integrated Approach," Paul A. Wawrzynek, May 1987.

9. "Analytical Study of Stresses in Transmission and Distribution Pipelines Beneath Railroads," J. Russell Blewitt, May 1987.

10. "Case Studies of Cracking of Concrete Dams--A Linear Elastic Approach," Shan - Wern Steve Lin, January 1988.

11. "Fracture Analysis Code: A Computer - Aided Teaching Tool," Maya Srinivasan, January 1988.

12. "Two-Dimensional Numerical Evaluation of Near Wellbore Phenomena: Perforation Performance & Interacting Hydraulic Fractures", Stephen James Lamkin, May 1990.

13. “On Finite Element Analysis of Face Sheet Cracking in Honeycomb Core Sandwich Panels”, Kenneth Ferguson, January 1999.

14. “Simulating Fatigue Crack Growth in Spiral Bevel Gears”, Lisa Eron Spievak, August 1999.

15. “Cracking Dams: An Interactive Web Site for K12”, Megann V. Polaha, August 1999.

16. "Experimental Investigations into Damage Tolerance of Honeycomb Sandwich Panels", Ani Ural, August, 1999.

17. “Simulations of Crack Initiation in Aluminum Alloys with Inclusions“, Ketan Dodhia, January, 2002.

18. “Decohesion of Grain Boundaries in Statistical Representations of Aluminum Polycrystals“, Erin Iesulauro, January, 2002.

19. “An Evaluation of Surface Cracks in Welded Components of Nuclear Reactor Vessels”, John Emery, May, 2003.

20. “Microstructural Reconstruction and Three-Dimensional Mesh Generation for Polycrystalline 7075-T651 Aluminum Alloy“, Michael Veilleux, May, 2007.

21. “A Two-Dimensional Multiscale Method for Fatigue Crack Nucleation in Polycrystalline Aluminum Alloys “, Jeffrey Bozek, May, 2007.

22. “Microstructural Simulation of Fracture Processes in Cortical Bone”, Erin Oneida, December, 2014.

Doctor of Philosophy

1. "Three-Dimensional Finite Element Analysis of Cyclic Fatigue Crack Growth of Multiple Surface Flaws." Corneliu Manu, June, 1980. Professor (Retired) University of Toronto.

2. "Automatic Two-Dimensional Quasi-Static and Fatigue Crack Propagation Using the Boundary Element Method." George E. Blandford, January, 1981. Professor, University of Kentucky.

3. "Interactive Finite Element Analysis of Reinforced Concrete: A Fracture Mechanics Approach," Victor E. Saouma, January, 1981. Professor, University of Colorado/Boulder.

4. "An Integrated Boundary Element Analysis System with Interactive Computer Graphics for Three - Dimensional Linear Elastic Fracture Mechanics," Renato S. Perucchio, January, 1984. Professor, University of Rochester.

5. "Finite and Boundary Element Modelling of Crack Propagation in Two- and Three - Dimensions Using Interactive Computer Graphics," Walter H. Gerstle, January, 1986. Professor, University of New Mexico.

6. "Modeling Mixed - Mode Dynamic Crack Propagation Using Finite Elements," Daniel V. Swenson, January 1986. Professor, Kansas State University.

7. "Simulation of Crack Propagation in Poroelastic Rock with Application to Hydrofracturing and *In - Situ* Stress Measurement," Thomas J. Boone, January, 1989. VP of Research, ESSO Canada.

8. "Topological and Geometrical Modeling Approach to Numerical Discretization and Arbitrary Fracture Simulation in Three-Dimensions," Luiz Martha, August, 1989. Professor, Catholic University of Rio de Janeiro, Brazil.

9. "Numerical Methods for Hypersingular and Near-Singular Boundary Integrals in Fracture Mechanics", Earlin Lutz, May, 1991. Senior Research Engineer, Bentley, Inc.

10. "Discrete Modelling of Crack Propagation: Theoretical Aspects and Implementation Issues in Two and Three Dimensions", Paul A. Wawrzynek, August, 1991. Chief Engineer, Fracture Analysis Consultants, Inc.

11. "Three-Dimensional Simulation of Near-Wellbore Phenomena Related to Hydraulic Fracturing from a Perforated Wellbore", José Sousa, May, 1992. Professor, University of Campinas, Brazil.

12. "Computer Simulation of Linear and Nonlinear Crack Propagation in Cementitious Materials", Tulio Bittencourt, May, 1993. Professor, University of Sao Paulo, Brazil.

13. "A Methodology for Simulation of Curvilinear Crack Growth in Pressurized Shells", David Potyondy, August, 1993. Senior Research Engineer, Itasca, Inc.

14. "Experimental Validation Testing of Numerical Prediction Techniques for Three-Dimensional Fracture and Fatigue", William Riddell, June, 1995. Assoc. Professor, Rowan University.

15. “Crack Growth Simulation and Residual Strength Prediction in Thin Shell Structures”, Chuin-Shan Chen, January, 1999. Assoc. Prof., National Taiwan University.

16. “Virtual Crack Extension Method for Calculating Rates of Energy Release Rate and Numerical Simulation of Crack Growth in Two and Three Dimensions”, Changyu Hwang, January, 1999. Professor, Seoul University of Venture and Information.

17. “Crack Turning in Integrally Stiffened Aircraft Structures”, Richard Pettit, August, 2000. Chief Engineer, FractureLab, LLC.

18. “An Experimental-Computational Evaluation of the Accuracy of Fracture Toughness Tests on Concrete”, James Hanson, August, 2000. Professor, Rose-Hulman Institute of Technology.

19. “Interface Modeling of Composite Material Degradation”, Tong-Seok Han, May, 2001 (with Prof. Sarah Billington). Research Engineer, Korea Electric Power Research Institute.

20. “Modeling and Simulation of Fatigue Crack Growth in Metals Using LEFM and a Damage-Based Cohesive Model”, Ani Ural, May, 2004 (with Prof. Katerina Papoulia). Assistant Professor, Villanova University.

21. “Decohesion of Grain Boundaries in Statistical Representations of Aluminum Polycrystals”, Erin Iesulauro, May, 2006. Staff Engineer, Los Alamos National Laboratory.

22. “A Hierarchical, Probabilistic, Damage and Durability Simulation Methodology”, John Emery, May, 2007, Staff Engineer, Sandia National Laboratory.

23. “Finite Element Simulation of Fatigue Crack Stages in AA 7075-T651 Microstructure”, Jacob Hochhalter, May, 2010, Staff Engineer, NASA Langley Research Center.

24. "Geometrically explicit finite element modeling of AA7075-T651 microstructure with fatigue cracks", Michael Veilleux, August, 2010, Senior Member of Technical Staff, Sandia Livermore National Laboratory.

25. “Numerical And Experimental Studies Of Three-Dimensional Crack Evolution In Aluminum Alloys: Macroscale To Microscale”, Ashley Spear, NSF Graduate Fellow, May, 2014, Asst. Prof., University of Utah.

26. “DDSim for Composite Structures“, Brett Davis, May, 2014, Staff Engineer, Exponent, Inc.

27. “Geometrical Simulation of Complete Process of Microstructurally Small Fatigue Cracking “, Albert Cerrone, May, 2014, Staff Engineer, General Electric Corporate Research.

APPENDIX B - Deposition and Trial Testimony

B-1 Depositions

Nolan Scott Ely et al. Plaintiff v. Cabot Oil & Gas Corporation Defendant, Case No. 3:09-cv-02284-MCC, United States District Court, Middle District of Pennsylvania, July 15, 2015.

Robert Andrews et al v. Antero et al., Civil Action No. 14-C-3000. Circuit Court of Ohio County, West Virginia, June 12, 2015.

Cody Murray et al. Plaintiffs v. EOG Resources; Fairway Resources et al., Cause No. 342-284983-16, District Court, Tarrant County, Texas, May 24, 2017.

B-2 Trial

Nolan Scott Ely et al. Plaintiff v. Cabot Oil & Gas Corporation Defendant, Case No. 3:09-cv-02284-MCC, United States District Court, Middle District of Pennsylvania, February, 2016.

Appendix C: References

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Air pollutant emissions from the development, production, and processing of Marcellus Shale natural gas

Anirban A. Roy , Peter J. Adams & Allen L. Robinson

TECHNICAL PAPER

Air pollutant emissions from the development, production, and processing of Marcellus Shale natural gas

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The Marcellus Shale is one of the largest natural gas reserves in the United States; it has recently been the focus of intense drilling and leasing activity. This paper describes an air emissions inventory for the development, production, and processing of natural gas in the Marcellus Shale region for 2009 and 2020. It includes estimates of the emissions of oxides of nitrogen (NO_x), volatile organic compounds (VOCs), and primary fine particulate matter (≤2.5 μm aerodynamic diameter; $PM_{2.5}$) from major activities such as drilling, hydraulic fracturing, compressor stations, and completion venting. The inventory is constructed using a process-level approach; a Monte Carlo analysis is used to explicitly account for the uncertainty. Emissions were estimated for 2009 and projected to 2020, accounting for the effects of existing and potential additional regulations. In 2020, Marcellus activities are predicted to contribute 6–18% (95% confidence interval) of the NO_x emissions in the Marcellus region, with an average contribution of 12% (129 tons/day). In 2020, the predicted contribution of Marcellus activities to the regional anthropogenic VOC emissions ranged between 7% and 28% (95% confidence interval), with an average contribution of 12% (100 tons/day). These estimates account for the implementation of recently promulgated regulations such as the Tier 4 off-road diesel engine regulation and the U.S. Environmental Protection Agency's (EPA) Oil and Gas Rule. These regulations significantly reduce the Marcellus VOC and NO_x emissions, but there are significant opportunities for further reduction in these emissions using existing technologies.

Implications: The Marcellus Shale is one of the largest natural gas reserves in United States. The development and production of this gas may emit substantial amounts of oxides of nitrogen and volatile organic compounds. These emissions may have special significance because Marcellus development is occurring close to areas that have been designated nonattainment for the ozone standard. Control technologies exist to substantially reduce these impacts. $PM_{2.5}$ emissions are predicted to be negligible in a regional context, but elemental carbon emissions from diesel powered equipment may be important.

Introduction

The Marcellus Shale is a rock formation lying below the states of Pennsylvania, Ohio, West Virginia, New York, and Maryland, spanning a basin area of 95,000 square miles. It is estimated to contain between 1.2 and 4.1 trillion m^3 of technically recoverable natural gas (U.S. Geological Survey [USGS], 2008). It is one of the largest natural gas reserves in the United States and recently has been the focus of intense drilling and leasing activity (Considine et al., 2009, 2010, 2011; Considine, 2010).

Gas development, production, and processing activities can be a significant source of air pollution (Archuleta, 2009; Katzenstein et al., 2003). In a large basin such as the Marcellus formation, these activities involve a large number of relatively small sources that are widely distributed in space. For example, drill rigs and hydraulic fracturing ("fracing") pumps powered by off-road heavy-duty diesel engines emit oxides of nitrogen (NO_x), fine particulate matter (≤2.5 μm aerodynamic diameter; $PM_{2.5}$), and volatile organic compounds (VOCs) (EPA, 2004a; 2013a,b). Diesel-powered trucks used to bring materials to and from the well site emit the same suite of pollutants (EPA, 2005). Completion venting performed to bring a well into production can be a significant source of VOCs (Bar-Ilan et al., 2008; Grant et al., 2009, Armendariz, 2009). Natural-gas-fired compressors used to maintain gas pressure emit NO_x and VOCs (Bar-Ilan et al., 2008; Grant et al., 2009). Speciation profiles such as the U.S. Environmental Protection Agency's (EPA's) SPECIATE database (EPA, 2006) and natural gas source speciation profiles (e.g., Hendler et al., 2009) indicate that VOCs emitted from these sources include alkanes (diesel engines, venting and fugitives), alkenes (diesel engines), aromatics (diesel engines), and aldehydes (diesel- and natural-gas-fired engines). NO_x and VOCs react in the presence of sunlight to produce ozone, which causes health problems such as asthma and decreased lung function (Bernard et al., 2001; Levy et al., 2001; Godish et al., 2004). The health effects of $PM_{2.5}$ are well documented and include premature mortality (Dockery and Pope, 1994; Kaiser, 2005). A major component of $PM_{2.5}$ emitted by diesel-powered engines is

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Color versions of one or more of the figures in the article can be found online at www.tandfonline.com/uawm.

elemental carbon (EC), which may be an important driver for climate change (e.g., Bond et al., 2004).

Previous studies indicate that the aggregate emissions from shale gas activities can be significant. For example, Armendariz (2009) estimated that the combined NO_x and VOC emissions from natural gas sources exceeded on-road mobile sources in the Barnett Shale region. Furthermore, field and modeling studies have also shown that these emissions can have important impacts on local and regional air quality. Schnell et al. (2009) reported peak 1-hr ozone levels as high as 100 ppb in the Jonah Pinedale region in Wyoming, which is a hotspot for gas development and production. Elevated VOC levels were also found in large regions of Colorado, Texas, Oklahoma, and Kansas, where there is significant gas production (Katzenstein et al., 2003; Zielinska et al., 2011; Archuleta, 2008). Cook et al. (2010) used a chemical transport model to predict that gas development in the Haynesville Shale could increase the maximum daily 8-hr average ozone levels by as much as 17 ppb over parts of Louisiana and Texas. In order to protect public health and welfare, the EPA has promulgated National Ambient Air Quality Standards (NAAQS) for ozone and $PM_{2.5}$ (EPA, 2012a). Many counties in the Marcellus region currently violate these standards (EPA, 2012c), and Marcellus development may complicate these existing problems.

The goal of this work is to develop an air emission inventory for gas development, production, and processing activities in the Marcellus Shale region. Emissions were estimated for a base year (2009) and then projected out to 2020 using well drilling and production projections from the literature. For 2020, three possible control scenarios were considered: pre-2009 controls, baseline, and tight controls. The inventory estimates NO_x, $PM_{2.5}$, and VOC emissions for major sources, including drilling, hydraulic fracturing, completion venting, compressors, and truck traffic. A Monte Carlo approach was used to derive distributions of estimates to account for the uncertainty in emissions. The inventory is designed for use in a chemical transport model to simulate the effects of gas development and production on regional air quality. Natural gas development can have other environmental impacts as well. These include groundwater contamination by fracing fluid and potential displacement of coal use by natural gas, a cleaner burning fuel. These issues are outside the scope of this study. Impacts of emissions on regional air quality will be considered in a future paper.

Methodology

The emission inventory was constructed using a bottom-up, process-level approach that combines activity and emission factor data for major source categories. A flowchart of the overall approach is shown in Figure 1. The inventory was constructed in a three-step process. First, emissions were estimated for each source or process associated with the development, production, or processing of Marcellus gas (e.g., emissions associated with drilling one well). Second, the process-level emission estimates were combined to estimate the emissions for three broad types of activities: well development, gas production, and midstream processing. Well development includes the emissions from all of the processes associated with setting up one well and bringing it into production, including drilling the well, fracturing the shale rock to release the gas, and completion venting. Production emissions are associated with one producing well; they include wellhead compressors and fugitive emissions from valves, pneumatic devices, and other sources. Midstream emissions are associated with processing one unit of gas downstream of the wellhead and include gas processing plants and compressor stations. Third, the activity-level emission estimates were combined with basin-level activity data (e.g., number of wells drilled, cumulative number of wells active, or volume of gas produced) to estimate the overall, Marcellus-wide emissions for each pollutant. The input data for basin-level activity data are shown in Table 1. This analysis was performed separately for NO_x, $PM_{2.5}$, and VOCs. Table 2 lists sources considered in this study, their activity category, the pollutants they emit, and basin-level scaling parameter.

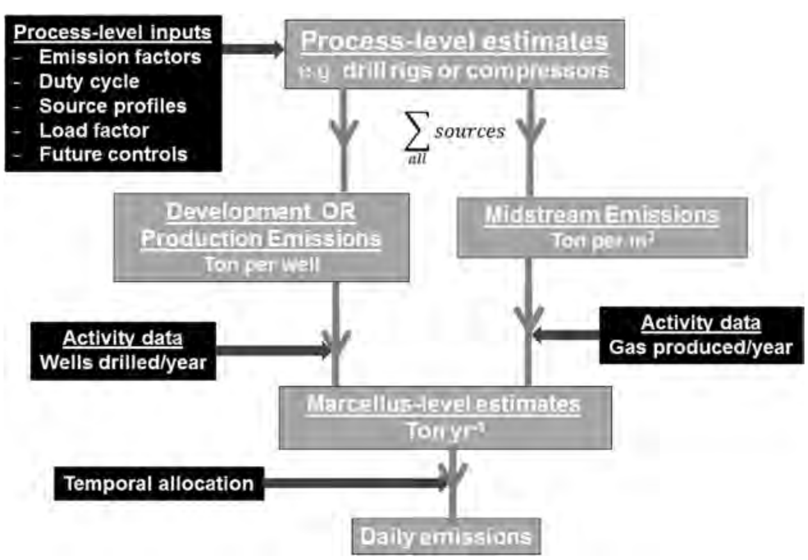

Figure 1. Flowchart showing inventory development.

Table 1. Activity data for the Marcellus region

Activity	State	2009	2020		
		Actual Data	Low	High	Reference
Number of new Marcellus wells drilled (per year)	Pennsylvania	710 (PADEP, 2011)	1500	3600	Considine (2010), Considine et al. (2011), The Nature Conservancy (2010)
	West Virginia	411 (WVGES, 2011)	273	883	Considine (2010), NETL (2010)
	New York	n/a	0	500	Considine (2010), Weinstein and Clower (2009), Lillpopp and Lindell (2011)
Cumulative number of Marcellus wells	Overall	2050 (PADEP, 2011; WVGES, 2011)	29000	49000	Considine (2010), NETL (2010), The Nature Conservancy (2011)
Marcellus gas production, billion cubic feet per day	Pennsylvania	8.6 (PADEP, 2011)	93.5	382	Considine (2010), Considine et al. (2009, 2010, 2011)
	West Virginia	5.2	17.3	382	Considine (2010), NETL (2010)
	New York	0	0	51	Considine et al. (2010)
	Overall	13.8	101	815	

Table 2. List of sources and their corresponding scaling activity parameters

Category	Source	Pollutant			Activity Scaling Parameter
		NO_x	$PM_{2.5}$	VOCs	
Well development	Drill rigs	Y	Y	Y	Number of wells
	Frac pumps	Y	Y	Y	Number of wells
	Truck Traffic	Y	Y	Y	Number of wells
	Well completion	N	N	Y	Number of Wells
Gas production	Production fugitives	N	N	Y	Cumulative number of wells
	Pneumatics	N	N	Y	Cumulative number of wells
	Wellhead compressors	Y	Y	Y	Cumulative number of wells
	Blowdown venting	N	N	Y	Cumulative number of wells
	Heaters	Y	Y	Y	Cumulative number of wells
	Condensate tanks	N	N	Y	Condensate production
Midstream	Dehydrators	Y	Y	Y	Volume of gas production
	Compressor stations	Y	Y	Y	Volume of gas production
	Fugitives:				
	Transmission	N	N	Y	Volume of gas production
	Processing	N	N	Y	Volume of gas production

Given the uncertainty in the activity and emission data, a Monte Carlo approach was used to develop distributions of emission estimates. Probability distributions were defined for each input parameter (e.g., activity and emission factors) based on a review of the literature and/or interviews with experts. To derive a single emission estimate, values for each parameter were chosen at random from each input distribution using the method of Ross (2006). The process was repeated 20,000 times to calculate a distribution of emission estimates for a given source or activity. Estimated emissions are reported as a mean value bounded by a 95% confidence interval. The basic approach is described by Cullen and Frey (1999); it has been used to develop inventories for different types of sources (Zhao and Frey 2004; Frey and Zhao 2004; Frey and Rhodes 1998; French et al., 2004; Van der Werf et al., 2010) but not for oil and gas development.

The Monte Carlo approach provides an estimate of the uncertainty in the emissions. This requires that each input parameter be represented by a distribution of population mean (or basin-wide) values. Unfortunately, relatively few measurements have been made in the Marcellus formation. Therefore, these distributions are uncertain, so data from other basins, published emission factors for comparably sized engines, and similar data sources must be used. This complicates making formal uncertainty estimates using Monte Carlo analysis.

For this work, published emission factors were often used as input distributions. These distributions represent the unit-to-unit variability in emissions, not the uncertainty in the mean (basin-wide) values. In principle, it would be preferred to sample from the distribution of the sample means during Monte Carlo analysis rather than unit-to-unit variability. However, given the thousands of units in the Marcellus region, the sample means are quite narrow and using them was judged to lead to unrealistically narrow uncertainty bounds on overall emissions. Sampling from the unit-to-unit variability is a conservative approach that results in wide uncertainty bounds in emission estimates. This approach has been previously used to construct Monte Carlo–based estimates of emission inventories with multiple sources, each having its own set of inputs, with the uncertainty being described by the 95% confidence interval of the resulting emission distributions (e.g., North American Research Strategy for Tropospheric Ozone [NARSTO], 2011; Bond et al., 2004; Frey and Zheng, 2002; Intergovernmental Panel on Climate Change [IPCC], 2000). This is the approach adopted here.

An alternative approach is to use a bootstrap or some other technique to construct distributions of means for each parameter, which would then be sampled using the Monte Carlo approach (e.g., Frey and Zhao 2004). For example, for equipment such as drill rigs that have multiple engines, a sample size equal to the number of engines on a rig (e.g., seven) was drawn every time to calculate a mean emission factor for the entire rig. This results in much narrower distributions of emission factors and other input data. For example, drill rig NO_x emission factors vary by a factor of 4, which reduces to a factor of 1.4 in the 95% confidence interval in the distribution of means.

The emission factors for major sources (which make up more than 10% of the total Marcellus emissions for a given criteria pollutant) are described in Table 3; other input data are listed in Table 4. The type of distribution assumed for each input parameter is listed in Table S10 in Supplemental Materials. For inputs with rich data sets (e.g., emission factors), the Monte Carlo analysis was performed using the distributions of actual data. For inputs with more limited data, triangular or uniform distributions were used to represent the available information. Triangular distributions were used if the available data indicated that there was a best estimate (e.g., drill rig horsepower); a uniform distribution assumes that each value was equally probable (e.g., projected future Marcellus development).

Spatial coverage of inventory

A map of the entire Marcellus formation is shown in Figure 2a. The inventory was constructed for the subset of this region shown in Figure 2b, specifically the Marcellus fairway in Pennsylvania, and portions of West Virginia and New York. The specific counties included in the inventory are listed in Table S1 in Supplemental Materials. Although there is currently a drilling moratorium in New York, it is an area where future development may occur and therefore is included in the analysis. The inventory does not include Maryland and Ohio. To date, there has been little Marcellus development in these states and projections of future development were deemed too uncertain.

Basin-level activity data

Emissions depend on the magnitude of the Marcellus well development and gas production and processing. Emissions associated with well development (e.g., drill rigs) depend on the number of wells drilled. Emissions associated with gas production depend on the cumulative number of producing wells. Midstream emissions depend on the total volume of gas produced. Data and future projections for these activity parameters are listed in Table 1. The values for 2020 reflect the wide range of projections

Table 3. Emission factors for key sources (similar data for minor sources is in Table S10 in Supplementary Materials)

Source	Pollutant	Mean	Range (Min–Max)	Comments
Drill rigs (g bhp^{-1} hr^{-1})	NO_x	5.8	2.5–10	Heavy-duty diesel engines of similar rating (500–1500 hp) (locomotives and generators)[a]
	$PM_{2.5}$	0.35	0.07–1	
	VOCs	0.6	0.25–1.6	
Frac pumps (g bhp^{-1} hr^{-1})	NO_x	5.7	2.5–10	Heavy-duty diesel engines of similar rating (1000–1500 hp) (locomotives and generators)[b]
	$PM_{2.5}$	0.4	0.09–0.9	
	VOCs	0.67	0.3–1.6	
Trucks (g $mile^{-1}$)	NO_x	50	9–90	Heavy-duty truck emission factors from literature[c]
	$PM_{2.5}$	0.32	7×10^{-4} to 1.3	
	VOCs	1.7	0.2–10	
Compressor stations (g bhp^{-1} hr^{-1})	NO_x	1.5	0.5–2.0	Data from PADEP[d]
	$PM_{2.5}$	0.014	2.5×10^{-4} to 4×10^{-2}	
	VOCs	0.46	0.1–1.8	
Condensate tanks (lb bbl^{-1})	NO_x	n/a	n/a	Data from Barnett Shale and CENRAP basins used as surrogate (Armendariz, 2009; Bar-Ilan et al., 2008; Hendler et al., 2009)
	$PM_{2.5}$	n/a	n/a	
	VOCs	29	0.7–215	

Notes: [a]EPA's AP-42, Shah et al. (2006), Chen et al. (2003). [b]Shah et al, (2006), Chen et al. (2003), Sawant et al. (2007), Comer et al. (2010). [c]FHWA (2011), Ban-Weiss et al. (2008), Prucz et al. (2001), Zhu et al. (2011), Shah et al. (2006), Johnson et al. (2009), Mazzoleni et al. (2007), Clagget and Houk (2008), Choi and Frey (2010). [d]Personal communication with Naishadh Bhatt, nabhatt@pa.gov.

Table 4. Values for input parameters for major sources

Source	Parameter	Range (Min–Max)	Mean	Comments
Drill rig	Horsepower (hp)	2000–7000	4260	Personal communication with PADEP (Chris Tersine, NYDEC (Leon Sedefian), and EQT Corporation (Andrew Place)[a]
	Load factor	0.25–0.9	0.57	Texas drill rigs used as surrogate (Baker and Pring, 2009)
	Engine on-time	0.2–1	0.5	CENRAP values as surrogate (Bar-Ilan et al., 2008)
	Drilling time (days)	14–35	26	PADEP (Chris Tersine), NYDEC (Leon Sedefian), and WVGES (Megan Murphy)[b]
	Control factors			Ignition timing retard and selective catalytic reduction for NO_x, diesel particulate filters for PM, diesel oxidation catalysts for VOCs (USEPA Tier 4 standards, 2004)
	NO_x	0.1–0.96	0.44	
	$PM_{2.5}$	0.6–0.97	0.81	
	VOCs	0.6–0.97	0.81	
	Cumulative % fleet turnover	50–100	76	USEPA Tier 4 (2004), Chesapeake Energy Corporation[c]
Fracing	Number of stages			Chesapeake Energy Corporation,[d] EQT Corporation (Andrew Place)
	2009	4–35	19	
	2020	10–35	25	
	Horsepower/stage	35000–45000	40000	Chesapeake Energy Corporation
	Emission control factors			Same controls as drill rigs
	NO_x	0.1–0.96	0.44	
	$PM_{2.5}$	0.6–0.97	0.81	
	VOCs	0.6–0.97	0.81	
	Cumulative % fleet turnover	50–100	76	NONROAD scrappage curve
Trucks	Truck trips/well			Jiang et al. (2011).
	Development	295–1215	661	
	Wastewater	200–1125	460	
	Distance per trip (miles)			Jiang et al. (2011), US National Park Service (2009)
	Distribution center to well (development)	0–20	9.9	
	Well to wastewater disposal facility	3–280	119	
	Emission control factors			NO_x adsorber and SCRs for NO_x, DPF for PM, and DOC for VOCs (EPA Clean Diesel Rule)
	NO_x	0.7–0.95	0.85	
	$PM_{2.5}$	0.6–0.99	0.8	
	VOCs	0.3–0.99	0.8	
Completion	Emission factors (MCF/well)	$(18–24) \times 10^3$	3700	Bar-Ilan et al. (2008), Armendariz (2009); CENRAP and Barnett Shale data as surrogate
	Mole Fraction of VOCs in gas			Chesapeake Energy Corporation
	Dry gas	5.9×10^{-3} to	0.034	
	Wet gas	0.064	0.25	
		0.17–0.33		
	Control factors (VOCs)	0.7–0.95	0.84	Green completion (Bar-Ilan et al., 2007)
Compressor stations	hp/BCF/day	125–145	135	PADEP, Considine (2010)
	Load factor	0.4–0.8	0.6	Data from DNREC (Robert Clausen), Burklin and Heaney (2005)
	Emission control factors			Selective and nonselective catalytic reduction
	NO_x	0.15–0.95	0.5	
	VOCs	0.3–0.95	0.6	
Condensate	Control factors (VOCs)	0.6–0.97	0.73	Flaring, vapor recovery units (Bar-Ilan et al., 2007)

Notes: [a,b]ctersine@state.pa.us; lxsedefi@gw.dec.state.ny.us; aplace@eqt.com. [c]http://www.chk.com/Affiliates/Chesapeake-Oilfield-Services/Documents/COO_Annual_Report.pdf. [d]E-mail from Grover R. Campbell, Manager Regulatory Affairs, Air Regulations, Chesapeake Energy Corporation, to Michael E. Hopkins, Assistant Chief, Permitting Ohio EPA (May 16, 2011, 11:31 a.m. EST).

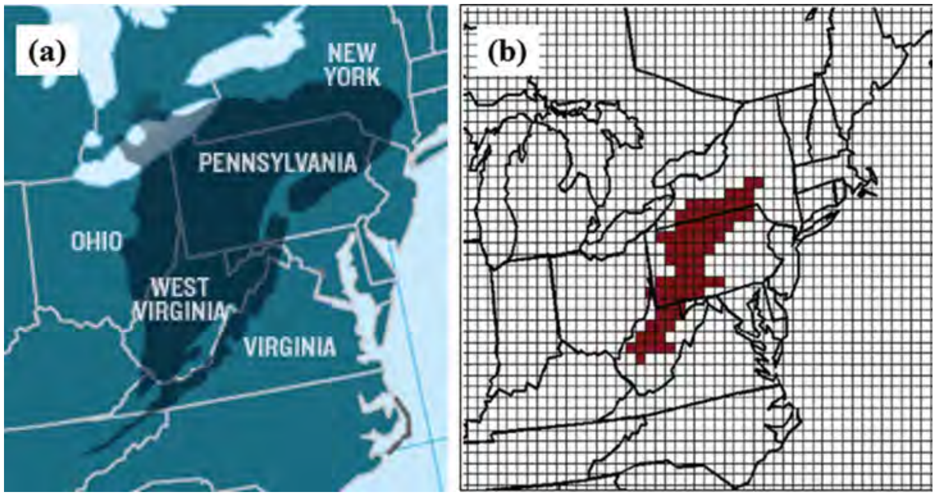

Figure 2. (a) Map of the Marcellus region (USGS, 2009) and (b) subregion covered by the new inventory.

that have been published for future gas production (Considine, 2010; Considine et al., 2011), which depend most critically on the price of gas. In order to account for this uncertainty, a uniform distribution was defined using upper- and lower-bound estimates from a large number of literature values. This assumes that all of the published estimates are equally probable. The moratorium on Marcellus development still exists in New York, but this analysis assumes that this ban will be lifted.

Emission controls

Emission estimates for the year 2020 must account for the effects of controls and fleet replacement with more modern technology. This was done by scaling the base (2009) emission factors using the methodology described in the EPA's National Mobile Inventory Model (NMIM) (EPA, 2009).

$$EF_i(2020) = EF_i(2009)[f_{\text{replaced}}(1 - f_{\text{control}}) + 1 - f_{\text{replaced}}] \quad (1)$$

where $EF_i(2020)$ is the projected distribution of emission factors for 2020, $EF_i(2009)$ is the distribution of emission factors for the base year of 2009, f_{replaced} represents the cumulative fraction of the fleet that has been replaced with newer, lower emitting sources between 2009 and 2020, and f_{control} represents the fractional reduction of emissions brought about by this fleet replacement. The base 2020 analysis assumes full implementation of the EPA's recently revised Oil and Gas Rule (EPA, 2012b) and the Tier 4 (EPA, 2004a) standard for off-road diesel engines. A list of the control technologies for the baseline case for key sources is given in Table 4. The ranges reflect variability across different control technologies.

Results and Discussion

Process-level emission estimates

Table 2 lists the sources or processes associated with the development, production, and processing of shale gas. This section describes the emissions from the major sources. Minor sources (wellhead fugitives, heaters, blowdown venting, and dehydrators) are discussed in Supplemental Materials. Some known sources are not included in the inventory. Due to lack of reliable emission factors, VOC emissions from frac ponds were not considered in this analysis. Road building was also not included.

In subsequent sections, these estimates are combined into activity-level and ultimately Marcellus-wide emissions. A set of process-level estimates along with the corresponding uncertainty associated with each source is presented in Table 5. There is a significant decrease in the emissions from each source between 2009 and 2020 (other than fracing) due to imposition of the controls listed in Table 4.

Drilling. A drill rig has 5–7 independent diesel-powered compression ignition engines, each rated between 500 and 1500 brake horsepower (bhp). These engines are major sources of NO_x and $PM_{2.5}$. Drill rigs are configured in either a direct drive or a diesel electric configuration (Bar-Ilan et al., 2008). These engines power the draw works, mud pump, and electricity generators. Emissions (tons/well) for drilling a single well are given as (Bar-Ilan et al., 2008a, Grant et al., 2009)

$$E_{\text{drilling}} = EF_i \times HP \times LF_{\text{average}} \times t_{\text{drilling}} \times \%\ \text{on-time} \quad (2)$$

where EF_i is the emission factor from a drill rig engine for pollutant i, HP is the combined horsepower of all the engines on the rig, LF_{average} represents the load factor or fraction of the total horsepower that is actually used, t_{drilling} is the time to drill one well, and % on-time is the fraction of t_{drilling} that the drilling equipment actually operates (Bar-Ilan et al., 2008).

The authors are not aware of any Marcellus-specific drill rig engine emission factors. Therefore, emission factors for the 2009 inventory were taken from the EPA's AP-42 (EPA, 2011a) and literature data for similarly sized engines used in diesel-electric locomotives and diesel generators (e.g., Shah et al., 2006; Sawant et al., 2007; Chen et al., 2003). The NONROAD model (EPA, 2008) was not used to estimate emission factors because it estimates point values and not distributions. These distributions

Table 5. Process-level emission estimates, means (95% confidence intervals), for major sources

	Pollutant					
	NO_x		$PM_{2.5}$		VOCs	
Source	2009	2020	2009	2020	2009	2020
Drill rigs (tons/well drilled)	4.4 (0.8–11.5)	2.9 (0.5–8.1)	0.3 (0.03–1)	0.1 (0.01–0.4)	0.5 (0.1–1.8)	0.1 (0.02–0.5)
Frac pumps (tons/well drilled)	2.2 (0.7–4.3)	1.8 (0.6–3.4)	0.16 (0.03–0.4)	0.1 (0.01–0.3)	0.25 (0.07–0.7)	0.14 (0.03–0.5)
Trucks (tons/well drilled)	6.9 (1.4–20)	1.5 (0.2–4.5)	0.07 (4×10^{-4} to 0.3)	0.02 (2×10^{-4} to 0.09)	0.4 (0.02–2.2)	0.2 (0.01–1.2)
Completion (tons/well drilled)						
Dry well	n/a	n/a	n/a	n/a	3.8 (2×10^{-3} to 29)	1.01 (5×10^{-4} to 8.3)
Wet well	n/a	n/a	n/a	n/a	21 (0.09–145)	5.5 (0.02–37.5)
Pneumatics (tons/producing well)						
Dry gas	n/a	n/a	n/a	n/a	0.5 (0.08–0.8)	0.1 (0.02–0.2)
Wet gas	n/a	n/a	n/a	n/a	3.3 (2.4–4.4)	0.8 (0.5–1)
Compressor stations (tons/BCF)	3.3 (1.0–5.2)	1.5 (0.3–3.0)	0.3 (4×10^{-4} to 0.1)	0.3 (4×10^{-4} to 0.1)	1.0 (0.3–3.0)	0.4 (0.06–1.0)

Note: Numbers presented for 2020 are for the baseline controls scenario.

of emission factors are summarized in Table 3 and plotted in Figure S1 (Supplemental Materials). The mean emission factors for NO_x, VOC, and $PM_{2.5}$, are 5.8, 0.63, and 0.35 g hp^{-1} hr^{-1}, respectively. These values are compared with the values for drill rigs used by other authors in Table S7 in Supplemental Materials. The average drill rig NO_x emission factor was 5.7 g hp^{-1} hr^{-1} (4.7–6.7), which is ~30% lower than to the value of 8 g bhp^{-1} hr^{-1} used by Grant et al. (2009) and Bar-Ilan et al. (2008). It is roughly comparable (10% lower than) to the value of 6.4 g hp^{-1} hr^{-1} used by New York Department of Environmental Conservation (NYDEC) to construct their Marcellus inventory. The Bar-Ilan emission factor corresponds to the 95th percentile of the distribution presented here. One of the reasons the values in this study are lower than those used by Grant et al. (2009) and Bar-Ilan et al. (2008) is that they assumed emission factors of an uncontrolled Tier 0 engine, with no accounting for fleet replacement with sources that meet more stringent standards (Tier 1 or higher). The majority of the diesel engine emission data used for the 2009 inventory met the Tier 1 standard. The emission factors in this study are based on standardized test cycles. For example, the generator engines in Shah et al. (2006) were tested on a 5-mode test cycle for nonroad compression ignition engines (Code of Federal Regulations 2004, Title 40, Part 89). One concern is that nonroad diesel vehicles are often operated under transient loads, which can significantly increase emissions (Clark et al., 2010; Lewis et al., 2011; Frey and Kim, 2006; Frey et al., 2010). However, the NONROAD model does not recommend any adjustment for transient loading in oil and natural gas equipment.

To estimate emissions for the 2020 inventory, the control factors listed in Table 4 were applied to the 2009 emission factors in Table 3. For example, for NO_x, a triangular distribution of control factors was used with a mode at 30% (the most probable value for the reduction in 2020 relative to 2009), which is somewhat smaller than the control factor (40%) assumed for the Haynesville Shale region (Grant et al., 2009). The maximum and minimum values of each distribution are based on implementation of specific technologies. For NO_x, the minimum control factor of 10% corresponds to ignition timing retard (ITR) and a maximum of 95% that corresponds to selective catalytic reduction (Bar-Ilan et al., 2007; EPA, 2004). A similar analysis was performed for $PM_{2.5}$ and VOCs (see Supplemental Materials for details). After applying the control factors, Figure S1a indicates that more than 85% of projected drill rig emission factors used for the 2020 baseline analysis meet the EPA nonroad diesel Tier 2 standards for similarly sized engines. Additionally, more than 70% of the projected emission factors for $PM_{2.5}$ and VOCs fall below the Tier 2 standards.

The cumulative percentage of the drill rig fleet estimated to be outfitted with new control technology in 2020 is summarized in Table 4. The lower end (50% cumulative fleet turnover by 2020) is from the Regulatory Impact Analysis for the Tier 4 Standards (EPA, 2004), and the upper end (100% fleet turnover by 2020) is from data reported by Chesapeake Energy (2011). Activity parameters (drilling time, engine horsepower) were obtained from interviews with personnel at state agencies (Pennsylvania Department of Environmental Protection [PADEP], New York Department of Environmental Conservation [NYDEC], West Virginia Geological and Economic Survey [WVGES]). They are summarized in Table 4. Drilling times in the Marcellus range from 10 to 35 days. The average time is 30 days, which is about half that in the Haynesville Shale because the Marcellus Shale is shallower (~6000 ft) than the Haynesville formation (~12000 ft) (Grant et al., 2009).

Drill rig engines often do not operate at full load or 100% of the time when they are on site (Grant et al., 2009; Bar-Ilan et al., 2008; Armendariz, 2009). In the absence of Marcellus-specific data for these parameters, data from Texas for load factor (Baker and Pring, 2009) and from the Central Regional Air Partnership (CENRAP) region for % on-time (Grant et al., 2009; Bar-Ilan et al., 2008) were used. Grant et al. (2009) and Bar-Ilan et al. (2008) used a point value of 67% for load factor, but the load factor on drill rig engines is highly variable and ranges from 10% to 90% (e.g., Baker and Pring, 2009). The assumption is that these activity parameters are not basin specific.

Figure 3 shows distributions of estimated NO_x, $PM_{2.5}$, and VOCs emissions to drill one well in the Marcellus formation in 2009 and 2020. The 2009 mean NO_x emissions is 4.4 (0.8–11.5; range denotes 95% confidence interval) tons/well, which is comparable to the NYDEC estimate of 3.8 tons/well (NYDEC, 2011). The 95% confidence interval here is the range of the emission distributions, resulting from inter-unit variability in the input parameters. The mean NO_x emissions to drill a single well is estimated to fall by ~35% from 2009 to 2020, from 4.4 to 2.9 (0.5–8.1) tons/well. The mean $PM_{2.5}$ emissions for drilling one well in 2009 is estimated to be 0.3 (0.03–1) tons/well and to fall by 60% to 0.11 (0.01–0.4) tons/well in 2020. The mean VOC emissions to drill a well are 0.5 (0.06–1.8) tons/well in 2009 and are estimated to fall to 0.1 (0.02–0.5) tons/well in 2020.

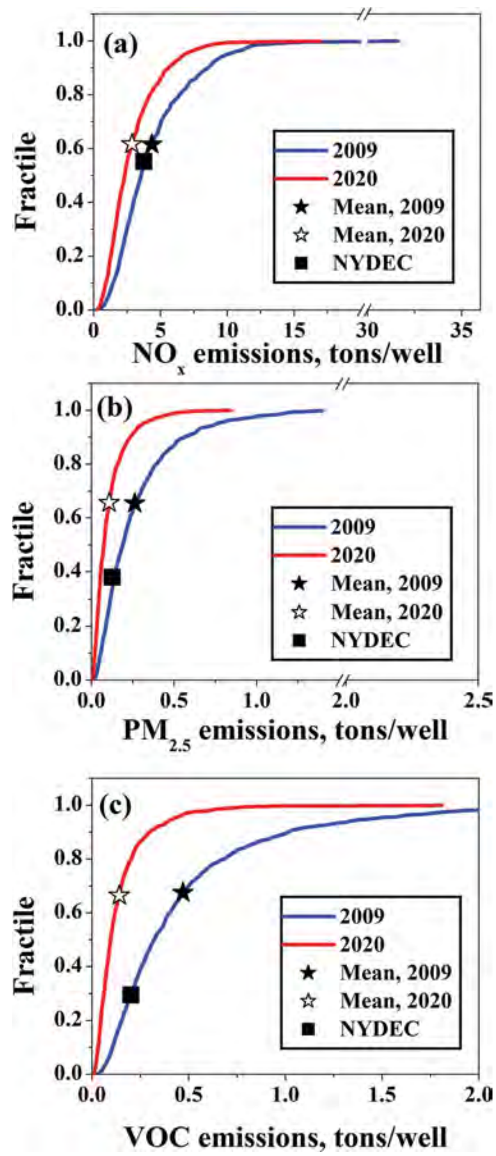

Figure 3. Estimated cumulative distributions of emissions for drilling one well: (a) NO_x, (b) $PM_{2.5}$, and (c) VOCs. The 2020 distributions correspond to the base scenario. The estimates made by (NYDEC, 2011) are shown for reference.

Hydraulic fracturing. Hydaulic fracturing (fracing) is performed to stimulate natural gas production after a well bore has been drilled. Pumps powered by 1000–1500 hp diesel engines pump large quantities of fluid and sand into the well bore to fracture the formation. Typically, there are 8–10 frac pumps per well. For each well, horizontal drilling of "laterals" is performed to access the gas. Perforations known as stages are made in the lateral lines at approximately every 100 m through which fracing fluid is pumped. Typically, there are 5–35 stages per well (Table 4). Emissions (tons/well) for fracturing a single well are estimated according to the number of stages per well:

$$E_{\text{fracing}} = EF_i \times HP \times LF_{\text{average}} \times N_{\text{stages}} \quad (3)$$

where EF_i is the emission factor from one pump engine for pollutant i (g bhp^{-1} hr^{-1}), HP_{total} is the combined horsepower-hour required for one fracturing stage, LF_{average} is the average load factor of the pump engine, and N_{stages} is the total number of stages needed to fracture one well. Distributions of these input parameters are plotted in Figure S2 in Supplemental Materials and summarized in Table 4.

The authors are not aware of frac-pump-specific emission factor data and therefore compiled emission factors for similarly sized heavy-duty diesel engines that are used in other applications, such as locomotives and generators, from the EPA's AP-42 and other literature (see Supplemental Materials). The locomotives considered were diesel electric switching locomotives rated between 1000 and 2000 hp, which use similar engines as those used for fracing oil shale wells (e.g., Sawant et al., 2007). The average NO_x, $PM_{2.5}$, and VOC emission factors for frac pumps are 5.4, 0.4, and 0.67 g hp^{-1} hr^{-1}, respectively, which are 30–50% lower than the data used by Grant et al. (2009) to construct the Haynesville Shale inventory.

The control factors for the 2020 baseline analysis are summarized in Table 4 and plotted in Figures S2f–h in Supplemental Materials. These distributions are the same as those for drill rigs. A distribution for the turnover of frac pumps was calculated by using a scrappage curve from the EPA's NONROAD model (EPA, 2008), assuming median lives of 5 and 10 yr, respectively.

Activity data for fracing include horsepower-hour required per stage and number of stages required to fracture one well. It was assumed that the length of the lateral will increase with time in order to provide more accessibility to the gas; therefore, the mode of the number of stages is assumed to increase to 33 in 2020 (Andrew Place, EQT Corporation, personal communication). Frac pumps usually operate at 50% of the load (Armendariz, 2009; Grant et al., 2009).

The NO_x, $PM_{2.5}$, and VOC emissions associated with fracturing one well are given in Table 5, and their distributions are plotted in Figures S3a–c in Supplemental Materials. The reductions in NO_x, $PM_{2.5}$, and VOCs for fracing in 2020 relative to 2009 are somewhat smaller than those used for drilling because of the assumed increase in the number of stages per well over time.

Trucks. Trucks are used to transport drilling and fracturing equipment, water, chemicals, waste water, and other material to and from a well site. These trucks are typically tractor trailers (U.S. Department of Energy [USDOE], 2009; Chris Tersine at PADEP). Other oil and gas inventories (Grant et al., 2009; Bar-Ilan et al., 2008) have not included truck traffic as a source. Emissions from trucks were estimated as (Jiang et al., 2011)

$$E_{\text{traffic}} = EF_i \times L_{\text{trip}} \times N_{\text{trip}} \tag{4}$$

where EF_i is the truck emission factor for a given pollutant i (g mile^{-1}), L_{trip} is the distance per trip, and N_{trip} is the number of trips associated with bringing a single well into production, which is multiplied by 2 to reflect the return trip. Distributions of these input parameters are plotted in Figure S4 (Supplemental Materials) and summarized in Tables 3 and 4.

Emission factors for trucks were taken from the large literature for diesel trucks. The average NO_x, $PM_{2.5}$, and VOC emission factors for trucks are 38, 0.33, and 1.71 g mile^{-1}, respectively. The literature documents tests performed on these engines under a wide range of conditions, which include varying load, cold start, hot soak, etc. (e.g., Fujita et al., 2007). The EPA's MOVES model (EPA, 2013c) was not used to estimate emissions, because, like NONROAD, it calculates point values and not distributions. Activity data for truck traffic are summarized in Table 4. The effect of truck load on emissions is not taken into account because there is no definitive conclusion about the behavior of emissions under load. For example, a report by the American Transportation Research Institute (ATRI, 2009) indicated that NO_x, VOC, and $PM_{2.5}$ emissions could decrease by 3–8% under increased loading. However, the work of Gajendran et al. (2003) indicated that NO_x emissions linearly increased with truck loading, whereas $PM_{2.5}$ and VOC emissions were unaffected. The number of truck trips per well ranged from 300 to 1300 based on data from the National Park Service (USGS, 2008). Different trip lengths were assumed for wastewater hauling and all other activities. The reported distances from a well site to a wastewater facility ranges between 3 and 280 miles (Jiang et al., 2011); a median of 80 miles was assumed. Vehicle miles traveled for well setup (from the trucking center to the well site) were assumed to range from 0 to 20 miles with a mode of 10 miles based on data from NYDEC (2011) and Jiang et al. (2011). Truck traffic for both well setup and wastewater disposal could be significantly reduced by the use of pipelines; this scenario is not considered in this analysis.

The trucking emissions per well and their associated uncertainty are presented in Table 5, whereas distributions of the truck emissions per well are presented in Figure S5 in Supplemental Materials. The 2020 baseline values are roughly a factor of 2–4 lower than their 2009 counterparts due to the implementation of controls.

Completion venting. After a well has been drilled and fractured, the well is vented to remove debris, liquids, and inert gases used to stimulate gas production. This procedure is called completion venting (also called flowback); it can be an important source of VOCs, especially for wet-gas wells (gas with significant amounts of higher-molecular-weight hydrocarbons). Emissions for completion venting are estimated as

$$E_{\text{completion}} = \rho_{\text{gas}} \times V \times f_i \tag{5}$$

where $E_{\text{completion}}$ is the emissions from a single completion event (tons/well), ρ_{gas} is the mass density of the gas, V is the volume of gas vented per completion, and f_i is the mass fraction of VOCs (nonmethane organic compounds) in the vented gas.

In the absence of Marcellus-specific data on the volume of gas vented per completion, data collected in other basins (Armendariz, 2009; Bar-Ilan et al., 2008), reported by the EPA's Natural Gas Star Program (EPA, 2004b), The Williams Companies (2007), and ENVIRON International Corporation (2006) were used as surrogates. The values span several orders of magnitude, ranging from 18 to 24,000 million cubic feet (MCF; 0.5–650 m^3), with a mean value of 3715 MCF (100 m^3) per well completion. The EPA's Oil and Gas Rule (EPA, 2012b) requires reducing these emissions by 90–95% using green completions.

VOC emissions from completion venting depend on whether the well is a dry- or wet-gas well. Dry gas is typically encountered in most of the Marcellus Fairway, but some wet gas is found in West Virginia and some parts of southwestern Pennsylvania (PADEP, 2010; WVGES, 2011; Brown, 2005). The reported VOC fractions, f, vary between 17% and 33% for wet gas and between 0.5% and 6% for dry gas (Chesapeake Energy Corporation, 2011). For 2009, the fraction of wet gas produced is taken from state reports (PADEP, 2010; WVGES, 2011). In 2020, it is assumed that 20–50% (uniform distribution) of gas produced comes from wet-gas-producing regions (Considine, 2010) and that 20–50% of the gas produced in these regions is actually wet (Andrew Place, EQT Corporation, personal communication).

A list of the dry- and wet-gas counties in each state is given in Table S1 in Supplemental Materials. Wet gas is typically encountered in the Washington and Butler counties in southwestern Pennsylvania and also in the counties of northern West Virginia. The rest of the Marcellus region is reported to be dry gas (Brown et al., 2005).

The mean emissions for both dry- and wet-gas wells are summarized in Table 5, and the distributions are plotted in Figure S7 in Supplemental Materials. The emissions per wet well for both years is around a factor of 5 higher than the dry wells because of higher VOC content. The average unit well estimates for both categories go down by roughly a factor of 4 in 2020 due to stricter controls due to the EPA's Oil and Gas Rule (EPA, 2012b).

Wellhead compressors. Wellhead compressors are relatively small (50–250 hp), natural-gas-fired spark-ignited reciprocating internal combustion engines located at the wellhead to raise the pressure of the produced gas to that required in the gathering line. Wellhead compressors emit NO_x, $PM_{2.5}$, and VOCs. Emissions from a single compressor are estimated as

$$E_{\text{Engine}} = EF_i \times HP \times LF_{\text{average}} \times t_{\text{annual}} \tag{6}$$

where EF_i is the emission factor of pollutant i in g $\text{bhp}^{-1}\ \text{hr}^{-1}$, HP is the horsepower rating of the engine, LF_{average} is the average load factor, and t_{annual} is the number of hours per year the engine operates.

Wellhead compressors are currently not common in the Marcellus formation, but shale gas wells typically have a steep decline curve. Therefore, wellhead compressors are often required as a field ages. For 2020, it was assumed that wellhead compressors are more common, with a mode at 7% and a range from 0% to 45%, which is based on CENRAP data (Bar-Ilan et al., 2008).

Emission factors for wellhead compressors were obtained from permits filed with PADEP (Naishadh Bhatt, PADEP, personal communication). The distributions of wellhead compressor horsepower ratings were taken from CENRAP data (Bar-Ilan et al., 2008) and distributions of load factor data from Texas (Pollution Solutions, 2008). These engines are assumed to operate 24 hours a day, 365 days of the year, with negligible downtime (Energy Information Administation [EIA], 2007; Grant et al., 2009; Bar-Ilan et al., 2008).

The control factor distributions for compressors used to develop the baseline 2020 case are listed in Table 4 and plotted in Figure S8 in Supplemental Materials. These are based on specific technologies (e.g., selective catalytic reduction [SCR]) and recent New Source Performance Standards (NSPS) promulgated by the EPA.

The emission distributions for wellhead compressors are shown in Figure S9 in Supplemental Materials. The NO_x and VOC emissions are reduced in 2020 by a factor of 2 and 4, respectively, due to controls, whereas $PM_{2.5}$ remains unchanged.

Condensate tanks. Condensate tanks store higher-molecular-weight hydrocarbons (carbon number >5) that are separated on site from the produced gases. Emissions from condensate tanks include working, breathing, and flashing (Bar-Ilan, 2008; Hendler et al., 2009). Emissions from condensate volatilization are estimated using the approach of Armendariz (2009) and Bar-Ilan et al. (2008):

$$E_{\text{Condensate,Tanks}} = EF_{\text{Condensate,Tanks}} \times P_{\text{Condensate,Tanks}} \tag{7}$$

where $EF_{\text{Condensate,Tanks}}$ is the VOC emission factor (lb bbl^{-1}) and $P_{\text{Condensate,Tanks}}$ is the region-wide condensate production rate (bbl yr^{-1}). Therefore, key inputs are the condensate production rate (bbl yr^{-1}) and an aggregate VOC emission factor. Condensate is typically produced in wet-gas regions.

In the absence of Marcellus-specific emission factors for condensate tanks, the data from the CENRAP region (Bar-Ilan et al., 2008) and the Barnett Shale (Armendariz, 2009) were used as a surrogate. The data span several orders of magnitude, ranging from 0.7 to 215 lb bbl^{-1} (2.6–850 kg m^{-3} of condensate liquid produced), with an average value of 29 lb bbl^{-1} (123 kg m^{-3}).

For the 2020 inventory, it was assumed that condensate tank emissions are significantly reduced by based on the implementation of the EPA's Oil and Gas Rule (EPA, 2012b). The control technologies include flaring and the use of vapor recovery units (VRUs).

Pneumatic devices. Pneumatic devices are used for a variety of wellhead processes that are powered mechanically by high-pressure natural gas as the working fluid; hence, they are pneumatically powered devices. They are required in remote well sites where electric power is not available (Grant et al., 2009). Because they operate on compressed gas, they can be a source of VOCs. The emissions typically depend on the type and number of devices (e.g., pneumatic-level controllers, valves, etc.), the bleed rate of gas from these devices, and the VOC content of the gas (wet or dry) (Bar-Ilan et al., 2008; Grant et al., 2009). The number and type of devices from the CENRAP region (Bar-Ilan et al., 2008) were used here. The EPA's Oil and Gas Rule (EPA, 2012) states that operators will be required to reduce emissions from pneumatic devices to 6 standard cubic feet (scf) hr^{-1} by 2020. The current and projected bleed rates are given in Table S3.The emissions for a single well are estimated as

$$E_{\text{pneumatics}} = f \times \left(\sum_i V_i \times N_i \times t_{\text{annual}} \right) \times \frac{P}{\frac{RT}{MW_{\text{gas}}}} \tag{8}$$

where V_i is the volumetric bleed rate from device i (scf hr^{-1} device^{-1}), N_i is the total number of device i present per well, t_{annual} is the total number of active hours (8760 per year), P is the pressure (1 atm), R the universal gas constant, MW_{gas} is the molecular weight of the produced gas, T is the atmospheric temperature (298 K), and f is the mass fraction of VOC in the vented gas. Because the VOC contents of dry and wet gas are significantly different, emissions for these two kinds of wells were estimated separately, using the same VOC content for dry and wet gas as for completion venting. Unit well emissions are listed in Table 5 and plotted in Figure S12 (Supplemental Materials).

Compressor stations. Compressor stations maintain the gas pressure in gas transmission lines. They typically contain multiple (3–15) large (1000–2000-hp) natural-gas-fired compressors, and therefore emit NO_x, VOCs, and $PM_{2.5}$. The emissions from compressor stations are calculated based on installed horsepower:

$$E_{\text{station}} = EF_i \times H \times t \times LF_{\text{average}} \tag{9}$$

where EF_i is the emission factor in g $\text{hp}^{-1}\ \text{hr}^{-1}$, H is the horsepower required to pump a billion cubic feet of gas per day (BCFD), t is the number of hours a day the compressor is in operation (typically 24 hr), and LF_{average} is the fraction of horsepower that is actually utilized by the compressor engine.

Emission factors for compressor stations are not documented in the literature, but comparison of NO_x emission factors of similarly sized engines (e.g., Bar-Ilan et al., 2008; Pring et al., 2010) indicates that the average NO_x emission factor of 1.5 g bhp^{-1} hr^{-1}, is significantly smaller than those in Texas, 3–12 g bhp^{-1} hr^{-1}. The total number of compressor stations is projected using online gas production data from the PADEP website (PADEP, 2011), and records of installed compressor capacity (Naishadh Bhatt, PADEP, personal communication). Quarterly installed horsepower data from December 2008 to December 2010 are plotted against gas production in Figure S15d (Supplementary Materials). There is a strong linear correlation between total gas produced and net installed compressor station horsepower. A linear regression yields a slope of 0.14 hp/BCFD ($R^2 = 0.95$), the uncertainty ranging from 0.125 to 0.15 hp/BCFD. This range was represented by a uniformly distributed random variable in the Monte Carlo analysis. Compressor engines operate at an average load factor of between 40% and 80% (Robert Clausen, Delaware Department of Natural Resources and Environmental Conservation, personal communication; Burklin and Heaney, 2005).

The control factors for NO_x and VOCs emissions from compressor stations are summarized in Table 4. The data are from Bar-Ilan et al. (2007) and from a draft technical report on oil and gas sector NO_x emissions prepared by the Ozone Transport Committee (Robert Clausen, Delaware Department of Natural Resources and Environmental Conservation, personal communication).

The distributions of compressor stations emissions are summarized in Table 5 and plotted in Figure S16 (Supplemental Materials). NO_x and VOC emissions are reduced by a factor of 2 and 3, respectively, from 2009 to 2020, whereas $PM_{2.5}$ emissions remain unchanged.

Gas processing and transmission fugitives. Processing and transmission fugitive emission factors are from the American Petroleum Institute (API, 2009), Armendariz (2009), and the Canadian Association of Petroleum Producers (CAPP, 2007). Given the limited data, these EFs were assumed to have a triangular distribution. These emission factor distributions ranged between the lower and higher values of 0.35 and 7 tons/BCF and have a mode at the average value of 3.5 tons/BCF. This distribution is then scaled by the gas production data in Table 1. Given the lack of fugitive-specific emission control factors, the same control factors were used as for completion venting.

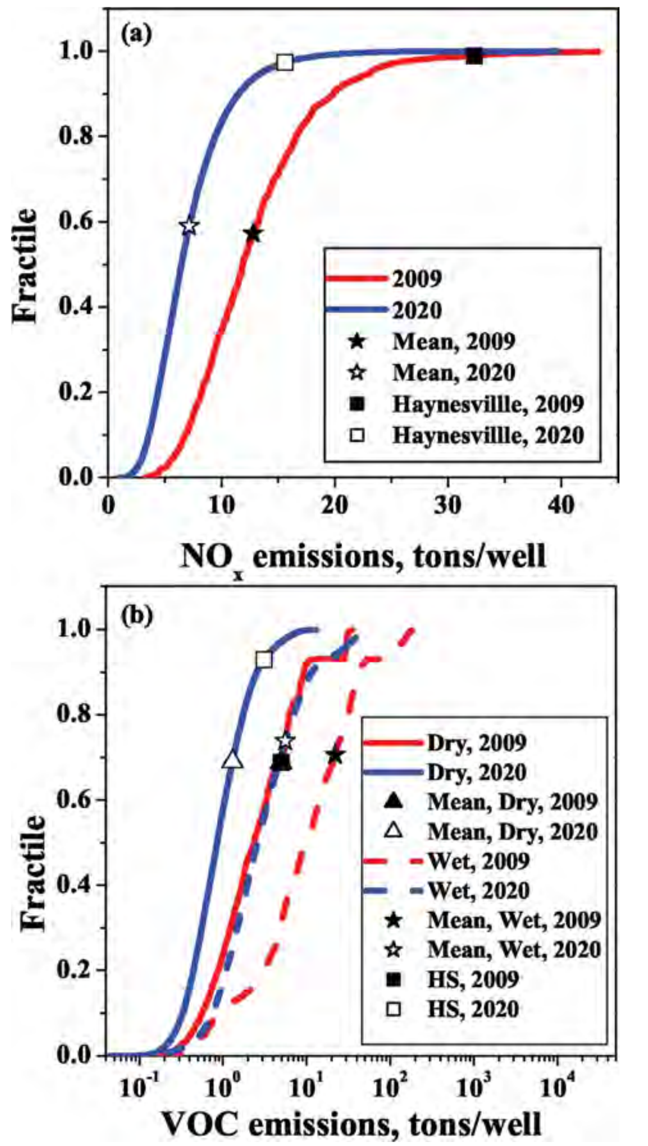

Figure 4. Cumulative distribution functions for well development emissions of (a) NO_x and (b) VOCs. The vertical lines labeled "HS" refers to the Haynesville Shale inventory developed by Grant et al. (2009).

Activity-level emissions

In this section, the different process-level estimates are combined into a unit activity basis for well development, gas production, and gas processing. Parentheses used henceforth denote a 95% confidence interval. Figure 4 plots distributions of NO_x and VOC emissions to develop a single well. Similar plots for gas production and midstream processing are shown in Figure S17 (Supplemental Materials). The mean and 95% CI associated with each of these unit activity estimates is summarized in Table 6. A significant decrease in these unit activity estimates is seen in 2020 as compared with 2009 due to the use of emission control technologies. The source-resolved emissions for each of these activities are plotted in Figure S18 (Supplemental Materials). The average NO_x emissions to bring a single well online in 2009 is 12.8 (5.1–28.3) tons/well, which is reduced by around 40% in 2020, to 7.2 (2.6–16) tons/well. The 2009 NO_x emissions are about 2 times lower than those reported by Grant et al. (2009) for the Haynesville Shale. Grant et al. (2009) used a higher drill rig NO_x emission factor (8 g bhp^{-1} hr^{-1} versus the average here of 5.6 g bhp^{-1} hr^{-1}), and the drilling time in the Haynesville Shale is much longer (63 versus 30 days).

Figure 4b plots distributions of VOCs to develop a single well; the mean VOC emission to set up a dry well in 2009 is 5.0 (0.3–30) tons/well, which is reduced to 1.3 (0.2–5.4) tons/well in 2020 due to the implementation of controls associated with the EPA's Oil and Gas Rule (EPA, 2012b). The 2009 VOC emissions are quite similar to the Haynesville estimate of 4.6 tons/well, which also is for a dry-gas well. The mean VOC emissions for a wet-gas well are much higher than a dry-gas

Table 6. Unit activity emissions: means (95% CIs)

Activity	Pollutant: NO_x 2009	NO_x 2020	$PM_{2.5}$ 2009	$PM_{2.5}$ 2020	VOCs 2009	VOCs 2020
Development (tons/well drilled)						
Dry well	12.8 (5.1–28.3)	7.2 (2.6–16)	0.5 (0.1–1.5)	0.2 (0.06–0.5)	5.0 (0.3–30)	1.3 (0.2–5.4)
Wet well	12.8 (5.1–28.3)	7.2 (2.6–16)	0.5 (0.1–1.5)	0.2 (0.06–0.5)	22 (0.4–145)	5.6 (10^{-3} to 36)
Production (tons/producing well)						
Dry well	1.2 (0.2–2.5)	0.6 (0.1–1.0)	0.01 (6×10^{-5} to 5×10^{-2})	0.01 (6×10^{-5} to 5×10^{-2})	0.9 (0.3–1.9)	0.2 (0.04–0.6)
Wet well	1.2 (0.2–2.5)	0.6 (0.1–1.0)	0.01 (6×10^{-5} to 5×10^{-2})	0.01 (6×10^{-5} to 5×10^{-2})	4.0 (2.6–6)	1.0 (0.6–1.5)
Midstream (tons/BCF)	3.3 (1.0–5.2)	1.5 (0.3–3)	0.3 (4×10^{-4} to 0.1)	0.3 (4×10^{-4} to 0.1)	8.1 (2.6–14)	2.2 (0.7–4.5)

well, 22 (0.5–149) tons in 2009, which reduces to 5.6 (0.4–36.4) tons in 2020. Although unit well development VOC emissions for dry gas in 2009, as plotted in Figure S18 in Supplemental Materials, are similar to that for the Haynesville Shale (Grant et al., 2009), the source distributions are different. For dry-gas wells, completion venting is predicted to dominate the VOC emissions in the Marcellus formation versus drilling in Haynesville. Drilling is dominant in the Haynesville inventory due to larger emission factors and longer drilling time compared with the Marcellus. Additionally, the average unit dry-gas well estimates in 2020 presented here are roughly a factor of 2 lower than the Hayesville estimates of Grant et al. (2009). They did not take into account new controls required by the EPA's recent Oil and Gas Rule (EPA, 2012b) for completion venting, which will significantly reduce VOC emissions. As shown in Figure S17 in Supplemental Materials, the mean NO_x emissions from one producing well are 1.2 (0.2–2.5) tons/well, which falls to 0.53 (0.1–1.0) tons/well in 2020 due to usage of controls. NO_x emissions from a producing well are dominated by wellhead compressors (>99%) with negligible contribution from heaters. The PM emissions remain unchanged because PM controls are unlikely to be implemented on natural-gas-fired engines.

VOC emissions from a single producing well follow the same trend as completion venting emissions, and the emissions from a wet well differ significantly from a dry one. As seen in Figure S18 (Supplemental Materials), these emissions are dominated by pneumatics in both categories (dry and wet). Average midstream NO_x emissions of 1.5 (0.3–3.0) tons/BCF are a factor of 10 lower than the Haynesville estimates of 15 tons/BCF, because the effect of future controls for compressor stations.

Source-resolved Marcellus-wide emissions

Figure 5a–c show the source-resolved Marcellus-wide emissions of total NO_x, $PM_{2.5}$, and VOC emissions for 2009 and the 2020 base case, which assumes that the equipment fleet will have a distribution of control factors in 2020. These values are derived by combining the distributions shown in Figure 4 with the activity data in Table 1. Although emissions decrease from 2009 to 2020 on a per-unit-activity basis, the Marcellus-wide emissions increase substantially in 2020 due to increased activity (Table 1). For example, the Marcellus-wide NO_x emissions increase from 58 (23–123) tons/day in 2009 to 129 (56–211) tons/day in 2020.

Figure 5a indicates that the dominant sources of NO_x include well development activities, including drilling, fracing, and truck traffic from wastewater disposal. In 2020, compressor stations are also predicted to be a major source of NO_x because of increased gas production. Figure 5b indicates that drilling and fracing are the major sources of $PM_{2.5}$ in both 2009 and 2020. Figure 5c indicates that completion venting is the major source of VOC emissions in 2009, but in 2020 VOC emissions are dominated by sources associated with gas production, including condensate tanks, compressor stations, gas plants, and transmission fugitives. The cumulative distributions of the NO_x, $PM_{2.5}$,

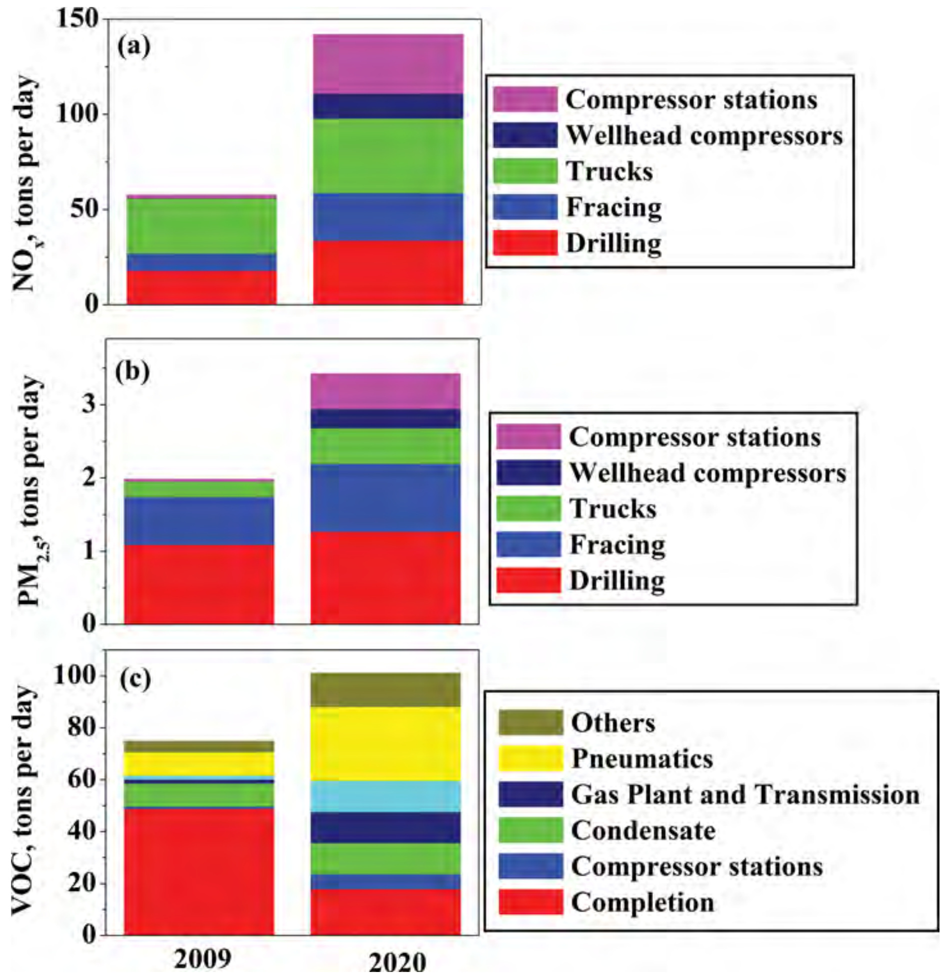

Figure 5. Source-resolved Marcellus emissions for (a) NO_x, (b) $PM_{2.5}$, and (c) VOCs in 2009 and 2020 (base scenario). The results are mean estimates. Other sources of VOCs include drilling, fracing truck traffic, and blowdown venting.

and VOC emissions are given in Figure S19 of Supplemental Materials.

Marcellus versus other sources. Figures 6a–c compare the predicted contribution from Marcellus activities with all the other sources in the Marcellus region, denoted by red grid cells in Figure 2b. These values are the averages from the distributions of emissions shown in Figure S19 (Supplemental Materials). The emissions for non-Marcellus sources are from the National Emissions Inventory 2008 (EPA, 2011b). In order to project these emissions to 2020, source-specific scaling factors were used, outlined in Table S7 in Supplemental Materials. For example, diesel NO_x emissions in 2020 are assumed to be 30% lower than in 2009 based on the projections of the Federal Highway Administration, the EPA's Clean Diesel Rule, and the various tier standards.

Figure 6a indicates that Marcellus development is predicted to contribute 12% (6–18%) of the regional NO_x emissions in 2020. In 2020, the Marcellus NO_x emissions will be roughly equal to those from gasoline vehicles and roughly half those from diesel vehicles.

Figure 6b indicates that Marcellus development will contribute negligibly to regional $PM_{2.5}$ emissions. However, it may be an important source for certain $PM_{2.5}$ components. For example, the contribution of Marcellus to elemental carbon was estimated using a distribution of diesel source profiles from the EPA's SPECIATE database (EPA, 2006). Marcellus development could contribute 14% (2–36%) of the regional elemental carbon emissions.

The contribution of Marcellus activity to regional anthropogenic VOC emissions is plotted in Figure 6c. Although Marcellus development is not as large a source as solvent usage and mobile sources, the increase in VOC emissions due to Marcellus development could significantly offset the reductions in emissions due to controls in other sectors.

Table S9 (Supplemental Materials) shows the predicted contributions to Marcellus NO_x and VOCs in 2020 for different states. It is predicted that Pennsylvania will contribute around 65% to Marcellus NO_x emissions, with West Virginia contributing 21% and New York contributing 14%, which follows the expected level of development in Table 1. Additionally, Pennsylvania is predicted to contribute 60% to Marcellus VOC

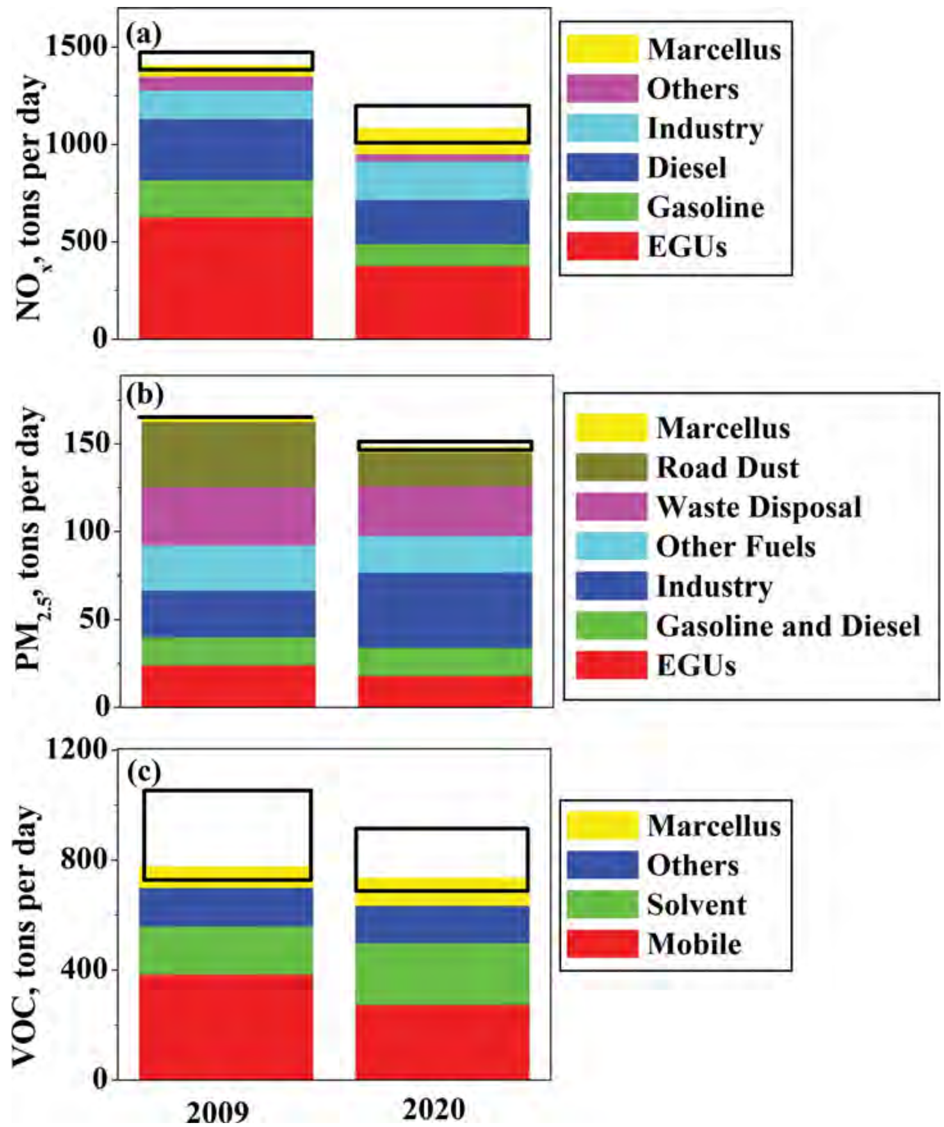

Figure 6. Source-resolved emissions of (a) NO_x, (b) $PM_{2.5}$, and (c) VOCs for the Marcellus region (Figure 1b). The 2020 emissions correspond to the average of the baseline controls scenario. The open black squares denote the 95% confidence intervals on the estimated Marcellus emissions. The cumulative distributions of emissions are plotted in Figure S19. VOCs correspond to anthropogenic VOC emissions.

emissions, with 30% from West Virginia and 10% from New York. West Virginia accounts for a larger share of Marcellus VOCs due to the wet gas and associated condensate in that part of the formation.

Effects of control technology on emissions

The 2020 base case accounts for the ongoing implementation of existing regulations. To investigate the benefits of these and potential future regulations, Figure 7 plots NO_x and VOC emissions for different control scenarios. Results are presented for three cases: base case described previously; "pre-2009" assumes that the equipment in 2020 have the same emission factors as in 2009; and "tight controls," which assumes that all the fleet equipment will be outfitted with the state-of-the-art control technology resulting in highest reduction in emissions, such as selective catalytic reduction (SCR) for NO_x emissions from internal combustion engines (e.g., drill rigs, frac pumps, well-head compressors, and compressor stations) and diesel particulate filter (DPF) for $PM_{2.5}$. Comparing the "pre-2009 controls" and "base" scenarios illustrates the benefits of existing regulations. Comparing the "base" and "tight control" scenarios indicates the potential additional emission reductions that are possible with existing technologies.

Figure 7a plots the cumulative distribution of NO_x emissions for these three scenarios. If the source-level emissions were the same in 2020 as in 2009, Marcellus activity could increase NO_x emissions by 251 (123–507) tons/day or 22% (11–35%) of regional NO_x emissions (Figure 7b). Here, percentage contribution is defined as the ratio of Marcellus emissions to the sum of Marcellus and regional emissions. This is much higher than the base case, which demonstrates the substantial benefit of existing

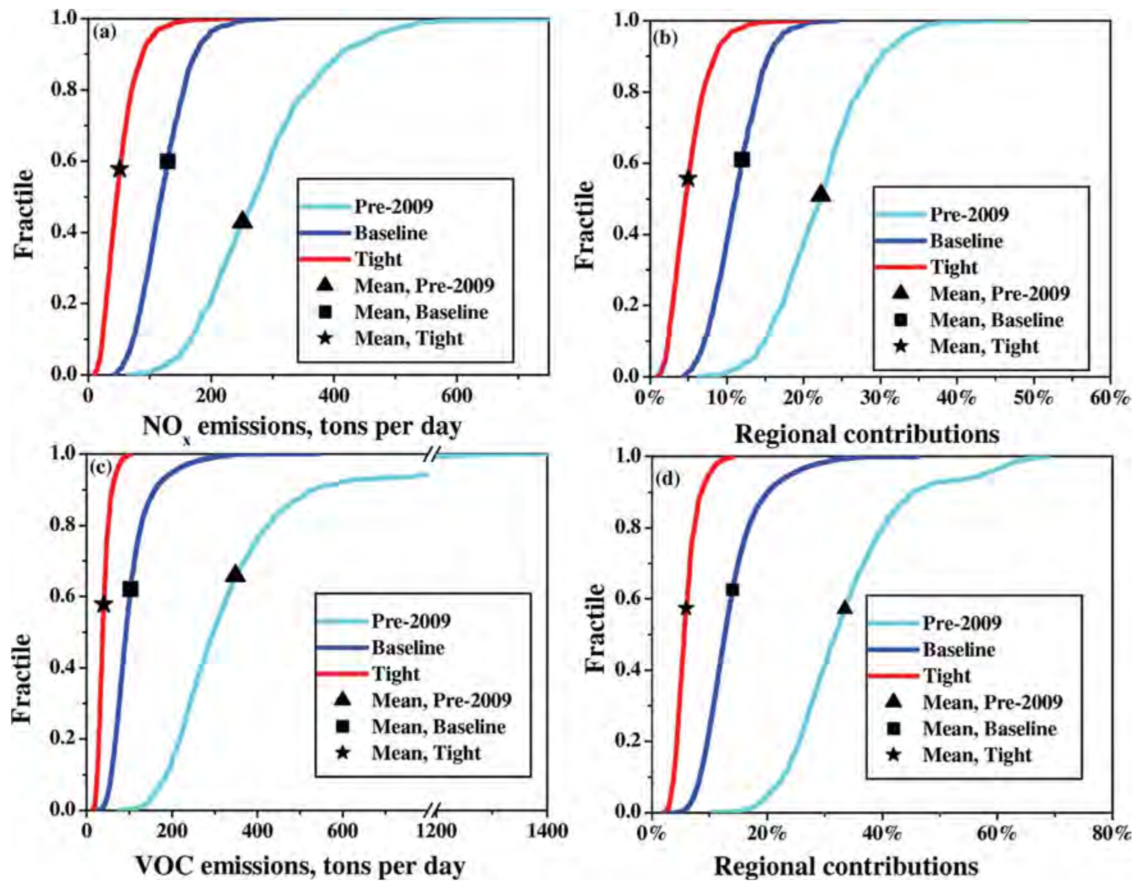

Figure 7. Comparison of different control scenarios for 2020 Marcellus emissions: (a) total NO_x emissions, (b) contribution of Marcellus to regional NO_x emissions, (c) total VOC emissions, and (d) contribution of Marcellus to regional VOC emissions.

regulations for reducing emissions from nonroad diesel engines and compressor stations. The "tight control" scenario reduces the 2020 NO_x emissions to 51 (16–121) tons/day, which is roughly 85% of the 2009 NO_x emissions, despite large increases in activity. Therefore, adoption of additional state-of-the-art controls could reduce Marcellus NO_x emissions to just 5% (1.6–11%) of regional NO_x emissions.

Figures 7c and d show the effects of different control scenarios on VOC emissions. If the source-level emissions were the same in 2020 as in 2009, Marcellus VOC emissions would be 345 (146–1020) tons/day or 34% (19–62%) of the regional anthropogenic VOC emissions in 2020. However, the implementation of tight controls indicates that Marcellus development would emit on average 41 (20–78) tons/day of VOCs into the region, contributing only 6% (3–11%) of the anthropogenic VOC emissions in 2020. A summary of the emissions and regional contributions from each control scenario is in Table 7.

Table 7. Estimates of 2020 Marcellus emissions for three control scenarios

	Pollutant	
Control Scenario	NO_x	VOCs
Pre-2009	251 (122–504)	345 (146–999)
	21% (11–35%)	34% (19–62%)
Baseline	129 (56–210)	100 (45–243)
	12% (6–18%)	14% (7–28%)
Tight	51 (16–120)	41 (20–80)
	5% (1.6–11%)	6% (3–11%)

Notes: The first line of data denotes absolute Marcellus-related emissions in tons per day: mean (95% CI). The second line denotes contributions to percent contribution to regional anthropogenic emissions: mean (95% CI).

Table 8. Correlation coefficients (R^2) between total emissions, key sources, and input parameters for 2020 baseline case

Pollutant	Source	Correlation of Source Contribution with Total Emissions	Key Uncertain Parameter	Correlation of Parameter with Source Emissions
NO_x	Drill rigs	0.61	Engine on-time	0.5
	Trucks	0.75	Trip VMT	0.5
VOC	Completion	0.73	Emission factor (volume vented/event)	0.9

Uncertainty and data limitations

As indicated by the distributions plotted in Figure 6 and in Figure S19 (Supplemental Materials), there is substantial uncertainty in the total emission estimates. For example, the projected 2020 NO_x emissions vary by almost a factor of 4 (56–211 tons/day) for the base case. In order to identify the major uncertainty drivers, sensitivity analysis was carried out on each input parameter listed in Tables 3 and 4 using correlation analysis (Saltelli et al., 2002; Jaffe and Ferrara, 1984). Briefly, the correlation coefficients between total emissions and emissions from a specific source category are computed. Next, correlation coefficients between the emissions from a specific source category and each input parameter are computed. Source categories and input parameters with the highest correlation coefficients are identified as the major sources of uncertainty.

Table 8 shows key findings from the sensitivity analysis. Drilling and truck traffic account for most of the uncertainty in NO_x emissions. Completion venting is the dominant uncertainty in VOC emissions associated with well development. Key uncertainties associated with NO_x emissions are engine on-time for drill rigs and distance driven by trucks; for VOCs, it is volume vented during completion venting. Large inter-unit variability amongst these parameters is the cause of uncertainty for their respective source estimates. Better data for these parameters will help improve emission estimates.

Conclusion

An emission inventory was developed for the Marcellus Shale to estimate emissions of NO_x, VOCs, and $PM_{2.5}$ in Pennsylvania, New York, and West Virginia. Emissions were estimated for 2009 and projected into 2020 using emission factor and activity data from a variety of sources.

The inventory predicts that Marcellus development will likely be an important source of regional NO_x and VOC emissions. In 2020, Marcellus development may contribute 12% (6–18%) of NO_x and VOC emissions in the Marcellus region. The new Marcellus emissions may offset projected emissions reductions in other sectors (mobile and electrical generating units). Given the potential magnitude of NO_x emissions in rural (NO_x-limited) areas, Marcellus development could complicate ozone management in this region. Marcellus development is not predicted to contribute significantly to regional $PM_{2.5}$ emissions. However, elemental carbon could be more of a concern, with Marcellus development predicted to contribute 14% (2–36%) of the regional elemental carbon emissions.

To investigate benefits of existing and potential future controls, the 2020 analysis considered three future control levels: current, baseline, and tight controls. VOC emissions from the base and tight control scenarios were similar (about a factor of 2), indicating a high level of control by existing regulations. However, more stringent controls could significantly reduce the contribution of Marcellus to regional NO_x emissions. For example, widespread implementation of SCR technology could reduce NO_x emissions to less than 3.5% (1.6–11.4%) of regional emissions versus 22% (11–35%) for the pre-2009 scenario.

An analysis was carried out to identify the major sources of uncertainty. Truck traffic (distance traveled) and drilling (engine on-time) were the key contributors to uncertainty in NO_x emission estimates. VOC emissions uncertainty was driven by volume of gas vented during completion. Because the major uncertainties in the inventory stem from activity data as well as emission factor measurements, these results suggest that improved data collection efforts could substantially constrain emission estimates from natural gas development.

The analysis does not consider the potential air quality benefits of increased end use of natural gas. For example, switching electricity generating from coal to natural gas could offset much of the increase in regional NO_x emissions associated with gas development and production. The impacts of the emissions from Marcellus development on regional air quality will be presented in a forthcoming paper.

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Supplemental Material

Supplemental data for this article can be accessed at http://dx.doi.org/10.1080/10962247.2013.826151.

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Article

Exploring the Relationship between Noise Sensitivity, Annoyance and Health-Related Quality of Life in a Sample of Adults Exposed to Environmental Noise

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Abstract: The relationship between environmental noise and health is poorly understood but of fundamental importance to public health. This study estimated the relationship between noise sensitivity, noise annoyance and health-related quality of life in a sample of adults residing close to the Auckland International Airport, New Zealand. A small sample (n = 105) completed surveys measuring noise sensitivity, noise annoyance, and quality of life. Noise sensitivity was associated with health-related quality of life; annoyance and sleep disturbance mediated the effects of noise sensitivity on health.

Keywords: noise; annoyance; noise sensitivity; health-related quality of life

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Abbreviation

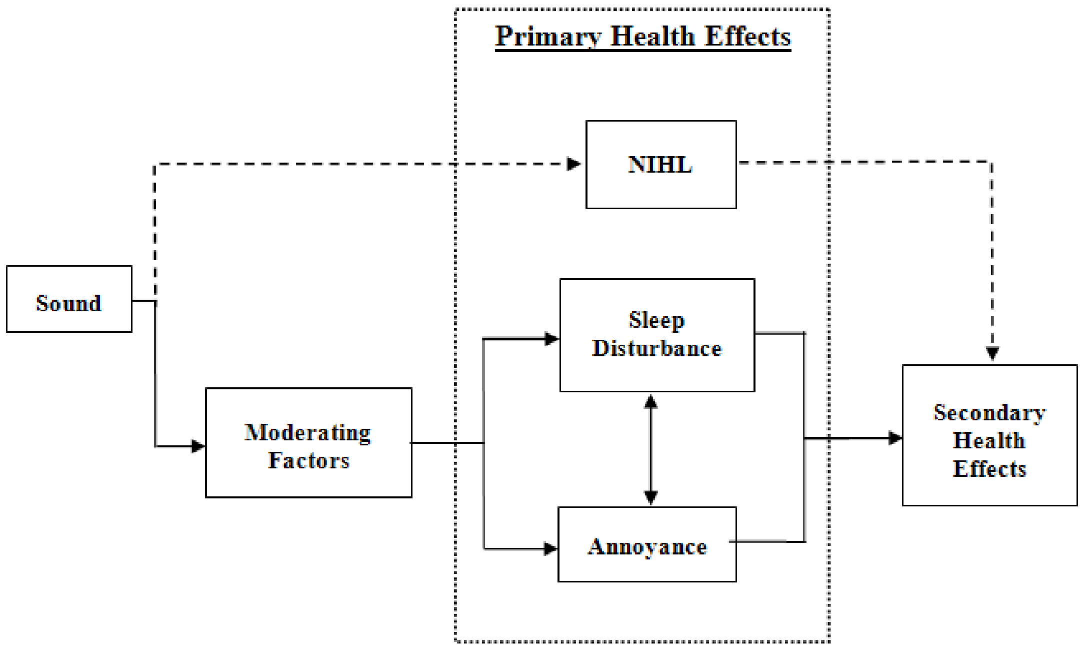
HRQOL = Health Related Quality of Life

1. Introduction

Health is multifaceted and encompasses not only disease and infirmity but also wellbeing [1]. Numerous factors interact to influence health and wellbeing, including biological (e.g., genetic makeup), lifestyle (e.g., diet), and environmental (e.g., air pollution) factors. Noise, defined at the psychological level of description as an unwanted sound, is increasingly being targeted as an environmental factor negatively impacting health. In some contexts noise can elicit annoyance or disrupt sleep in a manner detrimental to health, though the relationship between noise and health has yet to be satisfactorily elucidated [2-4]. Noise standards emphasize noise level as the primary factor in noise-induced health deficits, however, laboratory [5] and epidemiological (e.g., [6]) findings are increasingly challenging this stimulus-orientated approach, and have instead sought to uncover factors associated with the listener that predict health risk (for reviews see [7,8]).

Figure 1 is a schematic summarizing the relationship between noise and health. Two pathways are evident, the physical (dashed line) and non-physical (solid line) effects of noise. The physical effects of noise describe those noise-induced health deficits that are associated with sound level and frequency, with Noise-Induced Hearing Loss (NIHL) being an example. Health deficits incurred along this pathway may involve either wanted sound (e.g., attending a rock concert) or unwanted noise (e.g., working with loud equipment). The non-physical effects of noise are those which are mediated by psychological or psychophysiological processes.

Figure 1. Model detailing how noise might compromise health. The dashed lines indicate the physical effects of noise, which include Noise Induced Hearing Loss (NIHL), while the solid lines represent the non-physical effects of noise. The box labeled “moderating factors” represents the cumulative effect of traits, contextual factors, and noise parameters (e.g., amplitude modulation). Annoyance and sleep disruption act as mediators between predisposing factors and secondary health effects (e.g., health-related quality of life or disease).



There is general agreement in the literature that annoyance and sleep disruptions are the likely mediators of noise-induced health deficits (e.g., [3,6]). However, the relative contribution of noise parameters, personal characteristics, and contextual factors has yet to be determined. In relation to annoyance, the literature indicates that only 10 to 15 percent of the variability in ratings can be explained by noise level, arguing against the use of dose-response relationships as the sole basis for noise standards. The remaining variability is likely to be explained by a collection of interacting traits and contextual factors (*viz* moderating factors in Figure 1) including age [9], noise source and attitude to the noise source [10,11], personality [12,13], mental functioning [4], time of day [14] and noise sensitivity [15,16].

Noise sensitivity, considered a stable personality trait that is relatively invariant across noise level [17], is a strong predictor of noise annoyance [15,18,19], and has been correlated with sleep quality [3,20,21]. Stansfeld [15] described two key characteristics of noise sensitive individuals. First, they are more likely to pay attention to sound and evaluate it negatively (e.g., as threatening or annoying) and second, they have stronger emotional reactions to noise, and consequently, greater difficulty habituating. Noise sensitivity has a large impact on noise annoyance ratings, lowering annoyance thresholds by up to 10 dB [18], and a study of individuals exposed to low frequency noise in the workplace showed noise sensitive individuals were more annoyed by a low frequency noise than a broadband reference noise, while noise-resistant subjects reported that both noises were equally annoying [22]. However, while there is a strong correlation between noise sensitivity and annoyance, the correlation between noise sensitivity and noise level is weak, echoing the marginal relationship found between noise annoyance and noise level [3,7].

In this paper, we report data collected from individuals living in the vicinity of Auckland Airport, New Zealand's largest and most active airport. The survey area is designated a high aircraft noise area exposed to average outdoor noise levels between 60 and 65 dBA LDN. Consistent with the mode of transport effect [23], aviation noise is rated as more annoying than road traffic or rail noise [24], and we selected this area due to the presence of multiple sources of potentially annoying noise including road, rail, and neighborhood noise. In assessing the heath impacts of noise, a variety of outcome measures have been reported in the literature, including annoyance, sleep disturbance, cardiovascular disease, and wellbeing. One approach to health assessment involves a subjective appraisal of Health-Related Quality of Life (HRQOL), using tools measuring health satisfaction, irrespective of objective health status. The WHO [25] reports that noise-induced annoyance and sleep disturbance can, when chronic, compromise positive wellbeing and quality of life. Dratva *et al.* [26] using the Short Form (SF36) health survey, reported a negative relationship between annoyance and HRQOL in relation to road traffic noise. Published literature reviews indicate that HRQOL would be expected to co-vary more with annoyance than with objective noise measurements [7,8,27]. On this basis, we measured noise annoyance and HRQOL in a confined residential area exposed to constant levels of aviation noise. In accordance with the findings of Dratva *et al.* [26], negative correlations would be expected between HRQOL subscales and noise annoyance. Our main aim, however, is to further evaluate the model presented in Figure 1, specifically the relationship between noise sensitivity and health, and the mediating effects of annoyance and sleep. The interest in noise sensitivity arises due to an increasing number of studies indicating that noise sensitivity is the dominant non-acoustical influence of annoyance and sleep disturbance [3,28,29]. Furthermore, other studies have hinted that annoyance may be a mediating variable between noise sensitivity and mental health (e.g., [4]), though this relationship has yet to be conclusively demonstrated [16,27].

2. Methods

2.1. Participants

The participants were 105 adults residing in a cluster of relatively homogenous housing approximately 2.5 kilometres east of Auckland Airport's main runway. According to the New Zealand deprivation scores index [30] this area is ranked 9, where deprivation scores range from 1 (least deprived) to 10 (most deprived) and are calculated using census data corresponding to geographical areas containing a median of 90 people. The region in which Auckland Airport is located has the highest number of decile 9 and 10 (*i.e.*, most deprived) areas in New Zealand [30]. The sample area is designated a high aircraft noise area exposed to average outdoor noise levels between 60 and 65 LDN [31]. The demographic profile of the sample is displayed in Table 1.

Table 1. Demographic characteristics of participants (n = 105).

Variable	Category	Number	Percent
Sex	Male	25	23.8
	Female	72	68.6
	Unspecified	8	7.6
Age	18–20	5	4.8
	21–29	9	8.6
	30–39	18	17.1
	40–49	14	13.3
	50–59	28	26.7
	60–69	13	12.4
	70+	17	16.2
	Unspecified	1	1.0
Ethnicity	European	51	48.6
	Maori	20	19.0
	Pacific	12	11.4
	Asian	10	9.5
	Unspecified	12	11.4
Education	High School	59	56.2
	Technical	25	23.8
	University	20	19.0
	Unspecified	1	1.0
Occupation	Employed	49	46.7
	Retired/Sick	22	21.0
	Student	7	6.7
	Unemployed	5	4.8
	On leave	2	1.9
	Housewife	9	8.6
	Other	11	10.5
Total		105	100

2.2. Instruments

In addition to items requesting demographic information, the survey contained three self-report assessments, providing measures of HRQOL, noise annoyance, and noise sensitivity. Participants were asked to make their ratings with respect to the previous two weeks. Health-related quality of life was assessed using the World Health Organization Quality of Life (short-form) scale, the WHOQOL-BREF. The WHO ([32], p. 1404) defines quality of life as: "an individual's perception of their position in life in the context of the culture and value systems in which they live and in relation to their goals, expectations, standards and concerns. It is a broad ranging concept affected in a complex way by the person's physical health, psychological state, personal beliefs, social relationships and their relationship to salient features of their environment".

Quality of life, as defined above, is a multifaceted concept, and thus the WHOQOL-BREF produces a descriptive multi-dimensional profile of HRQOL, not a single index. The WHOQOL-BREF consists of 26 items divided into four domains: physical health (7 items), psychological wellbeing (6 items), social relationships (3 items), and environmental factors (8 items). There are two additional items probing overall quality of life and self-rated health. All 26 items in the WHOQOL-BREF are rated on a five point Likert-type scale. A low score on any domain or item equates to negative evaluations of that aspect of life, while a high score indicates a positive evaluation. The BREF is well suited to public health use, and the inclusion of environmental items extends the WHOQOL-BREF beyond traditional HRQOL measures which lack such perspective [33]. The WHOQOL-BREF has excellent reliability and validity [34] and the advantage of adopting a transcultural approach to QOL [34].

Noise sensitivity was estimated using the Noise Sensitivity Questionnaire (NOISEQ) scale [35] which measures global noise sensitivity as well as sensitivity for different domains of everyday life: leisure, work, sleep, communication, and habitation. The 35 NOISEQ items were adapted from the Weinstein Sensitivity Scale and Fragebogen zur Erfassung der Indiviuellen Larmempfindlichkeit (*the Individual Questionnaire of Noise Sensitivity*), and reformulated to increase face validity [35]. Each item asks the respondent to indicate their degree of agreement to statements about their responses to noise using a five point Likert-type scale, which we modified from the original 4-point NOISEQ scales [35]. Global noise sensitivity is computed as the average of the leisure, work, habitation, communication and sleep subscales, with higher means indicating greater sensitivity. The work, sleep and communication subscales have been reported to be sufficiently reliable, while the leisure and habitation subscales not nearly so [35,36].

Susceptibility to noise annoyance was assessed using a 12-item questionnaire developed as a composite of items: 5 items were based on Kroesen *et al.* [37] and focused on annoyance due to aviation noise, and 7 items were based on Thorne [38] and assessed annoyance due to other sources of neighborhood noise. Preliminary assessment using Cronbach's alpha suggested that it was appropriate to combine these items in that the overall alpha was >0.9 and all item-total correlations were >0.4. All 12 items were standardized and summed to create a General Noise Annoyance scale.

2.3. Procedure

Surveys were distributed to 350 randomly selected houses in a confined residential area adjacent to Auckland Airport. In this area, houses were of similar age and were constructed from similar materials. Each selected household received two copies of the survey accompanied by an information sheet and a postage-paid envelope to return the survey. Respondents completed the surveys independently in their own time, and no incentives were offered.

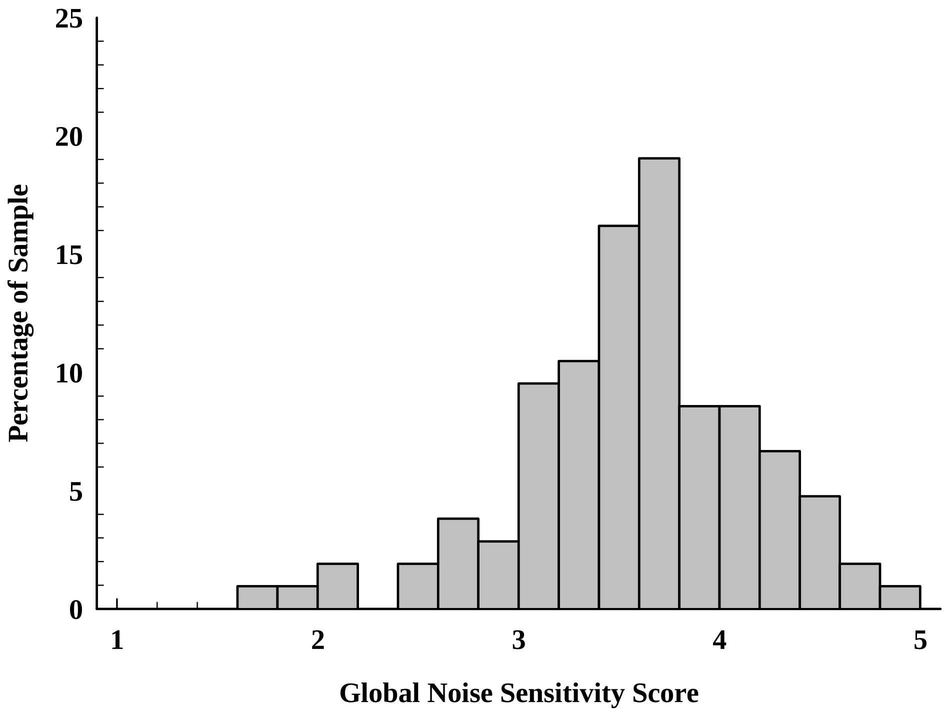
2.4. Analysis

All analyses were undertaken using the Statistical Package for Social Sciences (v.17). Prior to constructing summated variables any negatively-worded items were re-coded, and means and standard deviations calculated and inspected for evidence of floor or ceiling effects. Cronbach's alpha was computed for each scale and item-total correlations calculated to assess unidimensionality. Annoyance items were standardized prior to construction of a summated annoyance variable to remove unintended weightings. Modelling was performed using ordinary least squares linear regressions to scrutinize the relationship between Noise Sensitivity and HRQOL (the criterion variable), and the potential mediating roles played by Noise Annoyance and/or Sleep Quality. In the first step Noise Sensitivity was the sole predictor variable, while in the second step Noise Annoyance and/or Sleep Quality were included simultaneously in the models to test whether they mediated the bivariate relationships. Where regression coefficients between Noise Sensitivity and HRQOL measures were reduced by inclusion of the candidate mediator variables, it was taken as evidence consistent with a mediating role of Noise Annoyance or Sleep Quality on the original relationship.

3. Results

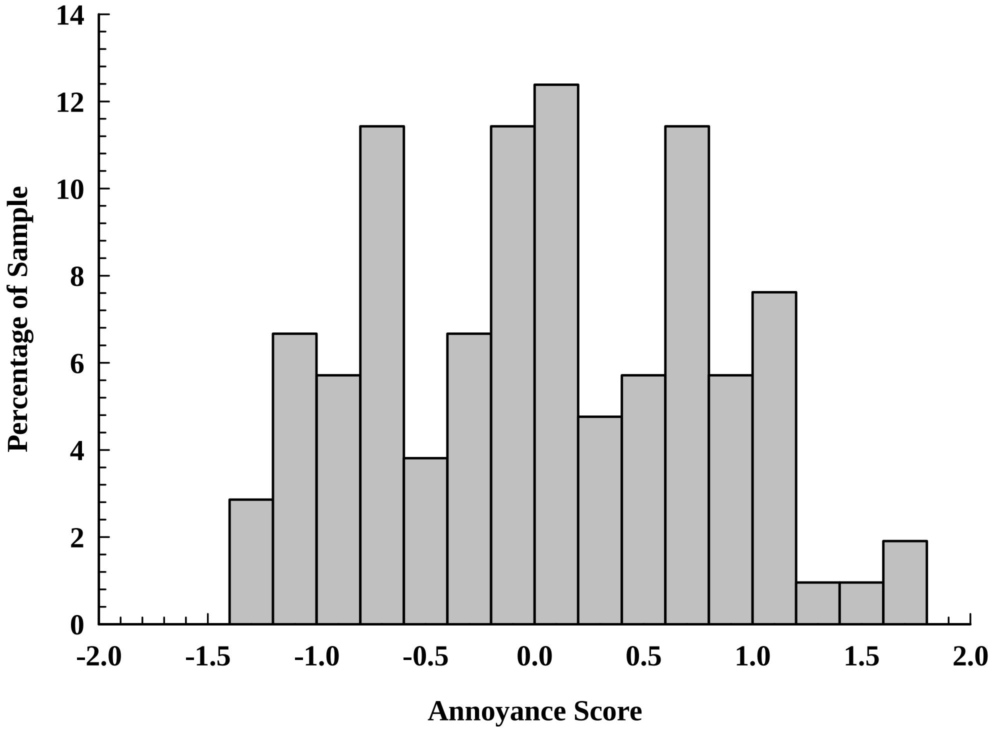
All subscales of the NOISEQ, including leisure and habituation, exhibited satisfactory psychometric properties, with means, standard deviations, and Cronbach's alphas (α_c) as follows: Leisure (M = 3.66, SD = 1.49, α_c = 0.816), Work (M = 3.51, SD = 1.3, α_c = 0.843), Habituation (M = 3.78, SD = 1.373, α_c = 0.836), Communication (M = 3.57, SD = 1.36, α_c = 0.827), and Sleep (M = 3.47, SD = 1.62, α_c = 0.864). From these subscales, a global noise sensitivity measure (see Figure 2) was computed by computing the average of the five NOISEQ subscales (M = 3.58, SD = 0.597, min = 1, max = 5, α_c = 0.918). The higher the global noise sensitivity score the more noise sensitive the individual, with 51% of our sample having mean scores greater than 3.5. Pearson's correlation coefficients (r) showed that general annoyance (see Figure 3) was positively correlated with all five NOISEQ subscales: Leisure ($r = 0.343$, $p < 0.001$), Work ($r = 0.354$, $p < 0.001$), Habituation ($r = 0.478$, $p < 0.001$), Communication ($r = 0.273$, $p = 0.005$), and Sleep ($r = 0.412$, $p < 0.001$), and also the global noise sensitivity measure ($r = 0.461$, $p < 0.001$).

Figure 2. Histogram of Global Noise Sensitivity scores. Global scores are calculated as the mean ratings for all 35 items contained in the NOISEQ. Higher scores represent greater sensitivity to noise.



To afford comparison with other reported aviation annoyance data [6,9,27] the five aviation annoyance items were summed to produce an aviation noise annoyance composite measure having a mean of 13.77 (*SD* = 6.37) and a Cronbach's alpha of .946. Here a mean close to 5 would indicate no evidence of annoyance towards aviation noise, whilst a mean close to 25 would represent extreme annoyance to such noise. Eighteen individuals scored greater than 20, and thus approximately 17% of participants can be considered severely annoyed. An independent samples *t*-test revealed no gender differences ($t(103) = –0.771$, $p = 0.443$) in overall aviation annoyance score and there were no linear associations with length of residence ($r = –0.124$, $p = 0.210$) or age ($r = –0.003$, $p = 0.974$). On the basis of the nonlinear relationship proposed by van Gerven *et al.* [9], a quadratic model was fitted to the age and aviation annoyance data, with the null hypothesis again supported ($r = 0.024$, $p = 0.871$). To examine the effect of education on aviation annoyance, "university" and "technical" were collapsed to make a higher education variable ($n = 45$), and when tested against those reporting a school-only education ($n = 59$) no differences were found in mean annoyance ($t(103) = 0.941$, $p = 0.349$).

Figure 3. Histogram showing General Noise Annoyance scores. Scores were the mean of 12 standardized noise annoyance items. Of remark is the multimodal nature of the distribution.



3.1. Noise Sensitivity, Noise Annoyance, Sleep Satisfaction, and HRQOL

Table 2 shows that all bivariate associations between measures of Noise Sensitivity and measures of HRQOL were negative (Table 2 (a), Model 1), implying that those with higher sensitivity to noise experienced lower HRQOL. After inclusion of General Noise Annoyance in the models (Table 2 (b), Model 2), the associations between Noise Sensitivity and HRQOL were reduced, implying that Noise Annoyance is a mediator. Note too in Table 2 that the associations between annoyance and the four HRQOL domains, and also self-rated health, reached statistical significance.

According to the literature, sleep quality is often affected by noise, and thus this item was removed from the WHOQOL Physical subscale and included in the modeling as a mediating factor in its own right (Table 2 (c), Model 3). Inclusion of Sleep Quality in the model relating Noise Sensitivity to measures of HRQOL showed that it acted as a mediator as well as introducing independent explanatory power (Table 2 (c)). Simultaneous inclusion of Sleep Quality and General Noise Annoyance in the model (Table 2 (d), Model 4) showed that the relationships between Noise Sensitivity and HRQOL were mediated independently by both General Noise Annoyance and Sleep Quality. The standardized regression coefficient between Noise Sensitivity and the Overall Quality of Life item remained relatively unchanged despite inclusion of Noise Annoyance and Sleep Quality in the model. Furthermore, standardized regression coefficients relating Noise Sensitivity to the Psychological and Environmental aspects of HRQOL remained quite high in Models 2, 3, and 4 despite being attenuated by inclusion of the mediators. Of additional interest is the moderate correlation between the NOISEQ's sleep subscale and the WHOQOL's item probing sleep quality ($r = –0.423$, $p < 0.001$).

Table 2. Standardized regression coefficients (β) associated with the relationship between Noise Sensitivity and measures of HRQOL (where the Physical subscale has the item reflecting sleep satisfaction removed) modeled using Ordinary Least Squares Linear Regression with (a) Noise Sensitivity alone (Model 1), (b) simultaneous inclusion of Noise Annoyance (Model 2) or (c) Sleep Satisfaction (Model 3), and (d) simultaneous inclusion of both General Noise Annoyance and Sleep Satisfaction (Model 4).

(a) Model 1 (Simple)

	Noise Sensitivity	
Measure	β	*p*-value
Overall QOL	–0.291	0.003
Self-rated health	–0.162	0.099
Physical QOL	–0.238	0.016
Psychological QOL	–0.349	<0.001
Social QOL	–0.124	0.231
Environmental QOL	–0.295	0.003

(b) Model 2 (Noise Sensitivity and General Noise Annoyance)

	Noise Sensitivity		Noise Annoyance	
Measure	β	*p*-value	β	*p*-value
Overall QOL	–0.220	0.042	–0.148	0.171
Self-rated health	0.026	0.807	–0.390	<0.001
Physical QOL	–0.071	0.500	–0.347	0.001
Psychological QOL	–0.183	0.073	–0.350	0.001
Social QOL	0.062	0.581	–0.383	0.001
Environmental QOL	–0.132	0.210	–0.338	0.002

(c) Model 3 (Noise Sensitivity and Sleep Satisfaction)

	Noise Sensitivity		Sleep Satisfaction	
	β	*p*-value	β	*p*-value
Overall QOL	–0.218	0.018	0.353	<0.001
Self-rated health	–0.076	0.408	0.406	<0.001
Physical QOL	–0.140	0.115	0.466	<0.001
Psychological QOL	–0.231	0.004	0.535	<0.001
Social QOL	–0.029	0.764	0.439	<0.001
Environmental QOL	–0.182	0.029	0.536	<0.001

Table 2. *Cont.*

(d) Model 4 (Noise Sensitivity, General Noise Annoyance, and Sleep Satisfaction)

	Noise Sensitivity		Noise Annoyance		Sleep Satisfaction	
	β	*p*-value	β	*p*-value	β	*p*-value
Overall QOL	–0.215	0.037	–0.007	0.946	0.351	0.001
Self-rated health	0.032	0.750	–0.262	0.016	0.321	0.001
Physical QOL	–0.064	0.507	–0.183	0.081	0.406	<0.001
Psychological QOL	–0.171	0.054	–0.150	0.114	0.496	<0.001
Social QOL	0.074	0.478	–0.246	0.029	0.365	<0.001
Environmental QOL	–0.122	0.186	–0.145	0.141	0.490	<0.001

4. Discussion

We undertook exploratory research examining the relationship between noise sensitivity, noise annoyance, and HRQOL. Our results show a broad range of noise annoyance ratings from residents living within a confined area exposed to equivalent levels of aircraft and other sources of neighborhood noise (see Figure 3). Such a finding is inconsistent with the notion that noise level is the main cause of noise annoyance, and instead emphasizes the importance of psychological and contextual factors. The prevalence of severe aviation annoyance (≈17%) found in this study is equivalent to that reported in other Australasian airport studies (see review by Morrell *et al.* [27]), and a model derived from a meta-analysis of European airport studies predict the prevalence of severe annoyance to be between 17% and 25% for aircraft noise between 60 and 65 LDN [24]. According to the WHO Guidelines for Community Noise [39], outdoor noise of 55 LDN is “seriously annoying”. Dose-response curves from 12 European airports suggest that our values are at the lower end of current annoyance estimates, and as such are unlikely to have been overestimated [40]. Note that our aviation annoyance data are consistent with the mode of transport effect [23], with severe annoyance ratings reported in studies on road traffic (13% [26], 9.2% [15]) generally less that aviation and wind turbine noise (25% [41]). Our findings of no significant relationships between aviation annoyance and gender and education are, generally speaking, consistent with the literature (e.g., [6,9,18]), though we found no relationship between aviation annoyance scores and age as reported by others (e.g., [9]). Finally, the lack of association between years of residence and aviation noise annoyance indicates that adverse reactions to noise have not dampened with repeated exposures, that is, there is no evidence of habituation.

There are no reported New Zealand studies measuring noise sensitivity incidence, but our estimate of 50% of individuals being noise sensitive is comparable to international studies (e.g., [15]). Our finding of an association between noise sensitivity and noise annoyance is not novel and adds to a plethora of studies indicating as such (e.g., [3,7]). The correlation we report between noise sensitivity and general noise annoyance (r = 0.461) aligns well with those reported elsewhere (e.g., [3,7]). How noise sensitivity influences annoyance has yet be to be described, and the underlying mechanisms of noise sensitivity are not well understood. There are few studies that have investigated the biological basis of noise sensitivity, and genetic studies using monozygotic and dizygotic twins suggest that noise sensitivity has a heritability of 40% [42]. A solitary brain imagining study [43] investigating noise sensitivity showed sensitive individuals had distinctive patterns of brain activity that distinguished them from non-sensitive individuals. Pripfl *et al.* [43] concluded that differences in noise sensitivity most likely reflect a greater strain on cognitive processing. These results concur with previous results suggesting that noise sensitive individuals do not only evaluate a noisy situation as more annoying but also experience higher levels of cognitive strain [44]. Interestingly, on the basis of statistical models, Kroesen *et al.* [37] argue that noise sensitivity does not substantially contribute to annoyance induced by aircraft noise. However, it should be noted that Kroesen *et al.* [37] tested only one of the many proposed models to account for noise annoyance, and furthermore, the analysis may have suffered from spurious relationships amongst empirically-correlated, but theoretically unrelated, variables due to over-specification. In contrast, Fyhri and Klæboe [45], examining the road noise—health relationship and also utilising structural equations modeling, found noise sensitivity to be the dominant variable explaining annoyance.

The standardized regression coefficients we report argue for a negative association between our general annoyance measure and HRQOL domains, and between general annoyance and self-rated health. Literature reviews on the health effects of aircraft noise conducted by Morrell *et al.* [27], and Kaltenbach *et al.* [40], indicate that when the WHO's definition of health is adopted, the detrimental impact of aircraft noise on health and quality of life are nontrivial. Passchier-Vermeer & Passchier [46] concur, arguing that noise can impair wellbeing and general quality of life, and Dratva *et al.* [26] report an inverse relationship between traffic-related noise annoyance and all SF36 domains excluding general health, especially for individuals who had lived in their homes for six years or less. Thus we reinforce these previous commentaries and the study of Dratva *et al.* [26] and present further quantitative data that noise annoyance can affect HRQOL.

Further to this, we also present evidence that both annoyance and sleep disruption mediate the relationship between noise sensitivity and HRQOL. In relation to sleep it has long been accepted that disrupted sleep reduces psychological wellbeing and effects day-to-day functionality. However, even noise insufficient to cause awakening may cause a brief arousal, with the sleeper moving from a deep level of sleep to a lighter level and back to a deeper level. Because full wakefulness is not reached, the sleeper has no memory of the event but the sleep has been disrupted just as effectively as if wakefulness had occurred. Arousals may be caused by sound events as low as 32 dB(A) and awakenings with events of 42 dB(A) [47]. In one study of aircraft noise, arousals were four times more likely to result than awakenings [48] and were associated with daytime sleepiness [49]. A study undertaken around John F. Kennedy airport in New York, USA, found that 60% of respondents living within 1.6 kilometres of the airport reported sleep disturbance and fatigue [50].

Our use of a cross-sectional design allows us to conclude only that there are associations between noise sensitivity, noise annoyance, and HRQOL, and we cannot confidentially ascribe causal status to any of these three variables. With reference to the health literature it is apparent that current thinking argues that any adverse relationship between noise exposure and physical health is likely to be mediated through psychophysiological processes. Any object or event that an individual perceives as a threat to their safety or to the resting and restorative characteristics of their living environments can be classified as a stressor. Noise is one such psychosocial stressor that can induce maladaptive psychological responses and negatively impact physical health *via* interactions between the autonomic nervous system, the neuroendocrine system, and the immune system [51]. The autonomic nervous system is a mediator of the stress response and expression of stress-related emotion, and consists of parasympathetic and sympathetic branches. Noise sensitivity may be explained by a hypoactive parasympathetic, and a hyperactive sympathetic nervous system. Noise sensitive individuals may delay the termination of sympathetic responses due to an uncoupling of the autonomic nervous system and the amygdala-prefrontal circuits that interpret stressful stimuli and enact the appropriate stress response. The result is that the sympathoexcitatory circuits get caught in a positive feedback loop leading to hyper-vigilance and misattribution that then produce maladaptive cognitions (*i.e.*, annoyance). As the stress accumulates, there is increased activation of the hypothalamic-pituitary-adrenal axis and the sympathetic-adreno-medullary system.

The speculative mechanism discussed above is based on Thayer's conception of the central autonomic network [52,53], and supports the notion that annoyance can be ascribed causal status in noise-induced health deficits. It must be asked, however, whether poor health itself cannot influence both noise annoyance and noise sensitivity? Our results indicate that while noise sensitivity is partly mediated by annoyance, it is also directly associated with psychological and environmental quality of life. This suggests that psychological wellbeing or environmental factors could potentially mediate noise sensitivity. In relation to psychological wellbeing it has been noted that inhibited restoration in individuals experiencing life stressors or degraded mental health could potentially increase annoyance responses to noise [19]. Causality then is likely to be bi-directional, and potentially create a positive feedback loop in which annoyance and health deficits increase without check. Annoyance can cause degraded health but health itself could potentially amplify annoyance or sensitivity to noise. Thus the model featured in Figure 1 would need to be modified to account for a possible relationship between health and annoyance. Irrespective of causal direction, however, there is still need to consider the effects of sound generators and to position them with care and consideration with respect to the communities hosting them.

Limitations

First, the sample size was a major limiting factor in the analysis and interpretation of the data. Our small convenience sample likely increased the probability of type I errors by preventing the use of more sophisticated multivariate techniques, and also invited type II errors by providing less than satisfactory power. However, while the findings we report here may be considered somewhat speculative and need to be confirmed with a larger New Zealand sample, they are congruent with findings reported overseas. Future studies capturing more participants would afford the use of structural equations modeling, a more powerful multivariate technique capable of elucidating and testing causal relationships. Second, women were over-represented in the sample (68%), which may have biased the findings in that women may tend to be affected by noise differently from men. Third, we make no attempt to undertake objective measures of noise exposure in this study, noting that while objective noise measurements have had some success in predicting health outcomes using aggregated data, they are severely lacking in predicting individual responses to noise. Dratva *et al.* [26] argue that the ability of subjective annoyance ratings to better account for the individual differences evident in the relationship between noise and health make it a superior marker of the impact of noise on health than noise itself. However, while we make use of outdoor noise contours measured by a professional acoustics company [31], it would have been desirable to undertake indoor noise measurements to further elucidate the relationship between noise and health. Additionally, estimating the time that residents are exposed to the measured noise would likely be an important covariate. Fourth, because we estimated sleep quality using only a single item from the WHOQOL-BREF we can expect greater measurement error around the true values than had we used a composite measure such as the Pittsburgh Sleep Quality Index. Fifth, the use of subjective *versus* objective health measures to detect changes in health due to environmental factors may be viewed as “soft” [27]. Lercher [2] has detailed the methodological challenges of assessing the health impact of noise. Objective outcome metrics such as blood pressure or cardiovascular disease are arguably well defined and easily measured, while noise-induced sleep disruption, stress, and similar subjective symptoms are less easily measured and distinguished from the background levels present in the population. However, objective manifestation of health effects associated with noise-related annoyance may emerge after 5 to 15 years since the onset of exposure [40], whereas subjective appraisals of wellbeing and health suffer no such time lag. Thus for cross-sectional studies as reported here subjective measures are more suitable.

5. Conclusions

The subjective experience of annoyance is a common reaction to noise. Different individuals can exhibit different annoyance reactions to the same noise, and these individual differences can be ascribed partly to differences in noise sensitivity. Conceptualized as a stable personality trait, noise sensitivity has no relationship to auditory acuity, instead reflecting a judgmental, evaluative predisposition towards the perception of noise. Our findings suggest that noise sensitivity can degrade HRQOL through annoyance and sleep disruption, though further research is needed to establish causation and afford greater generalizability.

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Review

Public health implications of environmental noise associated with unconventional oil and gas development

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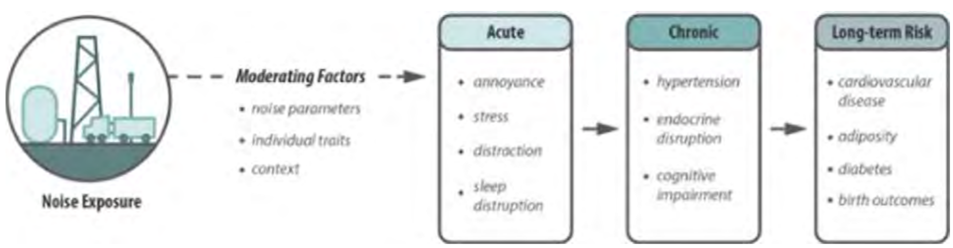
HIGHLIGHTS

- Reviewed non-auditory health outcomes from environmental noise exposure.
- Potential outcomes include annoyance, sleep disturbance, and cardiovascular disease.
- Oil and gas operations produce noises at levels that may increase health risks.
- Additional noise exposure research for oil and gas operations is needed.

GRAPHICAL ABSTRACT



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ABSTRACT

Modern oil and gas development frequently occurs in close proximity to human populations and increased levels of ambient noise have been documented throughout some phases of development. Numerous studies have evaluated air and water quality degradation and human exposure pathways, but few have evaluated potential health risks and impacts from environmental noise exposure. We reviewed the scientific literature on environmental noise exposure to determine the potential concerns, if any, that noise from oil and gas development activities present to public health. Data on noise levels associated with oil and gas development are limited, but measurements can be evaluated amidst the large body of epidemiology assessing the non-auditory effects of environmental noise exposure and established public health guidelines for community noise. There are a large number of noise dependent and subjective factors that make the determination of a dose response relationship between noise and health outcomes difficult. However, the literature indicates that oil and gas activities produce noise at levels that may increase the risk of adverse health outcomes, including annoyance, sleep disturbance, and cardiovascular disease. More studies that investigate the relationships between noise exposure and human health risks from unconventional oil and gas development are warranted. Finally, policies and mitigation techniques that limit human exposure to noise from oil and gas operations should be considered to reduce health risks.

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Contents

1. Introduction

Noise, or unwanted sound, is a biological stressor and potential public health hazard in a variety of contexts. Exposure to noise modifies the function of human organs and systems (Münzel et al., 2014) and can be a contributing factor to the development and aggravation of health conditions related to stress (e.g., high blood pressure) (Dratva et al., 2012). Numerous large-scale epidemiological studies have identified associations between environmental noise exposure and adverse health outcomes, such as cardiovascular disease (Babisch et al., 2013), diabetes (Sørensen et al., 2013), adiposity (Christensen et al., 2015), birth outcomes (Gehring et al., 2014), cognitive impairment in children (Lercher et al., 2002), depression (Orban et al., 2015), and sleep disturbance (Hume et al., 2012). Health outcomes due to environmental noise exposure may also carry economic consequences due to the size of populations exposed to hazardous levels of noise (Swinburn et al., 2015).

Recent combinations of technologies, including high-volume hydraulic fracturing and directional drilling, have unlocked oil and gas from low-permeability formations (e.g., shale, tight sands, etc.) that were previously not considered to be economically viable. As a result, oil and gas development activities are being cited in a wide array of new geographic locations, sometimes in urban areas and in close proximity to human populations (Adgate et al., 2014). Public concerns have advanced a large body of scientific research to assess various impacts of unconventional oil and gas development (UOGD). The term UOGD generally refers to oil and gas produced from atypical reservoir types that require techniques that are different than those required for conventional oil and gas production. However, in this paper, we use the term to refer specifically to onshore methods of oil and gas development enabled by hydraulic fracturing or “fracking” to produce oil or gas from shale and other tight formations.

Previous UOGD impact investigations have primarily focused on fugitive methane emissions, local and regional air quality degradation, surface and groundwater contamination, and the characterization of chemicals used in and produced by various processes (Jackson et al., 2014). Public health assessments have incorporated these data to assess the potential for human exposures to pollutants associated with UOGD through air and water pathways. Several reviews have identified health hazards and risks associated with UOGD and there is now an emerging body of epidemiology (Adgate et al., 2014; Shonkoff et al., 2014; Werner et al., 2015).

Air pollution and water contamination associated with UOGD are becoming increasingly well studied (Evans and Helmig, 2016; Hildenbrand et al., 2016). However, noise pollution related to UOGD remains understudied in the public health literature, even while the development of wind energy has generated a number of studies measuring potential health effects of noise exposure from wind turbines (Schmidt and Klokker, 2014; Van Renterghem et al., 2013). Many operations in various phases of oil and gas development produce transient and chronic noise (Maryland Institute for Applied Environmental Health, 2014). Although noise pollution has been cited as a primary concern among residents in areas of UOGD (Garfield County, Colorado, 2011), few researchers have evaluated noise levels and noise exposure associated with this industry. Measurements and estimates of noise levels are sometimes included in oil and gas environmental impact statements (Table 1), but to date there have been only a handful of reports that have evaluated noise associated with UOGD in the context of public health.

The types of noise associated with oil and gas operations can be complex in nature, owing to a wide variety of sources. Some of these noises are intermittent, some are continuous, and many vary in their intensity. Certain sources, such as compressor stations, produce low frequency noise (LFN), which is typically heard as a low rumble (Leventhall, 2003). There are also numerous source-dependent and subjective factors that may influence health outcomes, such as noise sensitivity (Hill et al., 2014; Schreckenberg et al., 2010), noise reduction technologies, and synergistic effects of noise and air pollution. Further, noise exposure, like other health threats, may disproportionately impact vulnerable populations, such as children, the elderly, and the chronically ill (van Kamp and Davies, 2013).

In this article, we explore the scientific literature on environmental noise to determine the potential hazards, exposures, and health outcomes that noise from UOGD may present. Many noise sources from UOGD are similar to those associated with conventional oil and gas development; however, some aspects can differ in important ways. For instance, drilling a horizontal well can take 4 to 5 weeks of 24 h per day drilling to complete whereas a traditional vertical well usually takes less than a week (Nagle, 2009). High-volume hydraulic fracturing also requires a greater volume of water and higher pressures to frac a horizontal well, resulting in more pump and fluid handling noise than traditional oil and gas development (Nagle, 2009). Nonetheless, because the data are limited we include noise measurements and estimates from some traditional oil and gas activities that are also relevant to UOGD.

This article expands on our initial findings presented in an appendix of the second volume of an independent scientific assessment of well stimulation treatments in California, commissioned by the California Natural Resources Agency pursuant to Senate Bill 4 and

Table 1
Noise levels associated with UOGD operations.

Category	Source	Distance (m/ft)		Average dBA[a]	dBA Range	Data type	Reference
Construction and preparation	General (unspecified)	<15	<50	–	70–90	Measurement	Bureau of Land Management, 2006
	Access road construction	15	50	89	–	Estimate	NYSDEC FSGEIS 2015
		76	250	75			
		152	500	69			
		305	1000	63			
		457	1500	59			
		610	2000	57			
	Site preparation	191	625	58–69	–	Measurement	McCawley, 2013
	Well pad preparation	15	50	84	–	Estimate	NYSDEC FSGEIS 2015
		76	250	70			
		152	500	64			
		305	1000	58			
		457	1500	55			
		610	2000	52			
	Truck traffic	<152	<500	–	65–85	Estimate	Garfield County, Colorado, 2011
		191	625	65	56–73	Measurement	McCawley, 2013
Production and completion	Horizontal drilling	15	50	76	–	Estimate	NYSDEC FSGEIS 2015
		76	250	62			
		152	500	56			
		305	1000	50			
		457	1500	47			
		610	2000	44			
	Vertical drilling	191	625	54	–	Measurement	McCawley, 2013
	Drilling (unspecified)	100	328	57.4–62	–	Estimate	Ambrose and Florian, 2014
		300	984	52.5		Measurement	
		1055	3461	36.9			
		2300	7546	30.4			
		191	625	75–80	–	Measurement	Witter 2011
		200	655				
		30	100	–	75–87	Measurement	Behrens and Associates, Inc., 2006
		61	200	–	71–79		
		91	300	–	65–74		
		122	400	–	60–71		
		152	500	–	56–68		
		183	600	–	54–59		
		213	700	–	51–55		
		244	800	–	51–54		
	Hydraulic fracturing	15	50	99–104	–	Estimate	NYSDEC FSGEIS 2015
		76	250	85–90			
		152	500	79–84			
		305	1000	73–78			
		457	1500	69–74			
		610	2000	67–72			
		191	625	52	47–60	Measurement	McCawley, 2013
	Hydraulic fracturing/flowback	191	625	58	55–61	Measurement	McCawley, 2013
	Flaring	On-site	On-site	97.9	–	Estimated	Bureau of Land Management, 2006
		161	528	66.3			
	Compressor station(s)	<305	<1000	63.15	35.3–94.8	Measurement	Maryland Institute for Applied Environmental Health, 2014
		305–610	1000–2000	55.48	35.3–77.6		
		610–762	2000–2500	54.09	35.3–80.3		
		>1067	>3500	51.50	35.3–74.1		
		On-site	On-site	69–86	–	Measurement	Bureau of Land Management, 2006
		1609	5280	58–75			
		2012	6600	54			
		100	328	53.8	–	Estimate	Ambrose and Florian, 2014
		140	459	50.9		Measurement	

[a] A-weighted decibel. This is a frequency dependent correction that is applied to a measurement to mimic the varying sensitivity of the ear to sound for different frequencies. dBA serves as an expression of a sound's relative loudness in the air as perceived by the human ear.

coordinated by the California Council on Science and Technology (Shonkoff et al., 2015). We highlight what is currently known and identify data gaps and research limitations. Additionally, we consider how these findings may inform discussions on the deployment of noise abatement techniques, such as the minimum surface setback distances between human populations and oil and gas infrastructure.

2. Health impacts of environmental noise exposure

Noise exposure can lead to adverse health outcomes through direct and indirect pathways (Fig. 1). Noise is an environmental stressor that activates the sympathetic nervous and endocrine systems (Ising and Braun, 2000). Acute noise effects are not limited to high decibel sound

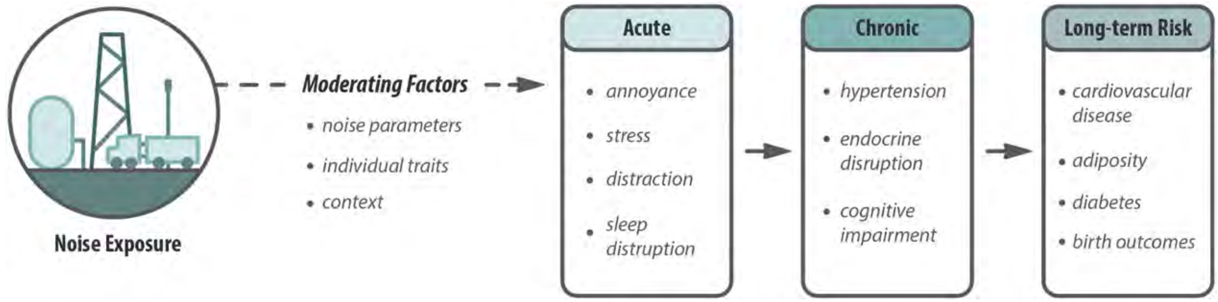

Fig. 1. Potential non-auditory health outcomes of environmental noise exposure. This figure is adapted from Shepherd et al. (2010) and depicts the relationships between exposure to noise and primary and secondary health effects. Non-physical effects of noise are also mediated by psychological and psychophysiological processes (Shepherd et al., 2010). The dashed lines indicate the physical effects of noise and the solid lines indicate the non-physical effects. Annoyance and sleep disturbance act as mediators between predisposing factors and secondary health effects, such as quality of life or cardiovascular disease.

levels such as those found in occupational settings, but also are evidenced at relatively low environmental sound levels when they cause disturbance of other activities (e.g., sleep, concentration, etc.) (Babisch, 2002). Both the sound level of the noise (objective noise exposure) and its subjective perception can influence the impact of noise on neuroendocrine homeostasis (Münzel et al., 2014). In other words, the way in which an individual perceives a particular sound can influence the impact of the noise.

Health outcomes associated with noise exposure have been studied for decades, although there has been an increasing body of literature on the non-auditory health effects of environmental noise exposure. Most of these studies analyze associations between adverse health outcomes and noise from airports, road traffic, and railways. Some of the more commonly identified non-auditory health endpoints for noise exposure are annoyance/perceived disturbance, sleep disturbance, and cardiovascular health outcomes (Basner et al., 2014). Although there are other health outcomes associated with noise exposure, here we focus on these three health endpoints. We also briefly discuss potential mechanisms and epidemiological evidence that considers threshold calculations and exposure-response relationships.

2.1. Annoyance

Annoyance appears to be one of the more common responses to general environmental noise exposure among communities. Noise annoyance may produce a host of negative responses, such as feeling of anger, displeasure, anxiety, helplessness, distraction, and exhaustion (World Health Organization, 2011). Annoyance affects both the wellbeing and quality of life among populations exposed to environmental noise. Noise sensitivity is a strong predictor of noise annoyance (Paunović et al., 2009; Stansfeld, 1992) and may also predict the risk of future psychological distress (Stansfeld and Shipley, 2015).

Annoyance is also source dependent, meaning that dBA (A-weighted decibel) readings alone are not always sufficient to gauge annoyance thresholds (Babisch et al., 2013). However, according to a 2010 report by the European Environment Agency (EEA), the thresholds are generally about the same for transport noises (European Environment Agency (EEA), 2010). Other agencies have slightly higher threshold averages for annoyance while differentiating between serious and moderate annoyance as well as outdoor and indoor activity interference (Table 2). Still, the results of studies that measure levels of annoyance vary and a number of uncertainties remain because of the noise dependent and subjective factors related to annoyance.

2.2. Sleep disturbance

Sleep disturbance is another common response among populations exposed to environmental noise (Muzet, 2007). Noise can impact sleep in a number of ways and can have immediate effects (e.g., arousal, sleep stage changes), after-effects (e.g., drowsiness, cognitive

Table 2
Noise level thresholds associated with various health outcomes.

Category	Effect	Threshold (average dBA)	Acoustic indicator	Time domain	Reference
Annoyance	Unspecified	42	L_{den}	Chronic	EEA, 2010
	Serious	55	LA_{eq}	Chronic	WHO 1999
	Moderate	50	LA_{eq}	Chronic	WHO 1999
	Outdoor activity interference	55	$L_{dn}/L_{eq(24)}$	Chronic	US EPA 1974
	Indoor activity interference	45	$L_{dn}/L_{eq(24)}$	Chronic	US EPA 1974
Sleep	Sleep disturbance	30	LA_{eq}	Chronic	WHO 1999
		45	LA_{max}	Acute	WHO 1999
	Sleep (polysomographic)	32	$L_{max,indoors}$	Acute, Chronic	EEA, 2010
	Self-reported sleep disturbance	42	L_{night}	Chronic	EEA, 2010
	Reported awakening	53	$SEL_{indoors}$	Acute	EEA, 2010
Cardiovascular	Hypertension	50	L_{den}	Chronic	EEA, 2010
	Ischaemic heart disease	65–70	LA_{eq}	Chronic	WHO 1999
		60	L_{den}	Chronic	EEA, 2010
General	Reported health/wellbeing	50	L_{den}	Chronic	EEA, 2010
	Health/welfare	55	L_{dn}	Chronic	US EPA 1974

L = sound level.
LA = A-weighted sound level.
L_{den} = Day-evening-night equivalent level.
LA_{eq} = A-weighted, equivalent sound level (dBA L_{eq}).
L_{dn} = Day-night equivalent level (A-weighted, L_{eq}).
LA_{max} = A-weighted, maximum sound pressure level occurring in an interval.
$L_{max\ indoors}$ = Maximum sound pressure occurring indoors.
L_{night} = Night equivalent level (L_{eq}, A-weighted, sound level).
$SEL_{indoors}$ = Sound exposure level (logarithmic measure of the A-weighted), indoors.

impairment), and long-term effects (e.g., chronic sleep disturbance) (World Health Organization, 2011). The body continues to respond to stimuli coming from the environment during sleep. Similar to annoyance, noise sensitivity plays a significant role in sleep disturbance as well, and is influenced by both noise dependent factors (e.g., noise type, intensity, frequency) and other subjective factors (e.g., age, personality, self-estimated sensitivity) (Muzet, 2007).

There is a large body of research on sleep and health with variable and controversial results. Because the effects of noise exposure on sleep are dependent on a number of objective and subjective factors, it is difficult to determine a clear dose-response relationship. However, reviews of evidence produced by epidemiological and experimental studies have identified relationships between noise exposure at night and adverse health outcomes (Ristovska and Lekaviciute, 2013). It is generally accepted that no effects on sleep tend to be observed below the level of 30 dBA L_{night} (average sound pressure level over one night) and there is no sufficient evidence to indicate that the biological effects that have been observed below 40 dBA L_{night} are harmful to health (World Health Organization, 2009). Adverse health effects such as self-reported sleep disturbance, insomnia, and increased use of drugs are observed at levels above 40 dBA L_{night} and levels above 55 dBA present a major public health concern (World Health Organization, 2009).

2.3. Cardiovascular health

Reactions to noise can occur at both a conscious and non-conscious level. Specifically, noise can trigger emotional stress reactions from perceived discomfort as well as physiological stress from interactions between the auditory system and other regions of the central nervous system (Basner et al., 2014). Exposure to noise can increase systolic and diastolic blood pressure, create changes in heart rate, and cause the release of stress hormones (e.g., catecholamines and glucocorticoids) (Basner et al., 2014). Studies have found positive correlations between chronic noise exposure and elevated blood pressure, hyptertension, ischaemic heart disease, and stroke (Halonen et al., 2015; Münzel et al., 2014; Vienneau et al., 2015). Systematic and quantitative reviews have collated and synthesized evidence of the relationship between noise exposure and cardiovascular disease (Babisch, 2000, 2006; Stansfeld and Matheson, 2003; van Kempen et al., 2002) and some meta-analyses have developed exposure-response curves that are used to quantify human health risks in health impact assessments (Argalášová-Sobotová et al., 2013). Table 2 provides EEA, World Health Organization (WHO), and United States Environmental Protection Agency (US EPA) threshold levels for increased cardiovascular risk.

3. Noise sources and levels during oil and gas development

There is currently no peer-reviewed literature on the noise levels and potential health impacts from noise exposure related to oil and gas development. However, measurements and estimates of noise levels for oil and gas development can be found in a number of government reports and independent analyses in the grey literature. These sources are subject to limitations and can vary significantly in terms of methodology and the type of oil or gas development for which the measurements were taken.

The main sources of noise from oil and natural gas operational activities can be grouped into the following two categories: (1) construction and preparation (e.g., road construction, site and well pad preparation, truck traffic) and (2) production and completion (e.g., flaring operations, drilling, hydraulic fracturing, compressor stations). Table 1 summarizes noise measurements and estimates from environmental impacts statements, reviews, and other reports. These findings are not necessarily commensurable, however, because of the heterogeneity of approaches and study systems across the reports (e.g., source of noise, measurement distance, type of oil or gas operations, etc.). Furthermore, some of the data contained in these reports are industry/consultant predictions and do not necessarily reflect actual field monitoring results. Nonetheless, these are the best available data for determining expected noise levels from various aspects of UOGD.

In a report prepared for the West Virginia Department of Environmental Protection, McCawley (2013) monitored noise levels associated with various stages of natural gas development from 2 to 4 sampling sites located 190.5 m (625 ft) from the center of five different well pads. McCawley (2013) provided actual monitoring results from a number of different sites and for a variety of stages in the development process, including site preparation, drilling, hydraulic fracturing, and truck traffic. Analysis of these data yields the percent of time particular noise levels were exceeded in minutes (Table 3 and Table 4). In all cases, for the five major operations the study surveyed, noise levels exceeded 55 dBA for >24 h, though not necessarily continuously. Pad Preparation in Wetzel County, WV was more frequently louder (on both the basis of total time and percent of time sampled) than was Hydraulic Fracturing in either Marion County, WV or Wetzel County, WV. As all sound levels were measured at least 190.5 m from the center of the pad it may not be

Table 4
Traffic noise levels, Wetzel County, West Virginia.[a]

Site 2A (next to road/construction)			Site 2C (far side of pad away from traffic)		
Time above sound level (minutes)	% of time above sound level	Sound level (dBA)	Time above sound level (minutes)	% of time above sound level	Sound level (dBA)
1	0.01	90	13	0.18	90
254	3.48	80	134	1.84	80
5213	71.32	70	499	6.84	70
7304	99.93	60	927	12.71	60
7309	100.00	50	6363	87.22	50
7309	100.00	40	7295	100.00	40
7309	100.00	30	7295	100.00	30

[a] These data come from a report prepared for the West Virginia Department of Environmental Protection (McCawley, 2013). Samples were continuous over the total time duration listed in the bottom row. The total sampling time for Site 2A was 7309 min (~122 h) and Site 2C was 7295 min (~122 h).

Table 3
Hydraulic fracturing noise levels, Marion County, West Virginia.[a]

Site A (near impoundment above pad)			Site C (near road)			Site D (1200 ft. from pad)		
Time above sound level (minutes)	% of time above sound level	Sound level (dBA)	Time above sound level (minutes)	% of time above sound level	Sound level (dBA)	Time above sound level (minutes)	% of time above sound level	Sound level (dBA)
53	0.357023	90	6	0.04	90	3	0.02	90
191	1.286628	80	52	0.35	80	19	0.13	80
644	4.338161	70	930	6.26	70	138	0.93	70
2277	15.3385	60	4949	33.32	60	658	4.44	60
4261	28.70327	50	11,331	76.30	50	2760	18.63	50
7353	49.53183	40	12,048	81.13	40	10,028	67.68	40
14,845	100	30	14,851	100.00	30	14,817	100.00	30

[a] These data come from a report prepared for the West Virginia Department of Environmental Protection (McCawley, 2013). Samples were continuous over the total time duration listed in the bottom row. The total sampling time for Site A was 14,845 min (~247 h), Site B was 14,851 min (~248 h), and Site C was 14,817 (~247 h).

surprising that Pad Preparation was more frequently loud. The heavy earth moving equipment was observed to frequently pass directly next to the sound monitoring equipment.

McCawley (2013) found that other operations also exhibited similar, apparently anomalous results – such as the vertical drilling operation in Wetzel County, WV, where no drilling took place during the time period of sampling. On the far side of the pad, away from the road and out on its own solitary point of land, but the same distance from the center of the pad as the second sampling site, sound levels exceeded 60 dBA far less frequently than did the sampling site next to roadway on the other side (approximately 180 degrees opposite) of the pad. The sampling site next to the roadway had sound levels exceed 70 dBA far more frequently than did the Hydraulic Fracturing site in Marion or Wetzel County. Again, heavy-duty traffic and construction equipment were frequently observed around the second sampling site and not around the first.

McCawley (2013) also concluded that air emissions should not be assumed to necessarily be coming from the center of the pad based on trends similar to the sound levels but for volatile organic compounds (hypothesized to emanate from the heavy duty diesel equipment). Since the sound levels appear to follow the same pattern, the sound levels could be hypothesized to also be coming from the heavy-duty equipment. Additional research is required here and the cautionary lesson is that site setbacks do not necessarily provide the expected attenuation if the source is not located solely at the center of the pad. One might therefore expect to see results for noise similar to the levels and frequencies in Table 4 along the roadways near the operations mentioned in the McCawley (2013) report due to traffic flow and ancillary pad site operations.

A 2014 pilot study conducted as part of a report prepared for the Maryland Department of the Environment and the Maryland Department of Health and Mental Hygiene monitored resident exposures to noise associated with natural gas compressor stations in West Virginia (Maryland Institute for Applied Environmental Health, 2014). The study found an average L_{eq} (equivalent continuous sound pressure level) for the combined compressor stations of 60.2 dBA (range 35.3 to 94.8 dBA) and an average short term L_{eq} of 61.4 (range 45.3 to 76.1 dBA), both of which decreased with distance from the compressor stations. For instance, for 24-h measurements the recorded average of 63.15 dBA at <305 m (1000 ft) decreased to 54.09 dBA at 610 to 762 m (2000 to 2500 ft). The average L_{eq} at control homes located >1067 m (3500 ft) from a compressor station was 51.40 dBA.

A 2006 Bureau of Land Management Environmental Impact Statement for the Jonah Infill Drilling Project (JIDPA) in Sublette County, Wyoming incorporated measurements from previous investigations to assess typical noise levels near gas field operations (Bureau of Land Management, 2006). Noise levels from one compressor station just south of the JIDPA were recorded between 58 and 75 dBA about 1.6 km (1 mi) and 54 dBA about 2 km (1.25 mi) to the southeast, while another station provided readings of about 65 dBA about 1.6 km (1 mi) east (Bureau of Land Management, 2006). Readings from construction activities ranged from 70 dBA to 90 dBA within 15 m (50 ft) from the source.

In 2006, the Fort Worth Gas Well Task Force commissioned Behrens and Associates, Inc. to produce a gas well drilling noise impact and mitigation report for drilling rigs operating within and near the City of Fort Worth, Texas (Behrens and Associates, Inc., 2006). Drilling noise levels for three different rigs were measured at various times from four directions (e.g., generator side of rig, rear side of rig, etc.) up to 800 ft away. Average drilling sound levels were 75–87 dBA at 30 m (100 ft), 71–79 dBA at 61 m (200 ft), 65–74 dBA at 91 m (300 ft), 60–71 dBA at 122 m (400 ft), 56–68 dBA at 152 m (500 ft), 54–59 dBA at 183 m (600 ft), 51–55 dBA at 213 m (700 ft), and 51–54 dBA at 244 m (800 ft).

In 2014, the Wyoming Game and Fish Department had sound levels recorded in order to measure the threat from noise to greater sage grouse (a species reliant on vocal communication for its propagation) in the Pinedale Anticline Project Area (PAPA) (Ambrose and Florian, 2014). The report provided estimates of sound levels at 100 m (328 ft) based on measurements taken at further distances for a number of common PAPA gas field activities (median (L_{50}) over a 24-h period). For instance, a reading of 53.8 dBA was estimated at 100 m based on an actual measurement of 50.9 dBA at 140 m (459 ft). Various sources produced median sound levels at least 50 dBA at 100 m, including an active drill rig (62 dBA), an injection well complex (56 dBA), a compressor station (54 dBA), and a well pad with 21 well heads and a generator (50 dBA) (Ambrose and Florian, 2014).

The New York State Department of Environmental Conservation's Final Supplemental Generic Environmental Impact Statement On The Oil, Gas and Solution Mining Regulatory Program provided the greatest number of estimates for noise levels associated with various aspects of UOGD. Composite noise levels at 15 to 610 m (50 to 2000 ft) ranged from 57 dBA to 89 dBA for access road construction, 52 dBA to 84 dBA for well pad preparation, 44 dBA to 76 dBA for horizontal drilling, and 52 dBA to 104 dBA for hydraulic fracturing (New York State Department of Environmental Conservation, 2015).

A 2011 Health Impact Assessment (HIA) conducted by the Colorado School of Public Health (CSPH) considered the health impacts of noise, vibration, and light pollution on health in the Battlement Mesa community in Garfield County, Colorado. CSPH obtained well pad noise monitoring data from Antero Resources, an oil and gas exploration and production company. Unmitigated noise levels during drilling operations were measured below industrial noise limits at 191 m (625 ft) to the northwest and 165 m (540 ft) to the southeast (75 and 80 dBA during night and day, respectively) (Garfield County, Colorado, 2011). According to Antero's models, however, mitigation could reduce noise from drilling to the 50–63 dBA range at 107 m (350 ft). The CSPH HIA found that heavy truck traffic, construction equipment, and diesel engines used throughout drilling and hydraulic fracturing would likely account for the most significant sources of noise.

4. Potential health outcomes from UOGD noise exposure

To determine the potential for health outcomes, thresholds and guidelines from Table 2 can be compared with data from Table 1. The health literature on noise exposure considered with dBA levels associated with oil and gas operations suggest that noise from UOGD present a number of potential adverse health outcomes. This finding is consistent with other studies and reports that consider potential health threats of noise exposure in the context of oil and gas development (Maryland Institute for Applied Environmental Health, 2014; McCawley, 2013; Witter et al., 2013). In particular, oil and gas operations have produced sound level measurements and estimates that could lead to all three of the non-auditory health outcomes considered in this review.

Of the potential health outcomes discussed above, there is a more significant risk for annoyance and sleep disturbance because these generally occur at lower noise thresholds. Although hypertension and cardiovascular diseases are associated with higher average dBAs than annoyance and sleep disturbance, many sources of noise from UOGD have produced noise at levels that are known to be associated with these outcomes. Most UOGD activities are not permanent, so there may be less of a risk for cardiovascular health outcomes, which are associated with chronic and continuous noise exposure (e.g., living next to a busy highway). However, some sources do produce chronic noise once drilling and other production processes are complete (e.g., compressor stations) and may contribute to the types of exposures associated with cardiovascular health outcomes. Further, these sources can produce LFN, which may considerably increase the adverse effects of noise exposure (Berglund et al., 1999).

When considering the health impacts of noise from a given source, the volume and intensity of the noise, whether it is prolonged and/or continuous, how it contrasts with the ambient noise levels, and the time of day must be taken into account. Noise levels depend not only on the type of source, but also on other factors such as distance from the source, air temperature, humidity, wind gradient, and the topography. The specific environment should also be taken into account, such as whether or not the dBA level is indoor/outdoor or whether it is heard in a hospital, school, daycare center or other facility.

4.1. Co-exposures

There are a number of health damaging air pollutants associated with UOGD that have been measured in high concentrations, including volatile organic compounds (VOCs), aromatic hydrocarbons, particulate matter (PM), and ground level ozone (Helmig et al., 2014; Oltmans et al., 2014; Pétron et al., 2014). Some of these pollutants have been shown to increase risk factors associated with heart disease and other adverse health outcomes. Numerous epidemiological studies have observed exposure to noise and air pollution simultaneously, since both often accompany transportation sources (e.g., busy roadways). It can be difficult to link one or the other to increased cardiovascular risks, and correlated exposures may lead to confounding in some epidemiological studies. It is not entirely clear from the available body of science whether air pollution is independent, additive, or synergistic to impacts from noise exposure.

Several papers have also acknowledged that light pollution resulting from nighttime UOGD operations may constitute an additional stressor and potential health hazard (Ferrar et al., 2013; Perry, 2013; Witter et al., 2013). Evidence suggests that light at night may impact health by disrupting normal circadian rhythms and altering melatonin and other hormone releases (Chepesiuk, 2009; Pauley, 2004). There has also been some epidemiological links of light at night to breast cancer (Hurley et al., 2014) and obesity (McFadden et al., 2014), although the research is still preliminary.

4.2. Low frequency noise

LFN is produced by some oil and gas operations (e.g., compressor stations), yet, there are few data available and concerns about LFN tend to focus more on wind turbines (Møller and Pedersen, 2011). LFN is not clearly defined and presents challenges for regulation based on conventional methods of assessing noise (based on A-weighted equivalent level) (Leventhall, 2004). LFN generally occurs below a frequency of 100 to 150 Hz (Hertz is a unit of frequency defined as one sound vibration or cycle per second) and at very low frequencies referred to as infrasound (20 Hz) people may complain about “pressure sensations” or describe an experience of “feeling the noise” (Department of the Environment, Nothern Ireland, 2001).

The association between exposure to LFN and adverse health outcomes has not received as much attention in the scientific literature as compared to higher frequency noise measured by traditional A-weighted bands (Murphy and King, 2014). However, the WHO has suggested that LFN may considerably increase the adverse effects of noise exposure (Berglund et al., 1999). Exposure to LFN has been associated with sleep disturbance (Leventhall, 2003), annoyance (Persson and Björkman, 1988), and other secondary health effects (Berglund et al., 1999). Residential exposure to LFN may even be a greater problem than noise measured in the normal frequency range given that most walls in buildings and homes are not able to attenuate LFN (Leventhall, 2003). Some evidence suggests that dBA may underestimate the level of annoyance experienced by exposed populations (Persson and Björkman, 1988).

4.3. Vulnerable populations

As with other environmental stressors, noise exposure may disproportionately impact vulnerable populations, including children, the elderly, and the chronically ill. In addition to these groups, the literature also considers those who are sensitive to noise, of a low socioeconomic status, suffering from tinnitus, mentally ill, and foetus or neonates (van Kamp and Davies, 2013). Overall, there is very little epidemiological literature on the effects of environmental noise exposure on vulnerable groups and so determining dose-response curves and setting specific limit values is difficult.

4.4. UOGD public health literature

There is an emerging body of epidemiology that suggests an association between UOGD and adverse health outcomes (Hays and Shonkoff, 2016). In a study using over 95,000 inpatient records from three counties in northeast Pennsylvania, Jemielita et al. (2015) noted an association between density of unconventional natural gas wells and increased inpatient prevalence rates for a number of medical categories, including cardiology and neurology. The authors hypothesized that this association could be due in part to potential toxicant exposure and stress responses (Jemielita et al., 2015), the latter of which may bear particular relevance to noise exposure. Several other studies have found associations between UOGD and some adverse birth outcomes (Casey et al., 2015; McKenzie et al., 2014; Stacy et al., 2015), which have also been associated with noise exposure. In light of these findings and our understanding of noise as a potential health risk factor for stress and adverse cardiovascular outcomes, additional research on noise levels and noise exposure associated with UOGD is warranted.

4.5. Limitations

Noise data from actual oil and gas operations are very limited and most are based on estimations rather than actual field measurements. Some of the oil and gas noise data from traditional operations may underestimate average noise levels from unconventional oil and gas operations, which may be more intense in terms of infrastructure, truck traffic, duration, etc. It may be difficult to assess the potential health outcomes associated with LFN from oil and gas operations due to a lack of data and because traditional dBA may underestimate particular health outcomes (e.g., annoyance) from LFN. Additionally, many of the noises from UOGD are transient in nature, making them challenging to capture. Further, some noise level thresholds included in this review (Table 2) may not adequately reflect the current science on health outcomes associated with environmental noise exposure. For instance, US EPA guidelines are now over 40 years out of date and do not incorporate the large body of epidemiology that has been published since 1974.

Due to the psychological dimension of noise exposure, the relationship between the source and the exposed individual can vary dramatically. While most of the epidemiology on noise exposure involves aircraft, road traffic, and railways, the dBAs associated with these sources are not necessarily transferable to oil and gas development for all health outcomes. Depending on the individual, levels of annoyance from noise exposure to oil and gas activities may be greater or less than levels of annoyance associated with road traffic. For instance, a landowner who has permitted oil or gas development to obtain production royalties may have a higher threshold for noise and/or annoyance than a landowner nearby without any economic incentive. Relatedly, some evidence suggests that annoyance felt by residents living in the vicinity of wind turbines occurs at significantly lower noise levels than noise from other environmental sources (Janssen et al., 2011). It is unclear whether or not UOGD will follow a similar pattern. Regardless, individual variation presents a high degree of uncertainty for most potential health outcomes associated with noise exposure.

5. Research and policy considerations

There are a number of factors that should be taken into account when assessing health risks from UOGD noise. These include the distance of populations to oil and gas operations, mitigation techniques, and differences in noise sensitivity among individuals, which are sometimes driven by age and pre-existing health conditions. The majority of populations living in communities with active oil and gas development may not experience many of the dBA readings and estimates mentioned in this report, depending on the siting of oil and gas operations, topography, and infrastructure. Likewise, some communities may already take preventive measures with policies and practices designed to limit exposure. Nonetheless, there is some evidence that oil and gas operations can, and do, produce noise levels that may adversely impact population and community health.

Policies aimed to protect the health and wellbeing of human populations should consider noise levels when determining minimum surface distances between residents and sensitive receptors (e.g., schools, hospitals, etc.), as noise measurements typically decrease with distance from the source. Setback ordinances for UOGD activities have ultimately been the result of political compromise since they have lacked a sufficient technical or empirical basis given the heterogeneity of factors that influence environmental hazards from UOGD (Fry, 2013). Profits and other economic considerations are weighed against environmental and health protection and other community concerns (e.g., nuisance, aesthetics, etc.). However, some evidence suggests that setback distances may not be adequate to reduce public health threats (Haley et al., 2016). Setback distances based on noise may offer a more empirical foundation than methods that have been used to date.

Policies should also require noise mitigation techniques, which are well known and already used by many oil and gas operators. These may include perimeter sound walls, sound control systems, acoustical enclosures and buildings, and the use of sound absorbing materials. Natural terrain can also play a role in mitigation and where possible pads may be sited to make use of hills, trees, and other natural objects to reduce exposure. Significant restrictions on nighttime operations should be put into place in order to minimize sleep disruption. Maximum allowable noise levels should take into account location and sensitivities of surrounding populations, which may be more vulnerable to noise exposure from UOGD. For instance, the data suggest that maximum allowable noise levels should be lower for schools and hospitals than for industrial or commercial areas.

As previously discussed, both the nature and duration of noise are relevant to potential health outcomes. Many of the noise levels associated with UOGD are transient in nature and only occur during certain development activities. For instance, some activities, such as well pad preparation, drilling, and hydraulic fracturing will only be encountered prior to the completion of a well. Certain adverse health outcomes usually only result from long-term noise exposure and may be less of a concern with most development activities. On the other hand, some sources, such as compressor stations, produce chronic noise that will continue for years after wells are put out of production. Although noise levels may fall under municipal and industrial noise limits, data indicate these limits may not be low enough to protect public health.

More research is needed to clarify noise exposure from UOGD as a potential health risk. Field campaigns to measure noise levels from UOGD activities should be undertaken to inform policies and to protect public health. Cohort or longitudinal studies should be developed to address the question about causal links between UOGD noise and adverse health outcomes. In particular, studies should be designed and implemented to investigate the following in the context of UOGD:

- the effectiveness of noise mitigation measures as well as the adequacy of setback distances;
- the implications of noise exposure on vulnerable populations, including children, the elderly, and communities with multiple and cumulative socioeconomic and environmental burdens;
- potential co-exposures of noise, air, and light pollution;
- LFN levels and associations between exposure to LFN and adverse health outcomes;
- relationships between noise exposure and stress related health outcomes associated with UOGD, such as cardiology inpatient prevalence.

Competing financial interests

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Assessment and risk analysis of casing and cement impairment in oil and gas wells in Pennsylvania, 2000–2012

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Casing and cement impairment in oil and gas wells can lead to methane migration into the atmosphere and/or into underground sources of drinking water. An analysis of 75,505 compliance reports for 41,381 conventional and unconventional oil and gas wells in Pennsylvania drilled from January 1, 2000–December 31, 2012, was performed with the objective of determining complete and accurate statistics of casing and cement impairment. Statewide data show a sixfold higher incidence of cement and/or casing issues for shale gas wells relative to conventional wells. The Cox proportional hazards model was used to estimate risk of impairment based on existing data. The model identified both temporal and geographic differences in risk. For post-2009 drilled wells, risk of a cement/casing impairment is 1.57-fold [95% confidence interval (CI) (1.45, 1.67); $P < 0.0001$] higher in an unconventional gas well relative to a conventional well drilled within the same time period. Temporal differences between well types were also observed and may reflect more thorough inspections and greater emphasis on finding well leaks, more detailed note taking in the available inspection reports, or real changes in rates of structural integrity loss due to rushed development or other unknown factors. Unconventional gas wells in northeastern (NE) Pennsylvania are at a 2.7-fold higher risk relative to the conventional wells in the same area. The predicted cumulative risk for all wells (unconventional and conventional) in the NE region is 8.5-fold [95% CI (7.16, 10.18); $P < 0.0001$] greater than that of wells drilled in the rest of the state.

shale oil and gas | casing integrity | cement integrity | onshore wells | wellbore integrity

Oil and natural gas production has increased substantially in the United States in recent years, predominantly due to innovations such as high-volume hydraulic fracturing and directional drilling in shale formations (1). Concurrent with this increase, concerns have mounted regarding effects of this oil and gas development process on groundwater quality, human health, public safety, and the climate, due, in part, to subsurface migration of methane and other associated hydrocarbon gases and volatile organic compounds. Economic development of gas and oil from shale formations requires a high well density, at least one well per 80 surface acres, over large continuous areas of a play. Osborn et al. (2) and Jackson et al. (3) identified a positive relationship between the concentration of thermogenic methane in private water wells in Pennsylvania and the proximity of those water wells to the nearest unconventional (i.e., Marcellus shale) gas production well. These studies also identified three possible mechanisms for explaining this relationship, and concluded that the most likely of these is subsurface migration from leaking gas wells. Other researchers have observed thermogenic and other subsurface-sourced methane in atmospheric concentrations high above background levels near conventional and unconventional gas development (4–6), suggesting that leaking wells may also contribute to fugitive methane and other associated gas emissions, with clear climatic and air quality consequences (7).

Leaking oil and gas wells have long been recognized as a potential mechanism of subsurface migration of thermogenic and biogenic methane, as well as heavier n-alkanes, to the surface (7–11). A leaking well, in this context, is one in which zonal isolation along the wellbore is compromised due to a structural integrity failure of one or more of the cement and/or casing barriers. Such loss of integrity can lead to direct emissions to the atmosphere through one or more leaking annuli and/or subsurface migration of fluids (gas and/or liquid) to groundwater, surface waters, or the atmosphere. Cement barriers may fail at any time over the life of a well for a number of reasons, including hydrostatic imbalances caused by inappropriate cement density, inadequately cleaned bore holes, premature gelation of the cement, excessive fluid loss in the cement, high permeability in the cement slurry, cement shrinkage, radial cracking due to pressure fluctuations in the casings, poor interfacial bonding, and normal deterioration with age (12). Casing may fail due to failed casing joints, casing collapse, and corrosion (13). Loss of zonal isolation creates pressure differentials between the formations intersected by the wellbore and the open barrier(s). The pressure gradient thus created allows for the flow of gases or other formation fluids between geological zones (i.e., interzonal migration) and possibly to the surface (14–16), where it might manifest as sustained casing pressure (SCP) or sustained casing vent flow.

Annuli are often vented, as noted in inspection records, and may contribute to fugitive emissions from the well site. Low-pressure

Significance

Previous research has demonstrated that proximity to unconventional gas development is associated with elevated concentrations of methane in groundwater aquifers in Pennsylvania. To date, the mechanism of this migration is poorly understood. Our study, which looks at more than 41,000 conventional and unconventional oil and gas wells, helps to explain one possible mechanism of methane migration: compromised structural integrity of casing and cement in oil and gas wells. Additionally, methane, being the primary constituent of natural gas, is a strong greenhouse gas. The identification of mechanisms through which methane may migrate to the atmosphere as fugitive emissions is important to understand the climate dimensions of oil and gas development.

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leaks may continue to be periodically bled off and monitored, although recent studies warn that bleeding pressure to zero may actually lead to gas migration (17). High-risk (e.g., rapid repressuring of the annulus following bleed down) leaks must be structurally remedied (i.e., cement squeeze, gel squeeze, use of packers, topping off cement). State regulations (Pennsylvania code 25 §78.86) mandate that wells with leaks that cannot be vented or adequately repaired be permanently plugged, which may reduce but not eliminate the interzonal flow of gases and liquids. Leaks that continue undetected or inadequately remedied may lead to the contamination of shallow aquifers, accumulation of explosive gases within and around residences and other structures, and emission of methane and other associated gases to the atmosphere.

Although not every instance of loss of zonal isolation will lead to such events, the incidence rate of cement/casing impairments and failures can provide some insight into the scale of current and future problems. However, the structural integrity failure rate of oil and gas well barriers continues to be a subject of debate. The rates most commonly cited (from 2 to >50%) are based upon industry reporting for offshore wells in the Gulf of Mexico (13, 14) and Canadian onshore (mostly conventional) wells (16). Watson and Bachu (16) note that wells drilled during periods of rapid development activity and/or wellbores deviated from vertical (e.g., horizontal wellbores) may be more prone to casing vent flow and/or gas migration away from the wellhead.

Due to the lack of publicly available structural integrity monitoring records for onshore wells from industry, more recent studies have used data from state well inspection records to estimate the proportion of unconventional wells drilled that develop cement and/or casing structural integrity issues. For instance, Considine et al. (18) analyzed Pennsylvania Department of Environmental Protection (PADEP) notice of violation (NOV) records for 2008–2011 and found that between 1% and 2% of wells had one or more potential structural integrity issues during that time period. Vidic et al. (19), using the 2008–2013 data from the PADEP database, found that 3.4% of all monitored unconventional wells drilled to date in Pennsylvania might have structural integrity failures based on NOVs related to cement/casing integrity. However, neither study adequately accounts for non-NOV indicators of cement/casing integrity impairment or temporal or spatial dimensions of such impairments.

Earlier work found that the NOV count alone does not account for all incidences of cement/casing failure (20). State regulatory agencies and the oil and gas industry monitor many of the wells showing signs of SCP or other indicators of cement and/or casing impairment. Remedial action is often attempted once or many times on a monitored well, but a NOV is not issued by the agency. Additionally, violation codes are sometimes entered incorrectly as non-cement/casing issues and later corrected in violation comments. By not accounting for these, previous assessments based on PADEP inspection records (18, 19) may underestimate the actual proportion of wells with cement and/or casing problems in Pennsylvania.

Failure to account for temporal dimensions of the data may also skew results. Previous studies on cement/casing impairment have noted that wells drilled during boom periods may be more susceptible to loss of zonal isolation because operators might cut corners in an attempt to increase the number of wells drilled over a short period (16). The increased risk of zonal isolation problems as wells age and the increased probability of identifying these issues with more inspections may also create a time lag between the date that drilling of the well commences (i.e., the spud date) and the entry of a cement/casing issue in the inspection records. This time lag is due to the fact that wells drilled in recent years have not been subject to the same duration of analysis or number of inspections as older wells. Thus, inspection records on newer wells are incomplete relative to those of older wells.

Here, we offer an in-depth analysis of the complete inspection records, including NOVs, observations and corrections noted in the inspector comments, for 32,678 oil and gas production wells drilled in Pennsylvania between 2000 and 2012. We use a time-dependent risk analysis model to assess the cumulative risk of cement/casing problems for wells based on the historical occurrence of cementing/casing impairment events.

Results and Discussion

Comparison of state inspection and well spud reports (where the "spud" date is the start date of drilling) indicates a loss of well integrity in 1.9% of the oil and gas production wells spudded between 2000 and 2012. This value agrees well with some previous estimates in the literature; however, this superficial indication comes with important caveats and is an incomplete assessment. The data suggest large differences in structural integrity issues between well types, with unconventional wells showing a sixfold higher incidence of cement and/or casing issues relative to conventional wells statewide (Table 1 and *SI Appendix*, Table S14). Even within the unconventional well category, a wide range (1.49–9.84%) of incident rates is observed among wells spudded during different time periods and in different regions. Unconventional wells spudded before 2009 in the northeastern (NE) counties of the state are associated with the highest occurrence of loss of structural integrity (9.84%). It can be argued that this subcategory reflects a small number of observed cases (61 wells) and the earliest industry experience in the Marcellus play, and thus should not be used as an indication of current practices. However, unconventional wells spudded in the NE region since 2009 (2,714 wells) show a similarly high rate of occurrence (9.18%).

As already noted, direct comparison of rates of loss of well integrity in young wells to those of much older wells is misleading. Assuming an increased risk of cement/casing issues as the materials (cement/casing) age, it must follow that the risk of structural integrity loss and likelihood of state inspectors identifying a cement/casing problem will increase through time as a well accumulates additional inspections. Thus, a well spudded 3 y ago, which will ideally have a 3-y record of inspections from which to draw observations, is more likely to have an indicator

Table 1. Percentage of wells showing loss of structural integrity by temporal (pre- and post-2009 spuds), geographic (non-NE and NE counties), and well type (conventional and unconventional) categories

	Non-NE counties		NE counties	
Wells spudded	Conventional	Unconventional	Conventional	Unconventional
Pre-2009	0.73%	1.49%	5.21%	9.84%
Post-2009	2.08%	1.88%	2.27%	9.14%

Statewide, rate of loss of structural integrity for conventional and unconventional wells spudded between 2000–2012 are 1.0% and 6.2%, respectively (weighted average = 1.9%).

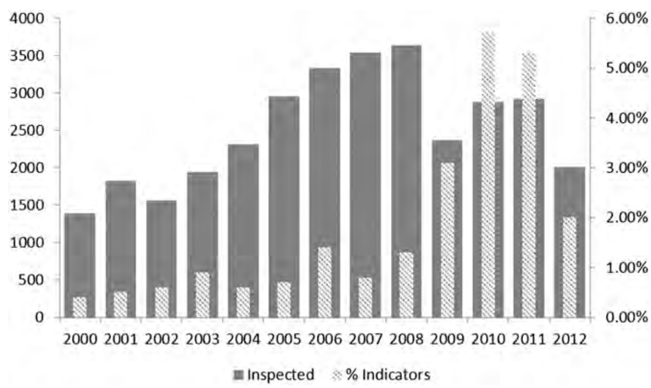

Fig. 1. Annual trends of indicators for wells spudded in the state of Pennsylvania, 2000–2012. The percentage of spuds with integrity issues reflects the number of unique wells spudded in a given year for which an indicator was found at any time within the inspection record (13 y). The rates of incidence noted in the inspection records for pre-2009 spuds hover around 1% for the several years before spiking in 2010. These trends may represent differences in state emphasis on locating leaking wells following widely publicized contamination events or actual increases in loss of structural integrity.

of cement/casing integrity loss noted in the inspection record than a similar well spudded only 1 y ago and associated with just one-third of the observation time. The effects of this temporal dependency can be seen in Fig. 1. Annual trends for wells spudded in 2010 and 2011 show rates of incidence similar to the cumulative unconventional rate reported in Table 1 (unconventional wells make up 57.5% and 66.3% of spuds in 2010 and 2011, respectively). However, wells spudded in 2012 and subject to an observation period ≤1 y appear to have a much lower incidence of cement/casing issues. This raises an important question: Are wells spudded in 2012 more sound than those spudded in previous years, or is the apparent decline in indicators in state inspection reports an artifact of an incomplete inspection history?

Note that incomplete inspection records may also occur in older wells that have not been regularly inspected through time. Inspection records for modeled wells indicate an average of 2.75 inspections per well statewide, despite nearly 71.6% of wells being >3 y old. Moreover, PADEP records indicate that of the more than 41,000 oil and gas production wells spudded between 2000 and 2013, 24% of conventional and 4% of unconventional well spuds have never received facility-level inspections or the relevant inspections are not included in the PADEP online database (8,703 wells in total). It should be noted that these wells might have received inspections under the client- or site-level category, which generally are carried out as part of large-scale contamination/gas migration investigations, but these types of inspections are not included in our analysis because the details of such inspections often do not include a full listing of wells of interest. Assuming that the individual wells observed in these larger scale investigations did, in fact, receive facility-level inspections and are included in our analysis, we would expect a negligible impact from excluding client- and site-level investigations because the individual well inspections would have likely been flagged by at least one of the indicators before a large-scale contamination event. The impact of wells investigated in the client- and site-level inspections but not receiving a facility-level inspection (i.e., not included in this analysis) may be significant but cannot be assessed with the data available. Not all wells inspected in large-scale contamination investigations are found to be leaking and, although the count of impairment events from such wells could increase, the rate of impairment (the number of events per wells inspected) might not.

Hazard analysis captures such temporal dependencies through the nonparametric baseline hazard rates and hazard ratios of the inspection count variable, thus allowing us to predict what the incidence rate for wells might be if they were to acquire comparable observation times and inspection counts. Results from hazard modeling of temporal and geographic strata are given next.

Hazard Model: Temporal Strata. Wells spudded before 2009 make up almost 72% of the total wells modeled but just 31% of the total count of unique wells with documented cement/casing indicator events from the 2000–2012 modeled dataset. Unconventional wells make up 16.8% of the wells in this stratum. The first unconventional well in the modeled dataset has a 2002 spud date; however, unconventional drilling activity remained relatively low until 2009 (Fig. 2). Pre-2009 unconventional wells show a modest but statistically insignificant increase in hazard [1.07-fold greater risk relative to pre-2009 conventional wells, 95% confidence interval (CI) (0.18, 1.52); Table 2]. However, in the post-2009 stratum, risk of a cement/casing event is 1.58-fold [95% CI (1.45, 1.67); $P < 0.0001$] higher in an unconventional well relative to a conventional well spudded within the same time period (Table 2).

Fig. 3 shows estimated cumulative hazards for conventional and unconventional wells across the state for pre- and post-2009 strata, respectively. These figures are plotted in the units of the Nelson–Aalen estimator of the cumulative hazard function (i.e., the definite integral, from zero up to the indexed time, of the hazard function). These plots are used for visually examining differences in distributions in time-to-event data and are interpreted here as the fractional probability that a well will be identified as having a cement and/or casing problem at time t, assuming that the event has not occurred before time t. Wells spudded after January 1, 2009, show significantly higher ($P < 0.0001$) predicted hazards across comparable analysis times, regardless of well type, relative to pre-2009 well spuds [4.58 hazard ratio, 95% CI (3.84–5.47)].

It is unclear whether these temporal differences reflect more thorough inspections and greater emphasis on finding well leaks, more detailed note taking in the available inspection reports, or real changes in rates of structural integrity loss. The percentage of wells inspected in the first year has risen, from an average of 76% in pre-2009 spuds to 88.7% in the post-2009 spuds (*SI Appendix*, Table S3), and this may partially account for the increase in documented cement/casing problems. Additionally, more than one-half (53.2%) of the nonevent wells (i.e., no indicator of loss of structural integrity found) lack inspector

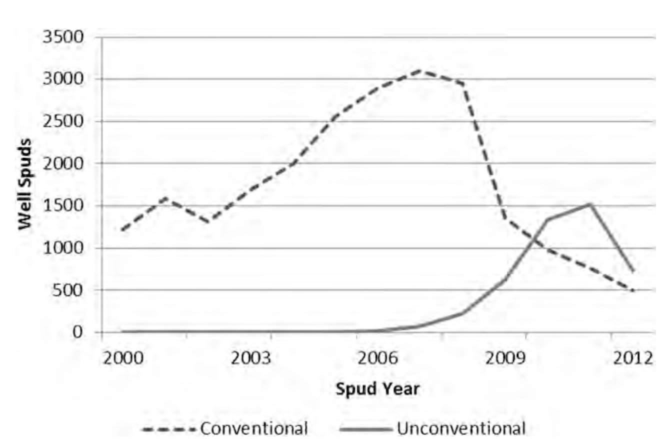

Fig. 2. Conventional and unconventional spud counts: 2000–2012 (Source: PADEP, 2013).

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Table 2. Statewide data: Effects of model covariates for pre- and post-2009 well spuds

Covariate	Pre-2009 spuds HR	Pre-2009 spuds 95% CI		Wells spudded 2009–2012 HR	Wells spudded 2009–2012 95% CI	
Well type	1.07	0.18	1.52	1.58	1.45	1.67
Inspection count	1.177	1.154	1.201	1.059	1.048	1.069

The hazard ratio (HR) reflects the multiplicative change in risk at any time due to a change in the covariate. A change in well type reflects the change from conventional to unconventional. A change in inspection count reflects a single (+1) increase to the total inspection count for a well.

comments and other information necessary to determine whether a cement/casing issue ever occurred. These wells, by default, are modeled as nonevents. The majority of such wells (73%) were spudded before 2009. This lack of data for older wells may result in an underestimation of events in the pre-2009 stratum. As such, results from our modeling should be considered conservative.

Note that the full analysis time for the statewide dataset is 676 wk (13 y). Naturally, more recently spudded wells will have a shorter analysis time (1–208 wk for wells spudded since 2009). However, inspection records indicate that 52.9% of pre-2009 spuds have a <2-y inspection record, with an average of 2.4 inspections per well across the entire time period (*SI Appendix*, Table S4). This suggests that the majority of these active, older wells are no longer being inspected. Continued annual inspections may increase the predicted cumulative risk of structural

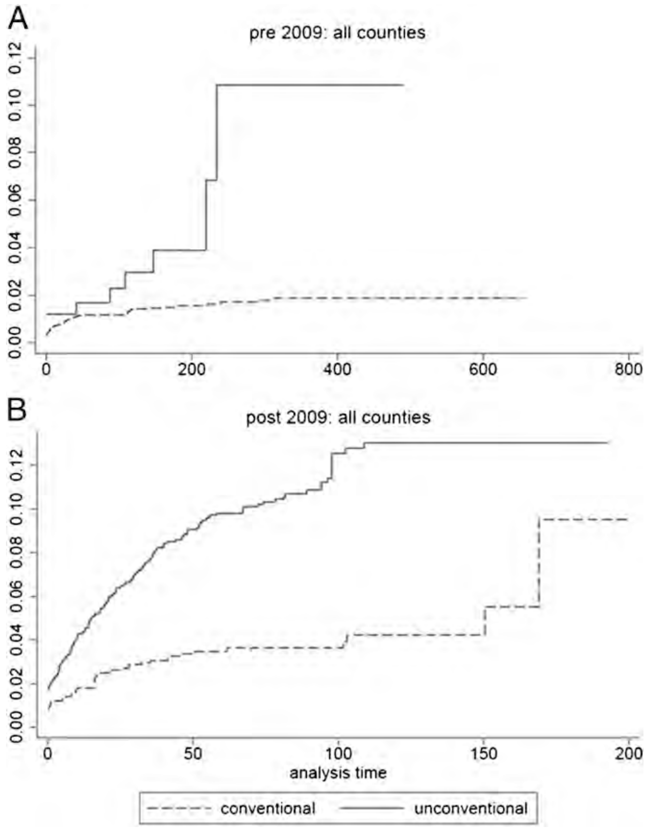

Fig. 3. Nelson–Aalen cumulative hazard for pre-2009 (*A*) and post-2009 (*B*) spuds by well type. The vertical axis is the fractional probability of an event occurring at a given analysis time.

integrity issues for these wells beyond what is reported here, indicating, again, that results from our analysis are conservative. Each additional inspection in the pre-2009 stratum increases the risk of identifying a cement or casing problem by 17.7% [1.18 hazard ratio, 95% CI (1.15, 1.20); Table 3] relative to the hazards shown in Fig. 3. The effect of increased inspections on younger wells (post-2009 spuds) is smaller but statistically significant [1.06 hazard ratio, 95% CI (1.05–1.07); Table 3].

Hazard Model: Geographic Strata. The NE counties of the state (Bradford, Cameron, Clinton, Lycoming, Potter, Sullivan, Susquehanna, Tioga, Wayne, and Wyoming) make up just 11% of the total wells spudded (3,030 wells) but 54.7% of the state's unconventional wells and 88.8% of the cement/casing events in unconventional wells. There are 266 total structural integrity indicator events in the NE region, or ∼52% of events statewide. The predicted cumulative hazard for all wells (unconventional and conventional) in the NE region is 8.5-fold [95% CI (7.16, 10.18)] greater than that of wells drilled in the rest of the state (Table 3). The log-rank test for this regional difference is extremely significant ($P < 0.0001$).

As with the statewide data, effects of covariates in the NE counties indicate significant increases in the risk of finding an indicator in the inspection records. Unconventional wells in the NE region are at a 2.7-fold higher risk relative to the region's conventional wells [95% CI (1.43, 4.95); Table 3]. Additional inspections in these counties have a similar effect on risk as that found for post-2009 spuds statewide [1.06 hazard ratio, 95% CI (1.05, 1.08); Table 3].

Figs. 4–6 reveal increased cumulative hazards for wells in the NE counties relative to other areas of the state, as well as increased cumulative hazards associated with unconventional wells ($P < 0.001$) and post-2009 spudded wells ($P = 0.005$) in the region. These figures, like Fig. 3, are plotted in units of the cumulative hazard function. Overall, NE wells show a risk of an identified integrity issue within the first 3 to 4 y (156–208 wk) of operation of ∼20% (Fig. 4). The cumulative hazard for unconventional wells in the region is predicted to increase upward of 40% by year 7 of the analysis (364 wk; Figs. 5 and 6).

Conclusion

Pennsylvania state inspection records show compromised cement and/or casing integrity in 0.7–9.1% of the active oil and gas wells drilled since 2000, with a 1.6- to 2.7-fold higher risk in unconventional wells spudded since 2009 relative to conventional well types. Hazard modeling suggests that the cumulative loss of structural integrity in wells across the state may actually be slightly higher than this, and upward of 12% for unconventional wells drilled since January 2009. This wide range of estimates is influenced by significantly higher rates of impairment in wells spudded in the NE counties of the state (average of 12.5%, range: 2.2–50%), with predicted cumulative hazards exceeding 40% (Figs. 5 and 6).

These results, particularly in light of numerous contamination complaints and explosions (21–23) nationally in areas with high concentrations of unconventional oil and gas development and

Table 3. NE counties data: Effects of model covariates

Covariate	HR	95% CI	
Well type	2.657	1.428	4.946
Inspection count	1.065	1.047	1.083
Temporal stratum	1.580	1.152	2.167

The HR reflects the multiplicative change in risk at any time due to a change in the covariate. A change in well type reflects the change from conventional to unconventional. A change in inspection count reflects a single (+1) increase to the total inspection count for a well.

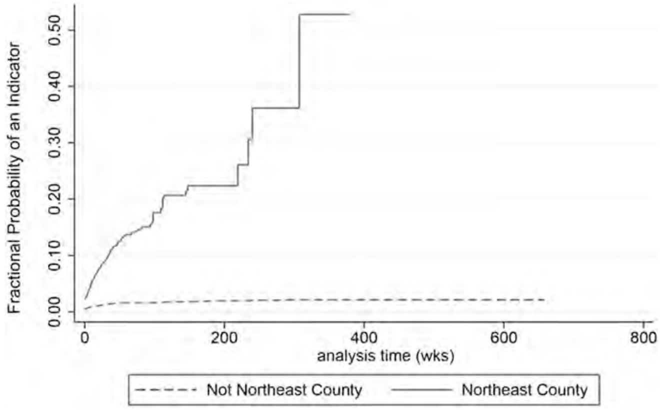

Fig. 4. Nelson–Aalen cumulative hazard: NE vs. non-NE counties for combined conventional and unconventional wells. The vertical axis is the fractional probability of an event occurring at a given analysis time.

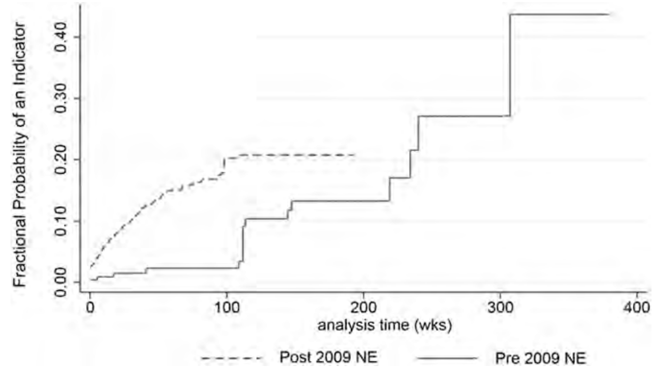

Fig. 6. Nelson–Aalen cumulative hazard for NE counties by temporal strata. The vertical axis is the fractional probability of an event occurring at a given analysis time.

the increased awareness of the role of methane in anthropogenic climate change (24), should be cause for concern. A recent investigative report of water contamination cases confirmed PADEP determination letters and enforcement orders indicating that at least 90 private water supplies across the state were damaged due to subsurface gas migration between 2008 and 2012 (25). The NE region of Pennsylvania, in particular, has experienced several widely publicized methane migration cases related to loss of structural integrity of wells, including the Dimock, Susquehanna County [Commonwealth of Pennsylvania Department of Environmental Protection (DEP) Consent Order to Cabot Oil & Gas, December 15, 2010] and Towanda, Bradford County (Commonwealth of Pennsylvania DEP Consent Order to Chesapeake Appalachia LLC, May 16, 2011) groundwater contamination cases. PADEP records cite unconventional wells spudded between 2009 and 2010 in both of these cases. Incidence rates inferred from direct comparison of indicator counts and the number of wells inspected in these townships as of December 31, 2012, are 21.2% and 15.4%, respectively; however, hazard modeling predicts a cumulative 7-y hazard for similar wells in the region twofold higher (Figs. 5 and 6; $t = 364$).

Our aim in this study was to quantify the rate of barrier impairment in a population of modern on-shore oil and gas wells, and in doing so, we have noted significant temporal and spatial differences in risk of impairment. It is beyond the scope of this paper to explain these spatial and temporal differences. Various biasing effects might influence these differences and are the focus of our continuing study of this problem. Moreover, results presented here represent a snapshot in time of an evolving situation. This study presents the state of structural integrity loss in oil and gas wells over a 13-y period in the state of Pennsylvania as inferred from publicly available data, while also presenting a risk assessment model of future performance. It should be a priority to update and validate this model with well monitoring and evaluation data reported to the PADEP from the industry as they are collected. Finally, although this study discusses one possible primary mechanism of methane migration to groundwater aquifers and fugitive emissions to the atmosphere, more studies are needed to investigate the association between the structural integrity loss in oil and gas wells and the incidence of these unwanted events.

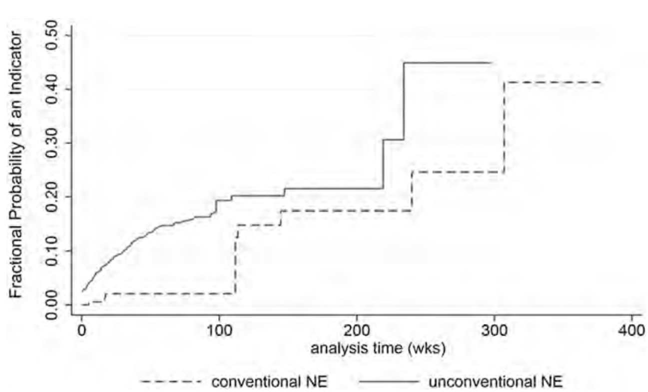

Fig. 5. Nelson–Aalen cumulative hazard for NE counties by well type. The vertical axis is the fractional probability of an event occurring at a given analysis time.

Methods

Database. The database created here is based upon spud reports from the PADEP Office of Oil and Gas Management website for conventional and unconventional gas, oil, combined gas and oil, and coal-bed methane wells spudded from January 1, 2000–December 31, 2012 (www.depweb.state.pa.us/portal/server.pt/community/oil_and_gas_reports/20297). Spud reports provide data on well characteristics, including American Petroleum Institute (API) well identification, spud date, well type, production type, and well location (county, municipality, and geographic coordinate information). We exclude storage, injection, and undetermined purpose wells to focus exclusively on oil and gas production wells.

Compliance Reports. The compliance reports for oil and gas well inspections carried out over the same time period (www.depweb.state.pa.us/portal/server.pt/community/oil_and_gas_compliance_report/20299) are then cross-referenced with the well inventory by matching API identification codes. PADEP compliance reports provide data on inspection category (i.e., site, client, facility), inspection type (e.g., administrative review, drilling, routine), inspection date, violations issued, and comments noted by PADEP inspection staff regarding the inspection and/or violation(s) issued. We exclude client and site inspection categories, because these inspections generally reflect multiwell, large-scale compliance assessments and rarely identify individual wells. We also do not include construction (i.e., site clearing), asbestos program, Chapter 94, joint external/internal, Nuclear Regulatory Commission, and road-spreading inspection types. Construction inspections occur before well spudding, and thus are not relevant to well integrity. The remaining excluded inspection types are also considered not relevant to the study question. Excluded inspections accounted for <0.5% of total inspections carried out over the 2000–2012 time frame.

Indicators Search. Inspector comments indicate barrier remediation and/or ongoing monitoring of annular gas or pressure (indicators of impaired structural integrity) for numerous wells that were not issued an NOV. To ensure that we captured these wells, we filtered both the "Inspection_Comment" and "Violation_Comment" fields for the most common keywords associated with failure of primary cement/casing or common remediation measures. Keywords used in the filtering and their relevancy to impaired primary cementing and casings are presented in *SI Appendix*, Table S6. Keyword filter results are then human-read thoroughly to confirm an indication of impaired well integrity and to separate filter results that do not indicate an integrity issue (e.g., gas meter readings = 0, nonremediation perforations, "no visible bubbling"). A detailed discussion of the indicators and their temporal and geographic distributions is provided in *SI Appendix*.

Violation codes provide a more direct indication of a potential well impairment. PADEP violation codes relevant to cement and casing integrity are listed in *SI Appendix*, Table S7. The compliance reports indicate multiple misentries in the original violation code noted by an inspector, which are later corrected in the "Violation_Comment" field. We assume that wells with any one of the violations or a combination of violations listed in *SI Appendix*, Table S7 and entered in either the "Violation_Code" or "Violation_Comment" field in inspection reports are indicative of a well with impaired cement and/or casing. We note that not all violations will result in groundwater contamination events. The relative importance of key violation codes and the temporal and geographic distributions of total violation counts are discussed in detail in *SI Appendix*.

Hazard Analysis. The Cox proportional hazards model (26) is a semiparametric model that uses a multivariate regression technique to model the instantaneous probability of observing an event (i.e., occurrence of a cement/casing indicator in the inspection record) at time t, given that an observed case (i.e., a well) has survived to time t (i.e., has not experienced an inspection where a cement/casing indicator was found) as a function of predictive covariates (well type and total number of inspections received). All wells enter observation at $t = 0$, regardless of spud date, and observation continues until the last known date of inspection or the occurrence of a cement/casing indicator in a well's inspection history. Addition details and definitions of key model terms and concepts are provided in *SI Appendix*.

Time of analysis of a well, as the dependent variable in the statistical model, cannot be a null or a negative value. Wells showing no record of inspection (8,703 wells) have null t values, and are therefore removed from the model dataset. We also found 5,223 wells, 100 of which were associated with comment or violation indicators, where the time since spud to first inspection was negative. Because construction/site clearing inspections were removed from the database in previous steps, we assume that either the spud dates or inspection dates for these wells were entered incorrectly; these data are also removed from the dataset. The impact of removing these inspections from the modeled dataset is negligible, because the overall impairment rate (1.9%) for these wells mirrors that of the statewide data. The resulting modeled statewide dataset contains 27,455 wells that are associated with 75,505 inspections.

Multiple inspections per unique well number are mined to return only a single set of entries per well: well characteristics (i.e., county, well type, spud date), event status (a binary code assigned to each well stating whether an indicator was found at any point in the life of the well: Y = 1, N = 0), date of first inspection, date of first mention of indicator if found, date of last inspection (for nonevent wells), and total number of inspections carried out.

An assumption of the Cox proportional hazards model is that the hazard ratio is constant over time. The validation of this assumption for the various models, using the Grambsch and Therneau test (27), is presented in *SI Appendix*, Table S1. The proportional hazards test for individual covariates passed for well type ($P = 0.06$) and inspection counts ($P = 0.09$) in the full dataset. The proportional hazards model assumption also holds for the pre/post-2009 analyses. Well type (i.e., unconventional, conventional) and inspection counts (i.e., number of times a well is inspected during the analysis time) are used as covariates in these models.

Temporal and geographic (i.e., county) strata are run in separate analyses. Interannual log-rank statistics were used to assess whether any groups of well spuds were statistically significantly different in terms of their predicted failure risk. We stratified the data accordingly to allow for separate regressions of temporal period (before January 1, 2009, and after that date). We also stratified the data by region to assess the relative geographic distributions [the NE counties (Bradford, Cameron, Clinton, Lycoming, Potter, Sullivan, Susquehanna, Tioga, Wayne, and Wyoming) compared with the rest of the state] of wells with indications of cement/casing problems. Log-rank tests (28) were used to assess geographic variation.

As robustness checks to the Cox proportional hazards model, parametric Weibull and Gompertz regression models (28) were also fit to the full data and the temporal and geographic strata, and the magnitude substantive conclusions did not change.

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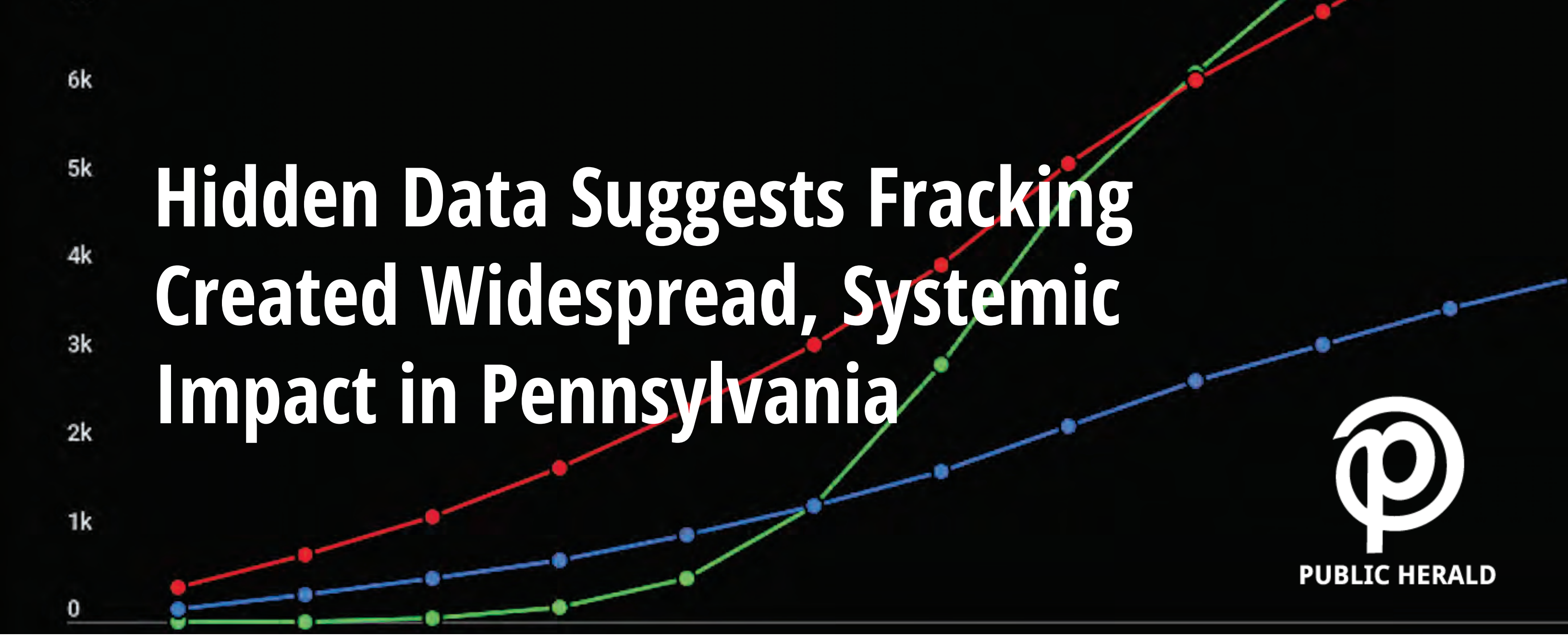
Hidden Data Suggests Fracking Created Widespread, Systemic Impact in Pennsylvania



Trends Show Impacts Are Getting Worse

by Melissa A. Troutman, Sierra Shamer
and Joshua B. Pribanic for Public Herald
January 23, 2017 | Project: INVISIBLE HAND

After a three-year investigation in Pennsylvania, Public Herald has uncovered evidence of widespread and systemic impacts related to "fracking," a controversial oil and gas technology.

Ending over a decade of suppression by the state, this evidence is now available to the public for the first time.

In Pennsylvania, the power over fracking rests in the hands of the Department of Environmental Protection (DEP). When residents observe a problem, they call the Department to report it. That call gets recorded as a "complaint" as required by Title 58 § 3218 of the state's oil and gas act.


Complainant noticed an odor to water about a year ago after sludge pond was put in above her. Son has been getting sick and having liver problems, dog has died and neighbor's 2 dogs and horse have died. Dogs and son had/have arsenic in urine. Bialosky was notified by ans. serv. at 5:02 p.m. 11/18 and told service to hold message for the a.m. Complaint also said Son and animals have arsenic in urine.

Problem got worse past August.

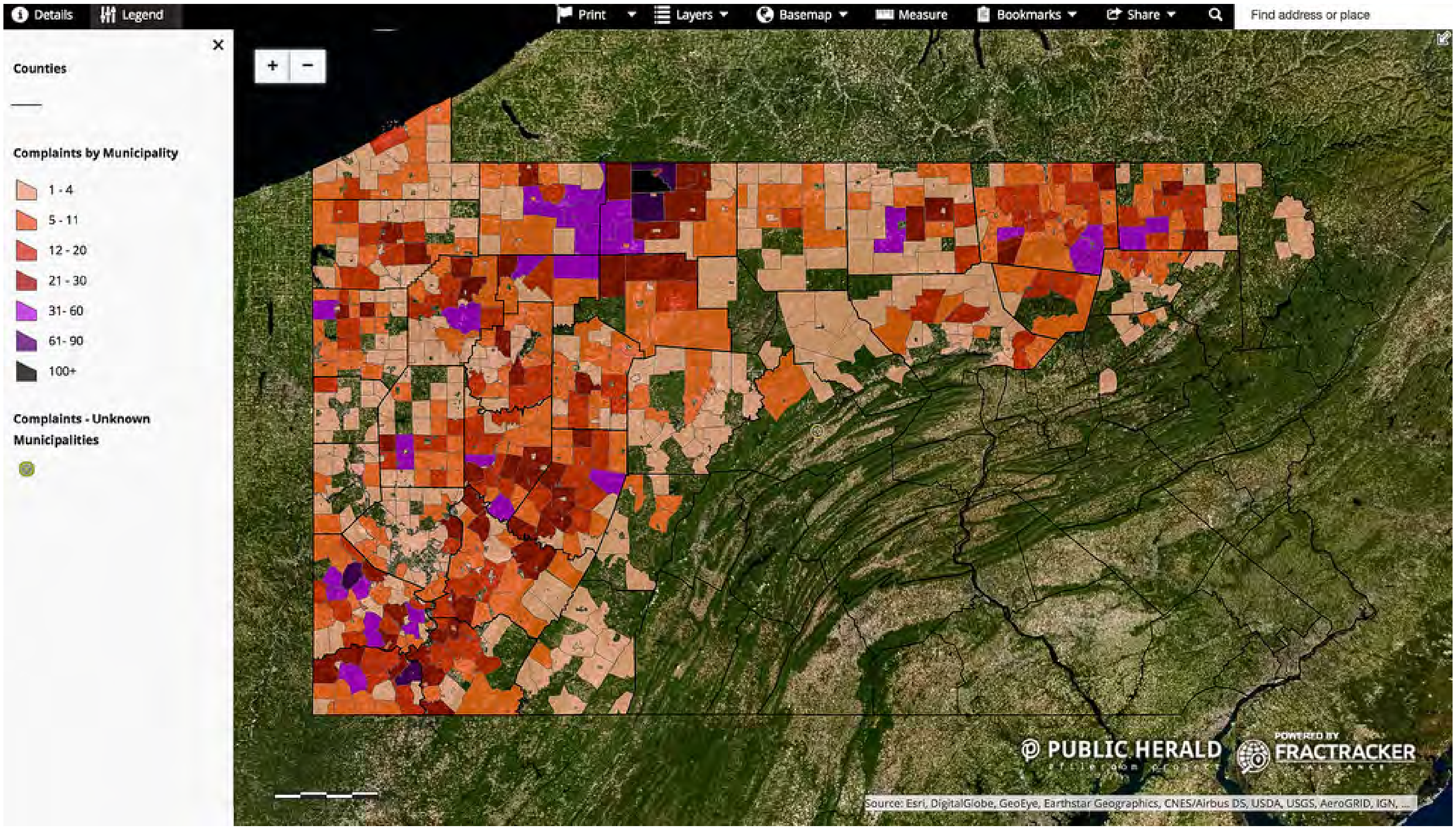
2ND COMPLAINANT SAID BACK IN AUGUST HER DAUGHTERS DOG GOT SICK. She said she called and talked to Bryan Miller regarding this in August. She said she also called Service Rep. I spoke to her today - I have nothing in system so I told her I would put into system along with this complaint as they live close by. She would like someone to test her water also. Range Resources sent Kimbell to draw water. They told her to

In 2011, Public Herald's first file request to DEP for complaints never produced a single document, and we learned that complaints were being held as 'confidential.' When asked why, an attorney from DEP's Southwest Regional Office explained that Deputy Secretary Scott Perry didn't want complaints to 'cause alarm.'"

After pushing through DEP's resistance to disclose these records, our team was able to conduct its first file review for complaints in the spring of 2013. Three years later, after more than 50 file reviews, Public Herald has scanned records for 6,819 complaint cases.

Today, due to this work, anyone can access these cases via the Pennsylvania Oil & Gas Complaint Map.

[image] A citizen complaint record from Amwell Township, Washington County, PA reported to the Pennsylvania Dept. of Environmental Protection on Nov. 28, 2010.



The Pennsylvania Oil & Gas Complaint Map by Public Herald & FracTracker Alliance shows the density of citizen complaints reported to the Department of Environmental Protection from 2004 - 2016. The widespread dispersal of complaints matches the shape of the Marcellus Shale formation. Clicking a township reveals a database of complaints where viewers can download files. © Public Herald

This map shows how citizen complaints are dispersed across counties where shale gas drilling has occurred. We shared our dataset with several scientists, including Dr. Anthony Ingraffea, an oil and gas engineering expert from Cornell University whose work on fracking is published in multiple peer-reviewed papers.

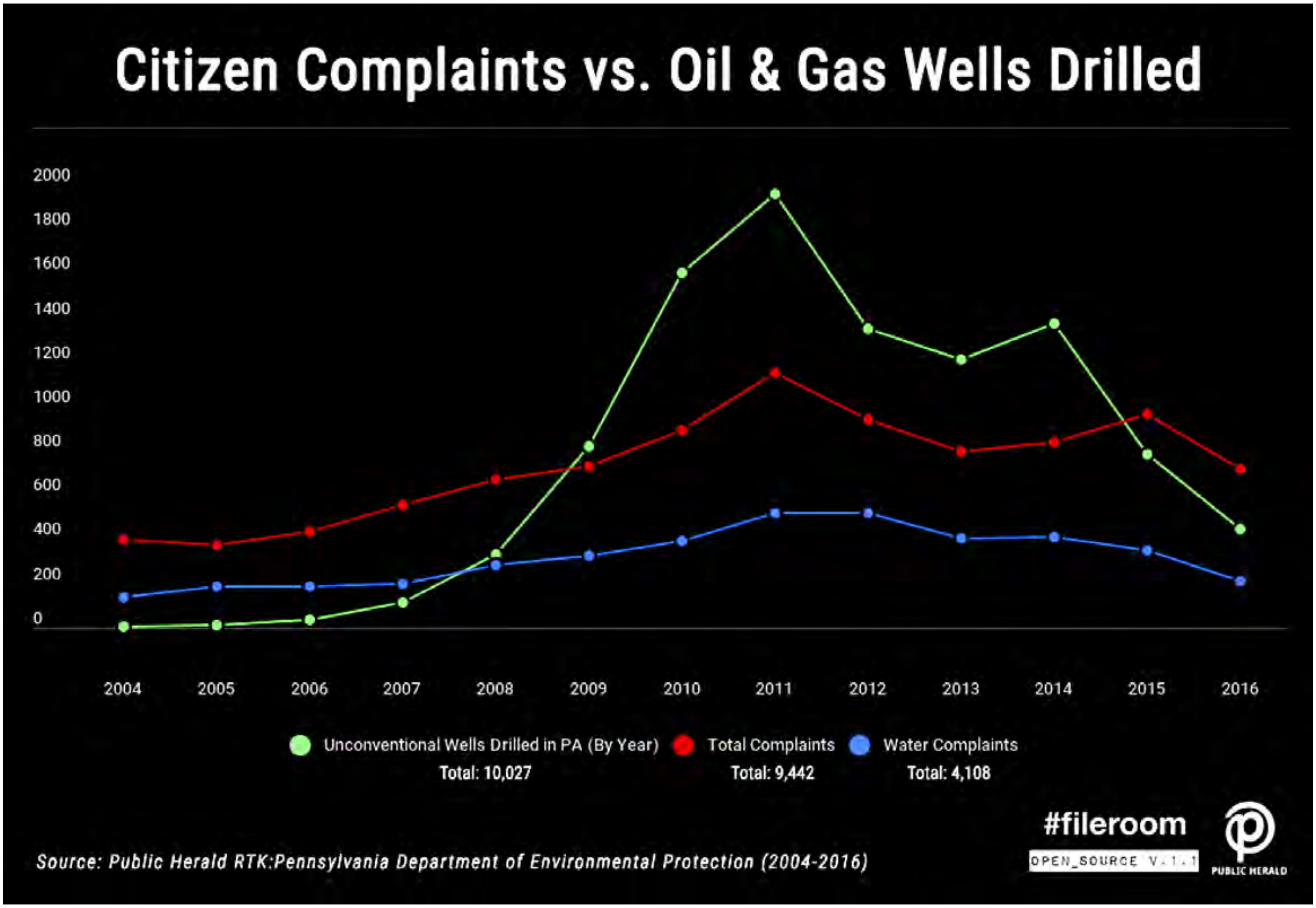
"It's not like all the bad stuff is happening up in the northeast. Pennsylvania is pretty widespread, and what the data shows, quite clearly, is that impact has been systemic."

At the end of our reviews, we submitted a final Right-to-Know request for the DEP database of all citizen complaints.

On December 30, 2016, DEP responded in an email with a new list revealing a statewide total of 9,442 complaints from 2004 through November 29, 2016.

The total number of complaints in the databases ended up being thousands more than anyone on our team had anticipated.

When we compared the annual number of complaints in Pennsylvania to unconventional shale gas development – a.k.a. "fracking" — it revealed a strong relationship.



Annual citizen complaints reported to PA DEP compared to the annual number of new unconventional oil and gas wells. © Public Herald

If you include conventional wells as a variable, the rise of impacts clearly increases with the rise of fracking development. [see graph on next page]

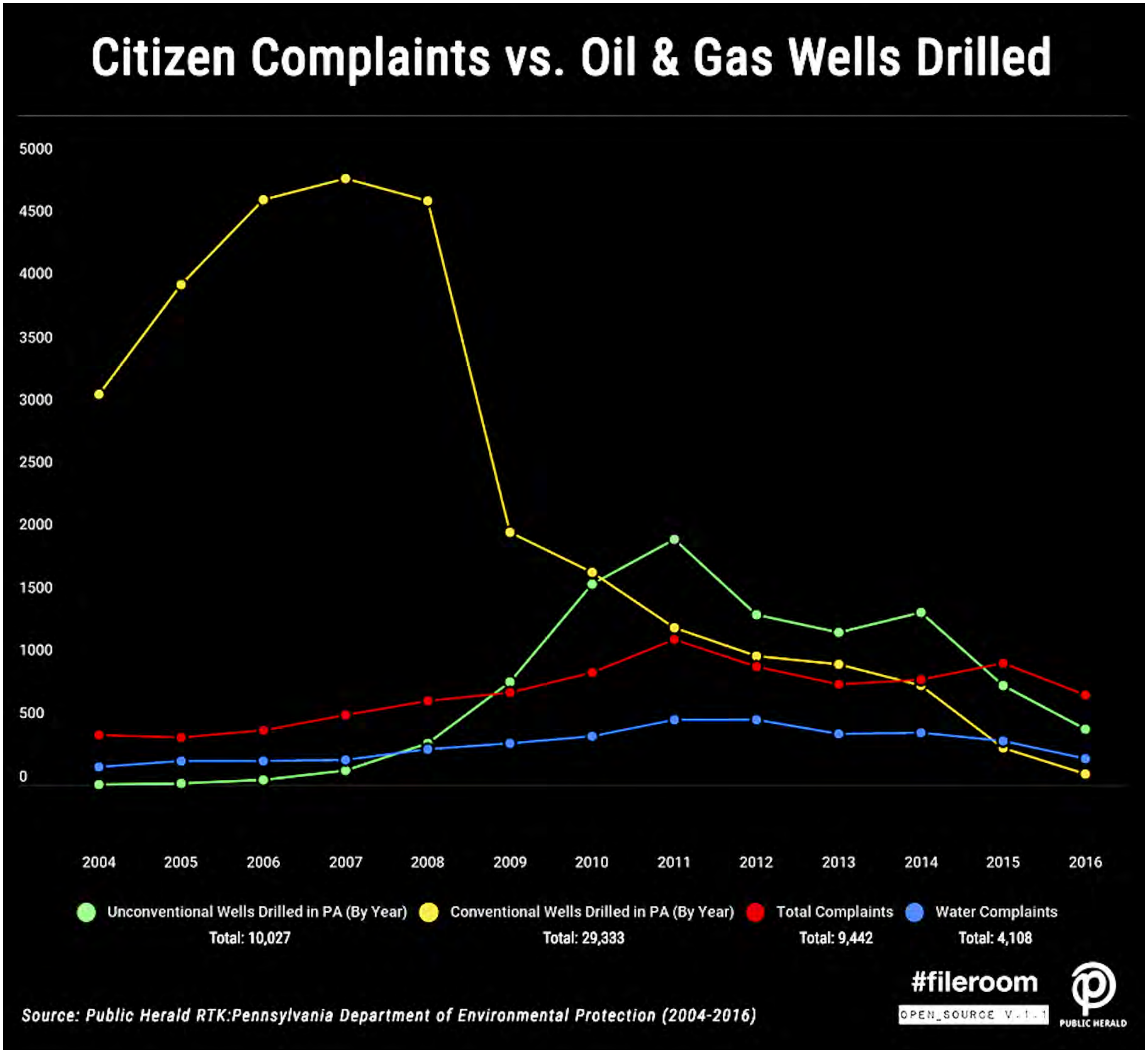
The Rise of Fracking & Systemic Impact

In the graph above, Dr. Ingraffea identified the years 2004 and 2005 as "baseline" or "what things were like in Pennsylvania before shale gas fracking really got started."

During that time, Ingraffea calculated that there was one complaint for every ten conventional wells drilled – then things clearly changed.

"When transitioning to unconventional wells [there] is typically one complaint per well. Even though the industry has had over a decade to learn its lessons and figure out how to get things right, in the last few years the number [has increased to] two complaints for every well drilled."

This increase in complaints per unconventional well is unexpected, given the recent decrease in drilling activity throughout the state. For Ingraffea, the data illustrates that the situation is getting worse by the year.



This graph shows the number of annual conventional and unconventional wells drilled in PA from 2004-2016. It also displays the number of complaints registered by DEP each year, and the subset of those complaints categorized as "water" supplies. "Unconventional wells" are horizontal, hydraulically "fracked" wells to access shale gas. "Conventional wells" are traditional vertical gas wells typically drilled at shallower depths, requiring less chemical additives and less pressure. © Public Herald

"If you drill a shale gas well in Pennsylvania today…the data says you are more likely to get a complaint now than in 2010."

In fact, when Governor Tom Wolf took office in 2015, after campaigning on the promise to make fracking "safe," the number of complaints exceeded the number of new shale gas wells for the first time since 2009.

Dr. John Stolz of Duquesne University in Pittsburgh is another scientist at the forefront of this issue who has conducted independent water investigations of areas impacted by fracking since 2010.

After reviewing this new data, Dr. Stolz. said, "Just looking at the raw numbers, you can say that unconventional wells, for whatever reason, generate more complaints per well. That's something the DEP should be concerned about."

Water Supply Complaints

Of the complaint total, 4,108 cases are categorized by DEP as "water supply" complaints. However, this is much lower than the actual number involving drinking water supplies. Hundreds of additional cases are categorized by DEP as gas migration, spill response, pollution, or leaking wells which can include impacts to water.

Throughout Pennsylvania, DEP has determined that only 284 water supplies have ever been impacted by oil and gas operations in the state. This means that DEP considers 94% of drinking water complaints to be completely unrelated to oil and gas.

"You're telling me that there are thousands of people [who say their water was impacted by oil and gas] in Pennsylvania that want to fool the DEP? I can't accept that," said Dr. Stolz.

According to Ingraffea, "This goes to the very heart of the meaning of this data – are the complaints pie in the sky, crying wolf…or are they real?"

EPA's National Study

"The question on a lot of people's minds, including myself, is – 'Does unconventional extraction pose a threat to drinking water?' If you suppress [complaint] information, it's very difficult to make a case." – Dr. John Stolz

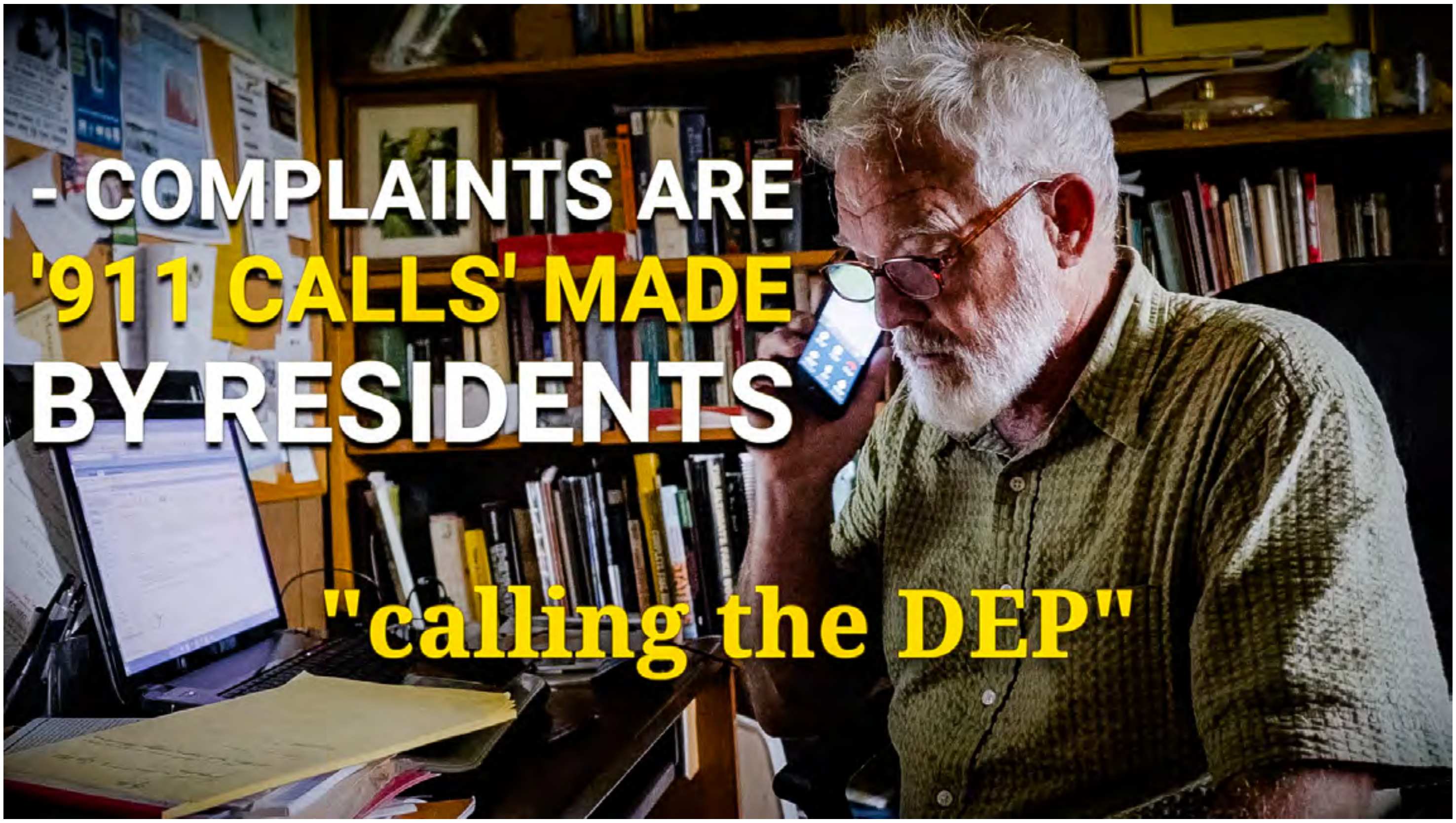
The United States Environmental Protection Agency concluded a five-year study in 2015 that stated fracking had no "widespread, systemic impacts on drinking water supplies."

But less than a year later, the EPA's own Science Advisory Board (SAB) called them out. In an August 2016 review, the SAB stated that EPA did not have the evidence to make such a conclusion.

This forced the EPA to retract their "widespread" and "systemic" claims in December 2016. In their final report, the agency states that fracking can cause water contamination, but they fail to make a broader conclusion citing insufficient data.

EPA used several sources of data from DEP, including the Department's oil and gas compliance database of inspections and violations. In a call with Public Herald, EPA's Jeff Frithsen could neither confirm nor deny whether the Agency reviewed any DEP complaint data for its study.

This isn't the first time EPA has studied the relationship between fracking and drinking water pollution. In fact, the Agency has linked fracking to drinking water contamination as far back as 1987 when "fracking fluids migrated" into a West Virginia water supply.



When a person's water becomes contaminated, the issue isn't whether impacts from fracking are "widespread" or "systemic." The issue is far more tangible – you've lost your water.

'People Are Not Crazy'

Filing a complaint is not rewarding or easy. Calling Pennsylvania DEP begins a process that most often leaves a resident with ongoing pollution problems and feelings of hopelessness.

Janet McIntyre is a resident of the Woodlands, a neighborhood in Connoquenessing Township, Butler County. After shale gas wells were constructed nearby, residents in the Woodlands began experiencing water problems. DEP investigated these complaints, but determined that they were not related to oil and gas activity.

Janet and her husband, along with 50 of their neighbors, have relied on donated, bottled water ever since – six years and counting.

According to Janet, when she asked how to appeal DEP's "non-impact" determination, Deputy Secretary of Oil and Gas Scott Perry told her that it was impossible because the agency acts as "both judge and jury."

But later, Janet learned that the Pennsylvania Environmental Hearing Board considers no action of the DEP final until an adversely impacted person has had the opportunity to appeal the action.

Perry has also publicly dismissed legitimate concerns about fracking's effects on drinking water by insinuating that people are looking for something that's not real.

"I feel like I'm trying to convince the public that Sasquatch doesn't exist," said Perry at an industry convention in 2011.

Desperate for information, Janet asked DEP for her complaint file. DEP failed to provide it to her. Fortunately for Janet, it was among the 271 complaints Public Herald had scanned for Butler County.

Dr. Stolz has conducted a case study of the Woodlands since 2010, and in all his research, he never found residents' complaints in any of the files that DEP provided to him.

"A big part of the problem is that [officials] don't take these complaints seriously," Stolz said. "But when you go out and you meet people…you realize that this is for real. And until that attitude changes in Harrisburg, we're going to continue seeing these complaints swept under the table."

Transparency: What Does DEP Disclose?

In their 2015 annual report, DEP described a plan to create a "Water Supply Complaint Tracking System."

In late 2016, DEP added an interactive report of resolved drinking water complaints to their website. DEP did not respond to questions about exactly when this report was added, though it coincided with Public Herald's final Right-to-Know request for all citizen complaints at the end of our investigation.

While this is a step toward transparency, it is only a list – no records are available to view or download.

Without access to the full complaint record, the public cannot see how DEP inspectors investigate. It's also impossible to see the details of each complainant's call, their water test results, or the determination letters issued.

The records provide invaluable insight into a caller's experience and an inspector's conduct during the investigation.

You can also see people's descriptions of their water problems, like foaming or bubbling, bad odors, and strange colors. In other cases, residents experience stomach aches, rashes, hair loss, dead animals, and even hospitalizations.

While DEP's annual report "highlights ongoing data trends" for violations, compliance, stray gas migrations, and other issues, the agency fails to include any trend analysis of oil and gas complaints.

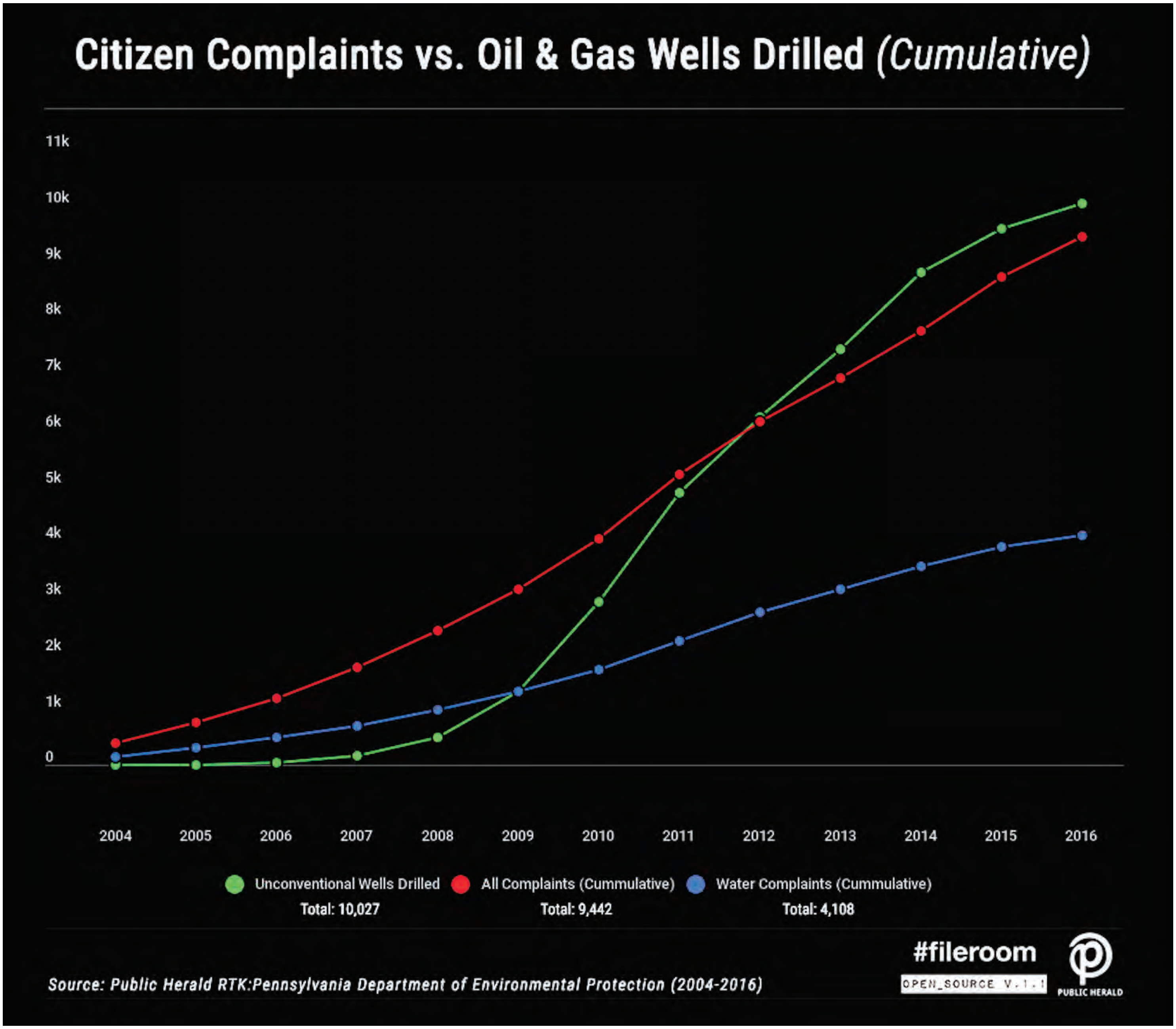
Why is this important?

After twelve years of oil and gas development, the secrecy surrounding complaints has prevented scientists, policymakers, and medical professionals from doing their jobs and has kept the impacts of fracking underground.

The Business of Complaints

"This level of complaints is not good business practice," remarked Dr. Stolz. "We're talking about at least 100,000 wells when all is said and done. At that level, all DEP will be doing is fielding calls for complaints. That's a real concern, and it needs to be addressed."

Over the past four years, DEP has received an average of three oil and gas complaints per business day, with just over 10,000 unconventional wells drilled. At this rate, with 100,000



This graph shows the cumulative number of unconventional wells drilled in PA from 2004-2016, alongside the cumulative number of DEP complaints as a whole and those categorized as water. © Public Herald

wells, DEP could be responding to an average 30 complaints related to fracking every day.

The projected rise in complaints would likely place a huge financial burden on DEP's shoulders, a burden carried under the weight of a decreasing budget and a legal mandate to permit new wells.

Since 2004, the agency has permitted 21,980 unconventional wells – to date, only half have been drilled.

It would be reasonable to think that the Department would conduct its own complaint analysis and report those findings to the state legislature, which has the power to either limit the expansion of fracking, increase the breadth of DEP's resources, or both.

But that's not what DEP is doing.

Public Trust

DEP has concluded that out of thousands of drinking water complaints that residents attribute to oil and gas activities, only 6% of these are related.

This means that thousands of people in shale gas counties, living near fracking operations, are experiencing water problems that DEP claims have nothing to do with oil and gas.

So why, then, are so many people noticing changes to their water? And what is really causing those changes? What evidence does DEP have that proves oil and gas is not responsible?

Public Herald dove into the complaint records to find this out.

In 2015, we reviewed 200 cases and discovered ways that DEP ignores, excuses, and dismisses evidence that indicates impact from oil and gas activities.

After our initial analysis, we tried to meet with Governor Wolf and former DEP Secretary John Quigley to discuss the Department's actions, but our requests were declined.

As our complaint database grew, we began an in depth analysis in search of further evidence.

For this report, Public Herald has reviewed over 1,000 drinking water complaint cases in Pennsylvania. Our analysis reveals shocking evidence of misconduct within DEP that includes and exceeds mere negligence.
READ PART 2 »

This story was made possible by generous donations from people like you, and is partly funded by grants from The 11th Hour Project and The Heinz Endowments. The work conducted by Dr. John Stolz has also received funding from The Heinz Endowments.

"The Heinz Endowments is devoted to the mission of helping our region prosper as a vibrant center of creativity, learning, and social, economic and environmental sustainability. Core to our work is the vision of a just community where all are included and where everyone who calls southwestern Pennsylvania home has a real and meaningful opportunity to thrive."

This story is part of the INVISIBLE HAND series. For more on complaint investigations, watch Public Herald's feature documentary TRIPLE DIVIDE, where we first started to investigate complaint cases.

If you have information to share about your story or others please take a moment to fill out our public survey. Information collected in the survey remains confidential until approved by the source for publishing.

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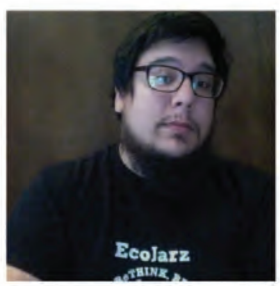

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pennsylvania
DEPARTMENT OF ENVIRONMENTAL PROTECTION

Water Supply Determination Letters

The following list identifies cases where DEP determined that a private water supply was impacted by oil and gas activities. The oil and gas activities referenced in the list below include operations associated with both conventional and unconventional drilling activities that either resulted in a water diminution event or an increase in constituents above background conditions. This list is intended to identify historic water supply impacts and does not necessarily represent ongoing impacts. Many of the water supply complaints listed below have either returned to background conditions, have been mitigated through the installation of water treatment controls or have been addressed through the replacement of the original water supply. This list is dynamic in nature and will be updated to reflect new water supply impacts as they are reported to DEP and a determination is made; however, the list will retain cases of water supply impacts even after the impact has been resolved.

A redacted copy of the water supply determination letter/order can be viewed by clicking on the “Complaint #” or “ORDER” cell in the table. Each row on the list represents a single water supply determination. A single water supply determination may be represented by multiple “Complaint #s” (i.e., when more than one Complaint # is included in the same row) and, conversely, separate water supplies may be identified using the same “Complaint #” (i.e., when multiple rows list the same Complaint #). The list also identifies the municipality and county where each water supply is located along with the date of the water supply determination letter or the date the order was issued.

	DOGO	Complaint #	County	Twp/Boro	Date Letter Sent
1	East	258482	Susquehanna	Dimock	Jan. 2009
2	East	ORDER	Susquehanna	Dimock	12/15/2010
3	East	ORDER	Susquehanna	Dimock	12/15/2010
4	East	ORDER	Susquehanna	Dimock	12/15/2010
5	East	ORDER	Susquehanna	Dimock	12/15/2010
6	East	ORDER	Susquehanna	Dimock	12/15/2010
7	East	ORDER	Susquehanna	Dimock	12/15/2010
8	East	ORDER	Susquehanna	Dimock	12/15/2010
9	East	ORDER	Susquehanna	Dimock	12/15/2010
10	East	ORDER	Susquehanna	Dimock	12/15/2010
11	East	ORDER	Susquehanna	Dimock	12/15/2010
12	East	ORDER	Susquehanna	Dimock	12/15/2010
13	East	ORDER	Susquehanna	Dimock	12/15/2010
14	East	ORDER	Susquehanna	Dimock	12/15/2010
15	East	ORDER	Susquehanna	Dimock	12/15/2010
16	East	ORDER	Susquehanna	Dimock	12/15/2010
17	East	ORDER	Susquehanna	Dimock	12/15/2010
18	East	ORDER	Susquehanna	Dimock	12/15/2010
19	East	ORDER	Susquehanna	Dimock	12/15/2010
20	East	258959	Susquehanna	Lenox	5/27/2009
21	East	258960	Susquehanna	Lenox	5/27/2009

22	East	259175	Tioga	Clymer	11/12/2008
23	East	260999	Tioga	Clymer	4/28/2009
24	East	260999	Tioga	Clymer	4/28/2009
25	East	260999	Tioga	Clymer	4/28/2009
26	East	263337	Susquehanna	Springville	9/9/2009
27	East	263337	Susquehanna	Springville	9/9/2009
28	East	263337	Susquehanna	Springville	9/9/2009
29	East	265150	Lycoming	McNett	12/4/2009
30	East	265150	Lycoming	McNett	12/4/2009
31	East	268097	Susquehanna	Rush	4/23/2010
32	East	269945	Bradford	Terry	2/7/2011
33	East	272059	Bradford	West Burlington	9/16/2010
34	East	272604	Bradford	Granville	9/2/2010
35	East	273310	Bradford	Terry	10/1/2010
36	East	273310	Bradford	Terry	10/1/2010
37	East	273310	Bradford	Terry	10/1/2010
38	East	273350	Bradford	Terry	11/15/2010
39	East	273403	Bradford	Terry	1/19/2017
40	East	273463	Wyoming	Washington	4/8/2011
41	East	273868	Bradford	Orwell	8/22/2011
42	East	274088 274465	Bradford	Tuscarora	3/25/2011
43	East	274348	Bradford	Tuscarora	3/7/2011
44	East	274484	Bradford	Wilmot	11/10/2010
45	East	274484	Bradford	Wilmot	11/10/2010
46	East	274484	Bradford	Wilmot	11/17/2010
47	East	274484	Bradford	Wilmot	11/10/2010
48	East	274484	Bradford	Wilmot	11/10/2010
49	East	274484	Bradford	Wilmot	11/10/2010
50	East	274484	Bradford	Wilmot	11/10/2010
51	East	274977	Bradford	Alba Boro	12/6/2010
52	East	275203	Bradford	Alba Boro	1/3/2011
53	East	275203	Bradford	Alba Boro	1/3/2001
54	East	275524 285034	Potter	Bingham	4/20/2011
55	East	275545	Potter	Bingham	4/20/2011
56	East	275833	Bradford	Monroe	12/3/2010
57	East	275834	Bradford	Monroe	12/3/2010
58	East	275834	Bradford	Monroe	12/3/2010
59	East	275992	Bradford	Alba Boro	12/6/2010
60	East	276069	Bradford	Terry	7/17/2017
61	East	276819	Bradford	Alba Boro	1/31/2011
62	East	277315	Bradford	West Burlington	6/18/2012
63	East	277726	Bradford	Troy	8/17/2011
64	East	277775	Bradford	Wyalusing	10/24/2011
65	East	277902	Bradford	West Burlington	6/18/2012
66	East	277927	Bradford	Wyalusing	10/24/2011
67	East	278614	Tioga	Charleston	5/4/2011
68	East	279070	Bradford	Wilmot	5/16/2011

69	East	279442	Potter	Allegheny	7/14/2011
70	East	279657	Wyoming	Meshoppen	7/13/2011
71	East	279838	Lycoming	Franklin	8/2/2011
72	East	280019	Lycoming	Franklin	8/2/2011
73	East	280020	Lycoming	Moreland	3/8/2012
74	East	280200	Bradford	Smithfield	8/1/2011
75	East	280207	Bradford	Stevens	2/20/2014
76	East	280209	Bradford	Stevens	2/20/2014
77	East	280219	Lycoming	Moreland	11/4/2011
78	East	280698	Bradford	Orwell	11/7/2011
79	East	281057	Tioga	Putnam	9/13/2017
80	East	282014	Tioga	Covington	11/1/2011
81	East	282304	Lycoming	Moreland	11/4/2011
82	East	282431	Susquehanna	Lenox	9/21/2011
83	East	284149	Clinton	Grugan	1/17/2012
84	East	284589	Susquehanna	Rush	11/7/2011
85	East	285804	Bradford	Asylum	1/6/2012
86	East	286295	Lycoming	Moreland	9/5/2012
87	East	286302	Wyoming	Nicholson	3/2/2012
88	East	286302	Wyoming	Nicholson	3/2/2012
89	East	286490	Lycoming	Moreland	9/5/2012
90	East	286491	Lycoming	Moreland	9/5/2012
91	East	286551	Bradford	Wysox	8/28/2013
92	East	286642	Bradford	West Burlington	6/18/2012
93	East	286643	Bradford	West Burlington	6/18/2012
94	East	286658	Lycoming	Moreland	4/22/2013
95	East	287005	Tioga	Delmar	5/16/2012
96	East	287198	Sullivan	Elkland	9/9/2013
97	East	288376	Tioga	Shippen	11/26/2013
98	East	289614	Clearfield	Gulich	8/24/2012
99	East	289642	Bradford	Leroy	8/13/2012
100	East	290009	Bradford	Leroy	8/13/2012
101	East	290279	Bradford	Leroy	8/13/2012
102	East	290453	Susquehanna	Lenox	9/11/2012
103	East	291156	Bradford	Leroy	8/13/2012
104	East	291551	Sullivan	Forks	9/11/2013
105	East	291551	Sullivan	Forks	9/9/2013
106	East	291602	Tioga	Union	1/14/2013
107	East	291603	Tioga	Union	1/14/2013
108	East	291931	Susquehanna	Bridgewater	5/22/2015
109	East	292425	Susquehanna	Jessup	1/14/2013
110	East	292459	Sullivan	Forks	9/9/2013
111	East	292761	Bradford	Armenia	4/12/2013
112	East	292819	Bradford	Burlington	2/21/2013
113	East	293040	Tioga	Putnam	9/13/2017
114	East	293067	Lycoming	Moreland	4/22/2013
115	East	293075	Bradford	Springfield	8/4/2014

116	East	293597	Bradford	Springfield	8/4/2014
117	East	293929	Bradford	Warren	5/6/2014
118	East	294115	Bradford	Wilmot	5/22/2015
119	East	294619	Susquehanna	Dimock	10/22/2013
120	East	294741	Sullivan	Forks	9/9/2013
121	East	295774	Wyoming	Washington	8/28/2013
122	East	296362	Bradford	Franklin	3/3/2015
123	East	297823	Susquehanna	Lenox	10/11/2011
124	East	297824	Susquehanna	Lenox	11/7/2011
125	East	297825	Susquehanna	Lenox	3/2/2012
126	East	289029	Susquehanna	Dimock	9/21/2011
127	East	298064	Bradford	Springfield	8/4/2014
128	East	303704	Susquehanna	Springville	5/14/2014
129	East	300692	Bradford	Wysox	11/13/2014
130	East	301074	Susquehanna	Dimock	10/28/2014
131	East	301998	Susquehanna	Springville	8/4/2015
132	East	306750	Susquehanna	Dimock	12/5/2014
133	East	308376	Susquehanna	Bridgewater	12/29/2014
134	East	308529	Lycoming	Eldred	12/12/2014
135	East	308755	Susquehanna	Hartford	11/21/2014
136	East	308786	Bradford	Herrick	2/11/2015
137	East	308946	Sullivan	Cherry	2/11/2016
138	East	309245	Wyoming	Windham	1/16/2015
139	East	309261	Lycoming	Eldred	2/2/2015
140	East	309747	Wyoming	Windham	5/19/2016
141	East	310458	Susquehanna	Hartford	5/19/2015
142	East	310486	Wyoming	Washington	6/4/2015
143	East	311069	Lycoming	Eldred	6/4/2015
144	East	312409	Suilivan	Fox	7/10/2015
145	East	315196	Potter	Sweden	10/27/2015
146	East	315269	Potter	Eulalia	12/14/2015
147	East	315271	Potter	Eulalia	12/14/2015
148	East	315272	Potter	Sweden	10/27/2015
149	East	315337	Potter	Eulalia	12/14/2015
150	East	315387	Potter	Sweden	12/14/2015
151	East	315646	Clinton	Chapman	8/9/2016
152	East	315738	Sullivan	Fox	11/13/2015
153	East	324291	Bradford	Wilmot	6/22/2017
154	East	326085	Tioga	Putnam	9/13/2017
155	East	327047	Tioga	Bloss	9/22/2017
156	East	327326	Susquehanna	Auburn	9/29/2017
157	Northwest	250746	Venango	Oakland	12/24/2007
158	Northwest	251599	Crawford	Woodcock	1/30/2008
159	Northwest	252267	Erie	Millcreek	4/11/2008
160	Northwest	252267	Erie	Millcreek	4/11/2008
161	Northwest	252818	McKean	Foster	4/4/2008
162	Northwest	253478	Forest	Hickory	4/29/2008

163	Northwest	254802	Crawford	Hayfield	5/22/2008
164	Northwest	254900	Forest	Howe	7/24/2008
165	Northwest	256043	McKean	Bradford	7/29/2008
166	Northwest	256642	Erie	Waterford	10/8/2013
167	Northwest	257185	McKean	Hamilton	9/12/2008
168	Northwest	257185	McKean	Hamilton	9/12/2008
169	Northwest	257867	Jefferson	Winslow	10/10/2008
170	Northwest	258217	Jefferson	Clover	10/28/2008
171	Northwest	258396	McKean	Hamilton	10/30/2008
172	Northwest	258396	McKean	Hamilton	10/30/2008
173	Northwest	258483	McKean	Foster	10/30/2008
174	Northwest	258484	Warren	Sheffield	11/10/2008
175	Northwest	258625	Clarion	Limestone	1/27/2009
176	Northwest	258625	Clarion	Limestone	1/27/2009
177	Northwest	259040	Elk	Jones	11/13/2008
178	Northwest	259064	Clarion	Limestone	3/26/2009
179	Northwest	259354 261083	Jefferson	Knox	3/27/2009
180	Northwest	260043	Warren	Sheffield	12/23/2008
181	Northwest	260496	McKean	Corydon	2/17/2009
182	Northwest	260565	Venango	Cranberry	8/13/2009
183	Northwest	260916	McKean	Foster	3/10/2009
184	Northwest	261105	Jefferson	Oliver	4/2/2009
185	Northwest	262473	Warren	Mead	8/3/2009
186	Northwest	262648	Jefferson	Knox	5/27/2009
187	Northwest	262648	Jefferson	Knox	5/27/2009
188	Northwest	262683	McKean	Foster	6/1/2009
189	Northwest	262771	Jefferson	Knox	7/13/2009
190	Northwest	263617	Warren	Glade	2/18/2010
191	Northwest	263963	McKean	Bradford	7/21/2009
192	Northwest	264898	McKean	Bradford	3/5/2010
193	Northwest	265297	Jefferson	Knox	9/11/2009
194	Northwest	265323	Clarion	Elk	9/10/2009
195	Northwest	266017	Jefferson	Warsaw	10/19/2009
196	Northwest	266591	Crawford	Oil Creek	6/24/2011
197	Northwest	267033	Clarion	Elk	1/15/2010
198	Northwest	267519 268448	McKean	Bradford	12/11/2009
199	Northwest	267519 268448	McKean	Bradford	12/11/2009
200	Northwest	267880	Clarion	Elk	1/20/2010
201	Northwest	267880	Clarion	Elk	1/20/2010
202	Northwest	269055	Forest	Kingsley	3/22/2010
203	Northwest	269244	Warren	Glade	9/27/2010
204	Northwest	271422	McKean	Bradford	10/19/2010
205	Northwest	271490	Warren	Sheffield	6/17/2010
206	Northwest	272189	Forest	Hickory	8/2/2010
207	Northwest	272948	McKean	Bradford	12/17/2010
208	Northwest	273024	Clarion	Madison	7/18/2014
209	Northwest	273321	Crawford	Spring	1/28/2011

210	Northwest	273460	McKean	Corydon	Oct. 2010
211	Northwest	274735	Elk	Jones	12/23/2010
212	Northwest	276220	McKean	Foster	2/9/2011
213	Northwest	276776	Forest	Hickory	3/28/2012
214	Northwest	276776	Forest	Hickory	10/20/2011
215	Northwest	276776	Forest	Hickory	3/28/2012
216	Northwest	276776	Forest	Hickory	3/28/2012
217	Northwest	276776	Forest	Hickory	3/28/2012
218	Northwest	276776	Forest	Hickory	3/28/2012
219	Northwest	276776	Forest	Hickory	3/28/2012
220	Northwest	276776	Forest	Hickory	3/28/2012
221	Northwest	276776	Forest	Hickory	3/28/2012
222	Northwest	276776	Forest	Hickory	3/28/2012
223	Northwest	276776	Forest	Hickory	3/28/2012
224	Northwest	276776	Forest	Hickory	3/28/2012
225	Northwest	276776	Forest	Hickory	5/3/2011
226	Northwest	276823	Forest	Hickory	5/4/2011
227	Northwest	277438	McKean	Bradford	7/13/2011
228	Northwest	278982	Warren	Pleasant	5/4/2012
229	Northwest	281151	Elk	Jones	8/8/2011
230	Northwest	287891	Butler	Winfield	6/4/2013
231	Northwest	288690	Butler	Jefferson	11/5/2012
232	Northwest	289916	Clarion	Toby	11/29/2012
233	Northwest	290406	Lawrence	Pulaski	11/13/2013
234	Northwest	290406	Lawrence	Pulaski	11/19/2013
235	Northwest	290406	Lawrence	Pulaski	11/20/2013
236	Northwest	290406	Lawrence	Pulaski	10/7/2013
237	Northwest	291029	Butler	Winfield	9/7/2012
238	Northwest	292020	Warren	Sugar Grove	Sept. 2012
239	Northwest	293565	Warren	Pleasant	1/4/2013
240	Northwest	294446	Forest	Kingsley	7/19/2013
241	Northwest	294734	Warren	Pleasant	7/11/2013
242	Northwest	294947	McKean	Foster	8/28/2013
243	Northwest	296020	Butler	Forward	8/28/2013
244	Northwest	297302	Elk	Bennezette	12/10/2015
245	Northwest	297871	Clarion	Porter	3/24/2014
246	Northwest	298337	Warren	Glade	10/1/2013
247	Northwest	299917	Forest	Kingsley	6/9/2016
248	Northwest	300296	McKean	Lafayette	Nov. 2013
249	Northwest	305257	Butler	Connoquenessing	12/12/2014
250	Northwest	305506	Warren	Mead	7/28/2014
251	Northwest	306890	Warren	Farmington	10/28/2014
252	Northwest	307002	Venango	Cranberry	12/9/2014
253	Northwest	307679	Jefferson	Eldred	10/30/2014
254	Northwest	308544	Forest	Kingsley	8/24/2016
255	Northwest	309793	Butler	Oakland	12/10/2015
256	Northwest	309804	McKean	Otto	3/9/2016

257	Northwest	310559	Clarion	Porter	6/13/2017
258	Northwest	311304	Lawrence	Pulaski	2/2/2016
259	Northwest	314644	Lawrence	Pulaski	6/9/2016
260	Northwest	314763	Butler	Muddycreek	12/10/2015
261	Northwest	316381	Clarion	Redbank	8/3/2017
262	Northwest	321627	Butler	Comcord	3/31/2017
263	Northwest	ORDER	McKean	Bradford	2/23/2010
264	Northwest	ORDER	McKean	Bradford	2/23/2010
265	Northwest	ORDER	McKean	Bradford	2/23/2010
266	Northwest	ORDER	McKean	Bradford	2/23/2010
267	Northwest	ORDER	McKean	Bradford	2/23/2010
268	Northwest	ORDER	McKean	Bradford	2/23/2010
269	Northwest	ORDER	McKean	Bradford	2/23/2010
270	Northwest	ORDER	McKean	Bradford	2/23/2010
271	Northwest	ORDER	McKean	Bradford	2/23/2010
272	Southwest	281911	Indiana	West Wheatfield	8/30/2013
273	Southwest	288825	Greene	Morgan	3/2/2015
274	Southwest	291965	Westmoreland	Donegal	6/4/2013
275	Southwest	294666	Washington	Cross Creek	6/17/2013
276	Southwest	301088	Westmoreland	Donegal	12/16/2013
277	Southwest	302442	Westmoreland	Donegal	8/25/2014
278	Southwest	306873	Westmoreland	Donegal	12/5/2014
279	Southwest	309063	Westmoreland	Hempfield	1/6/2016
280	Southwest	310158	Westmoreland	Donegal	3/20/2015
281	Southwest	314330	Greene	Morgan	12/14/2015
282	Southwest	314341	Greene	Cumberland	10/27/2015
283	Southwest	314841	Washington	North Bethlehem	11/25/2015
284	Southwest	317342	Westmoreland	Derry	7/7/2017
285	Southwest	ORDER	Indiana	East Wheatfield	9/2/2008
286	Southwest	ORDER	Indiana	East Wheatfield	9/2/2008
287	Southwest	ORDER	Indiana	East Wheatfield	9/2/2008
288	Southwest	ORDER	Indiana	East Wheatfield	9/2/2008
289	Southwest	ORDER	Indiana	East Wheatfield	9/2/2008
290	Southwest	ORDER	Indiana	West Mahoning	2/12/2008
291	Southwest	ORDER	Washington	West Pike Run	3/27/2008
292	Southwest	ORDER	Fayette	Jefferson	1/4/2008
293	Southwest	ORDER	Indiana	Cherryhill	1/15/2008
294	Southwest	ORDER	Greene	Washington	9/11/2014

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