

# Isotech - Stable Isotope Analysis

Determining the origin of methane  
and its effect on the aquifer.



# Agenda

- Geologic history
- Methane characteristics
- The ratio of carbon isotopes in methane.
- The unique ratio of hydrocarbons in the Marcellus Formation
- Identifying the age of the methane.
- The effects methane and drilling have on the aquifer and trend over time.
- Conclusions.

# Environment of Deposition Middle Devonian (385 MA)

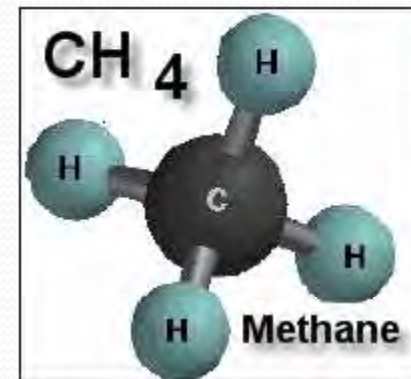




Osborn S G et al. PNAS 2011;108:8172-8176

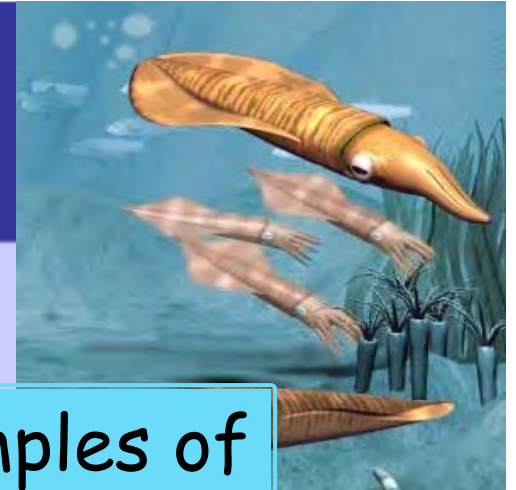
# Methane is the principal hydrocarbon detected in all stray natural gas migration incidents

- Exposure limit (gas phase): TLV-TWA: 1,000 ppm (ACGIH, 10/2009)
- Methane (CH<sub>4</sub>) is the simplest paraffin hydrocarbon gas
- Methane is generated by microbial & thermogenic processes
- Flammable, colorless, odorless.
- Specific gravity: 0.555 (NTP) air = 1
- Explosive range: 5-15% in ambient air
- Solubility in water: 26-32 mg/l (1 atm.)
- Non toxic, no ingestion hazard
- Simple asphyxiant, explosion hazard



Methane can migrate as free gas or dissolved in the groundwater

# Delta notation



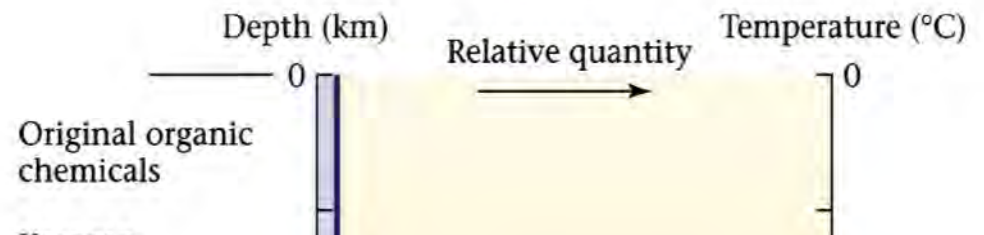
So by collecting numerous gas samples of known origin a database has been developed and fingerprinting of gas samples may performed.

$R_{reference} =$  VPDB (Vienna Pee Dee Belemnite)

$$\delta^{13}\text{C} = \delta(^{13}\text{C}) = \delta(^{13}\text{C}/^{12}\text{C}) = \frac{n_X(^{13}\text{C})/n_X(^{12}\text{C}) - n_{ref}(^{13}\text{C})/n_{ref}(^{12}\text{C})}{n_{ref}(^{13}\text{C})/n_{ref}(^{12}\text{C})}$$

# Shale Gas

- Increasing formation temperature leads to diagnostic



The normal sequence of carbon isotopic compositions is:

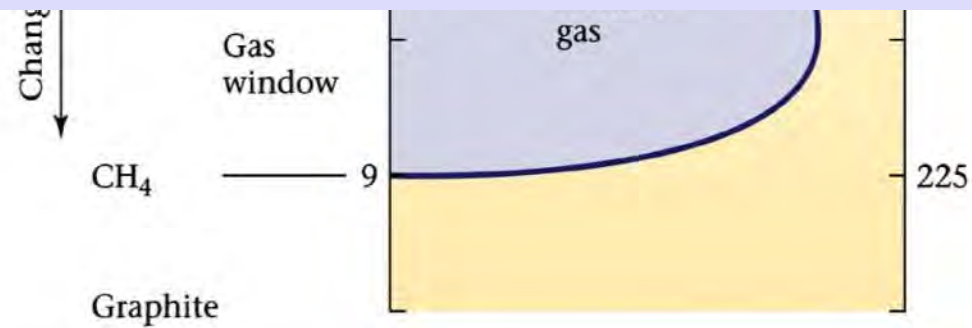
$\delta^{13}\text{C}$  methane ( $\text{C}_1$ ) <  $\delta^{13}\text{C}$  ethane ( $\text{C}_2$ ) <  $\delta^{13}\text{C}$  propane ( $\text{C}_3$ ) and <  $\delta^{13}\text{C}$  butane ( $\text{C}_4$ )

$$\delta^{13}\text{C}_1 < \delta^{13}\text{C}_2 < \delta^{13}\text{C}_3 \text{ and } < \delta^{13}\text{C}_4$$

In the Marcellus they are fully reversed -  $\delta^{13}\text{C}_1 > \delta^{13}\text{C}_2 > \delta^{13}\text{C}_3$

Also hydrogen isotopic compositions ( $\delta^2\text{H}$ ) of  $\text{C}_1$  and  $\text{C}_2$  are also reversed.

- Uniquely identifiable when paired with additional proxies (e.g. noble gases)



# Isotope Geochemistry

## Easily Distinguishes:

- Molecular: Methane/Ethane
- Isotopic: Carbon and Hydrogen isotopes ( $\delta^{13}\text{C}-\text{CH}_4$ ,  $\delta^2\text{H}-\text{CH}_4$ ,  $\delta^{13}\text{C}-\text{C}_2\text{H}_6$ )
- Noble Gases

☑ Biogenic vs. Thermogenic  
(e.g. Schoell, 1983; Coleman et al, 1991; Baldassare and Laughrey, 1998)

☑ Distinguishing different thermogenic gases  
(e.g. Schoell et al, 1983; Jenden et al, 1993; Revesz et al, 2010; Tilley et al, 2010)

? What's best for distinguishing thermally mature gases?





Lab #: 235488 Job #: 17407  
 Sample Name/Number: HW02z  
 Company: TechLaw, Inc.  
 Date Sampled: 1/25/2012  
 Container: Dissolved Gas Bottle  
 Field/Site Name: A3TA  
 Location:  
 Formation/Depth:  
 Sampling Point:  
 Date Received: 2/03/2012 Date Reported: 2/20/2012

**<sup>13</sup>C fractionation**

**<sup>2</sup>H fractionation**

**% argon**

**% nitrogen**

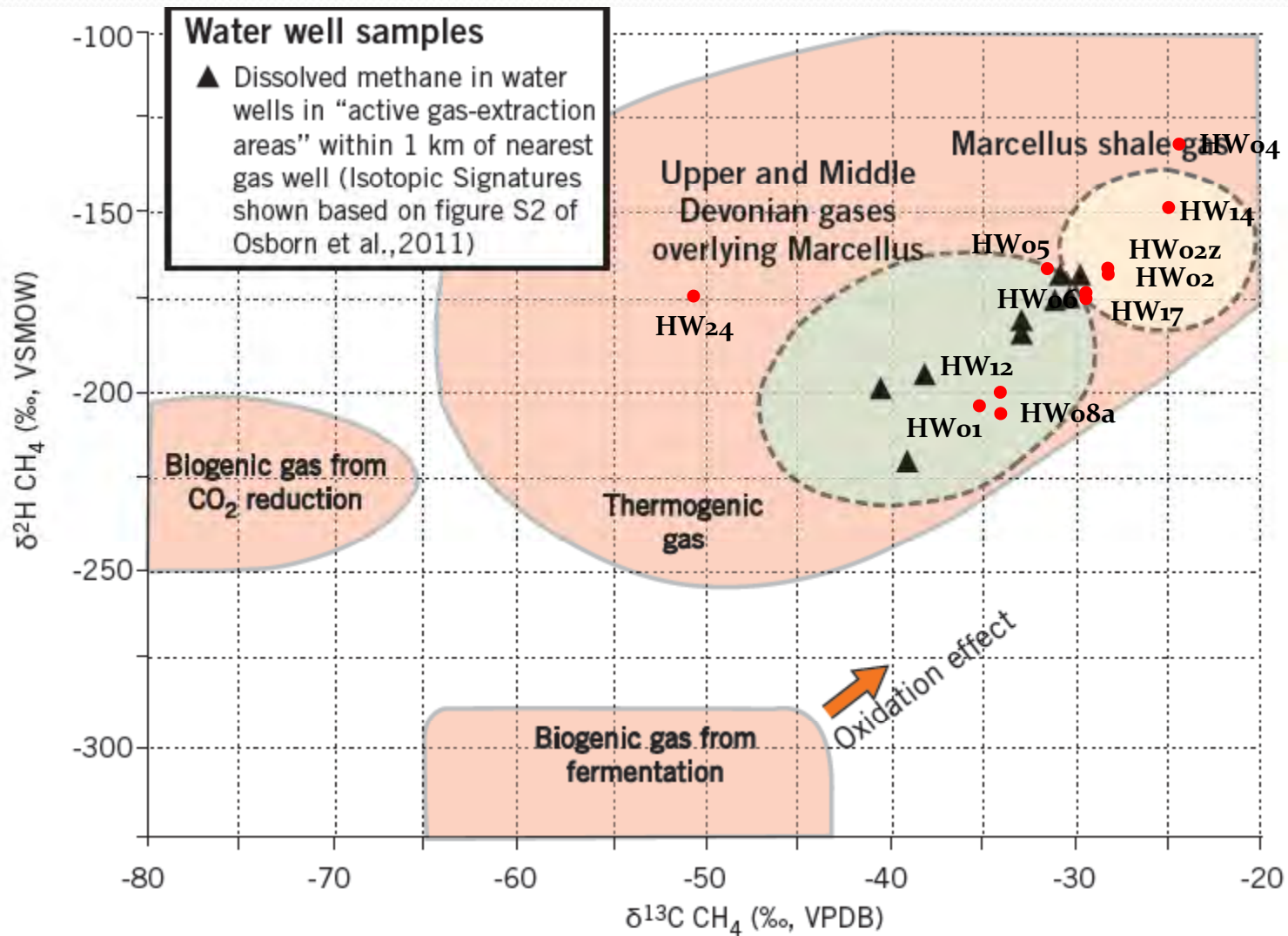
Component	Chemical mol. %	$\delta^{13}\text{C}$ ‰	$\delta\text{D}$ ‰	$\delta^{18}\text{O}$ ‰
Carbon Monoxide -----	nd			
Hydrogen Sulfide -----	na			
Helium -----	0.0112			
Hydrogen -----	nd			
Argon -----	0.628			
Oxygen -----	0.80			
Nitrogen -----	40.72			
Carbon Dioxide -----	0.094			
Methane -----	57.06	-29.30	-160.6	
Ethane -----	0.687			
Ethylene -----	nd			
Propane -----	nd			
Propylene -----	0.0001			
Iso-butane -----	nd			
N-butane -----	nd			
Iso-pentane -----	nd			
N-pentane -----	nd			
Hexanes + -----	nd			
Water -----			-64.6	-9.66

**-29**

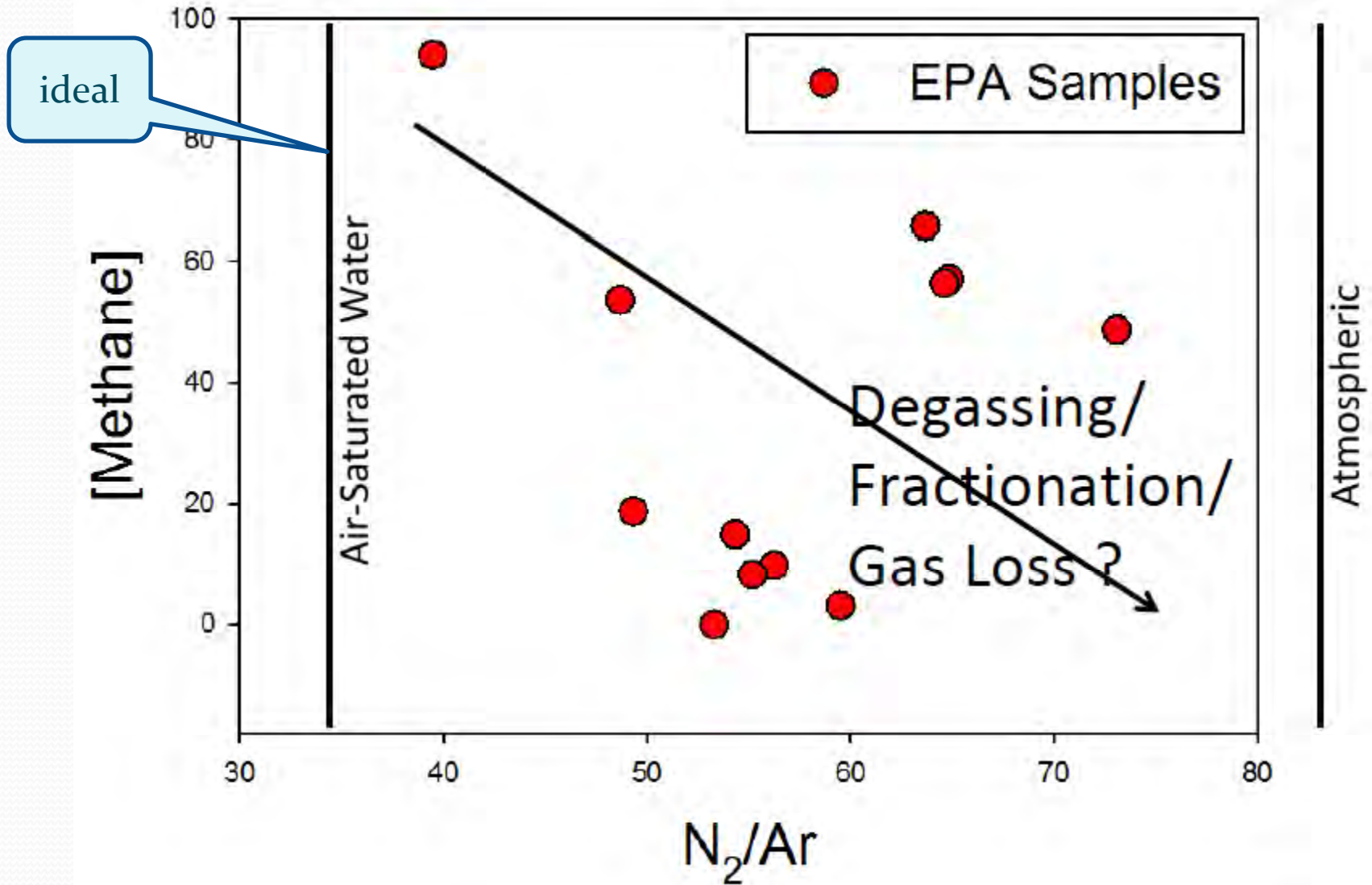
**-160**

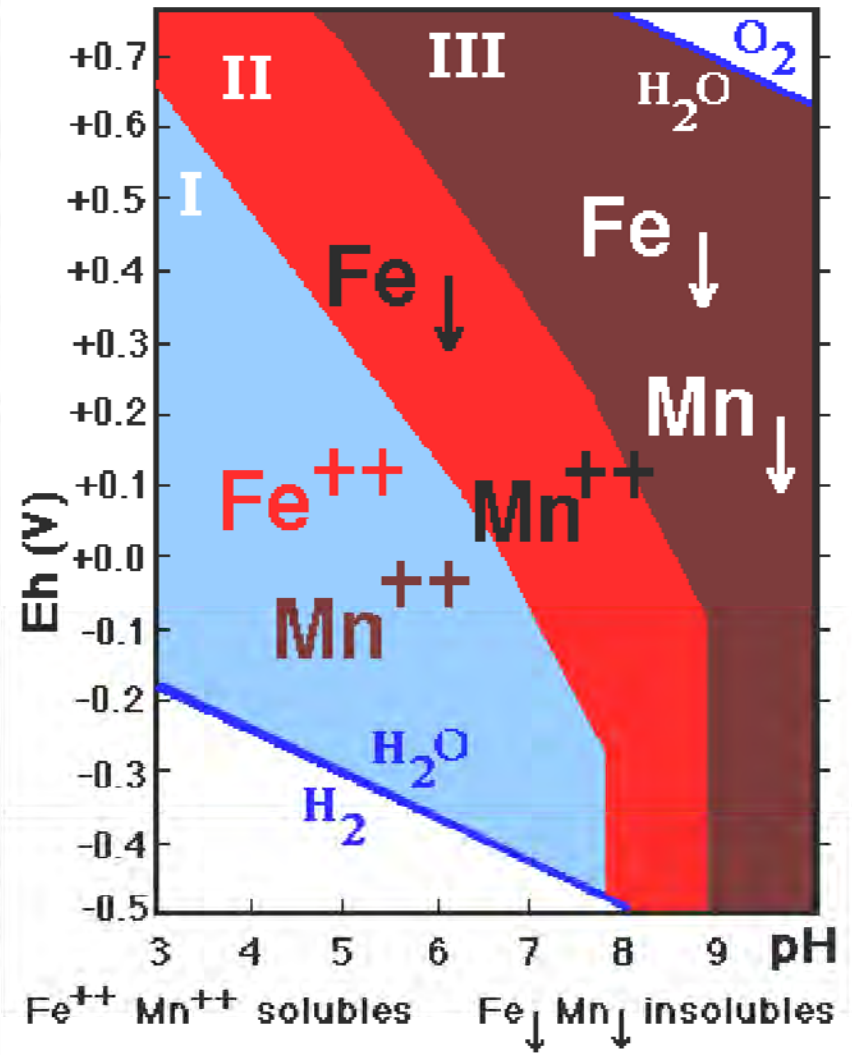
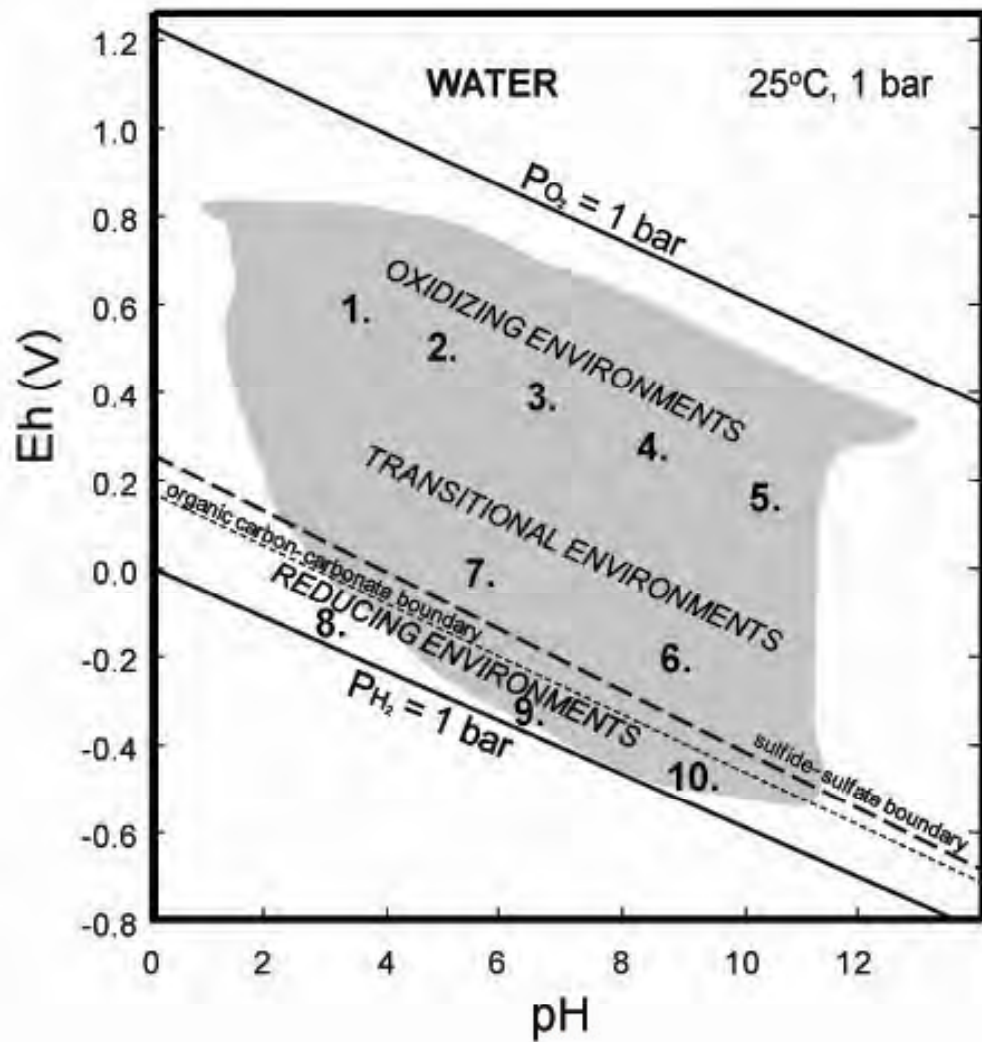
Total BTU/cu.ft. dry @ 60deg F & 14.7psia, calculated: 590

Specific gravity, calculated: 0.736



# Sample Quality - degassing?





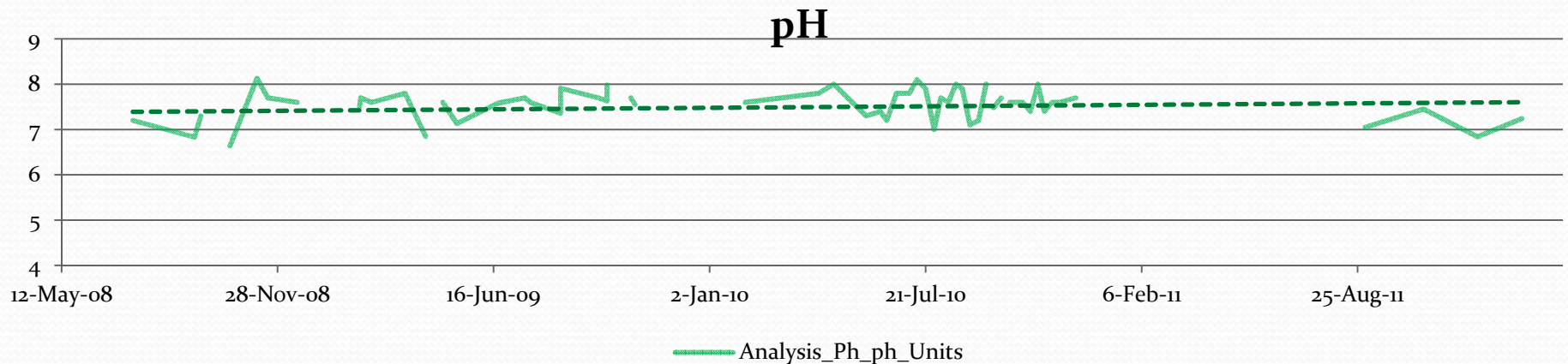
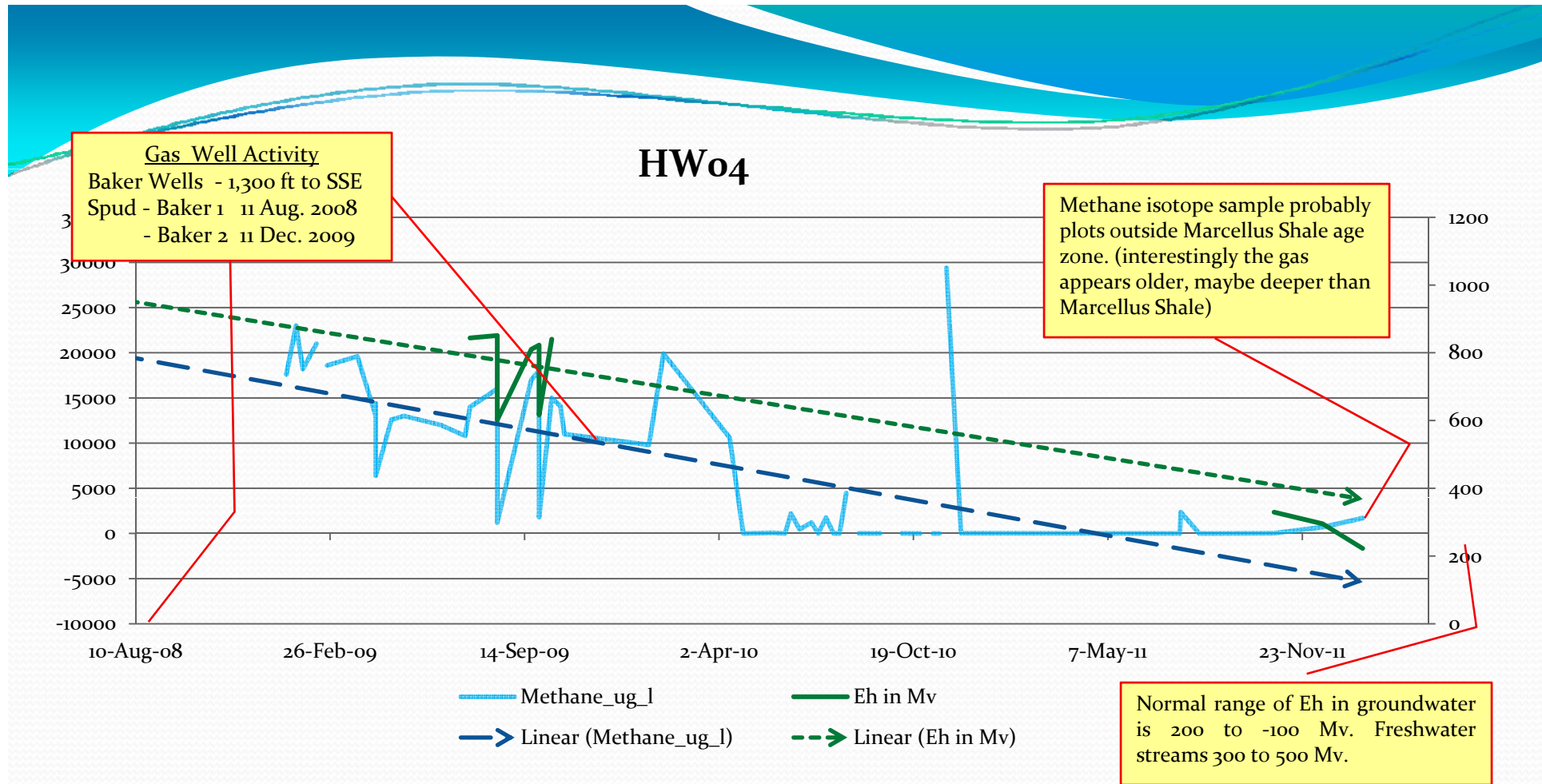


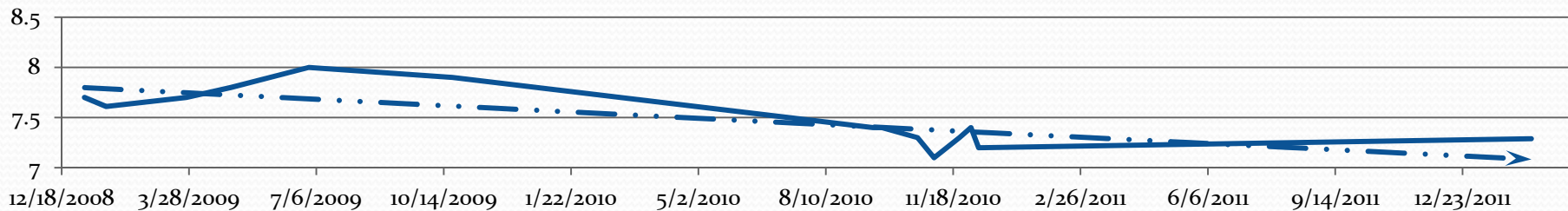
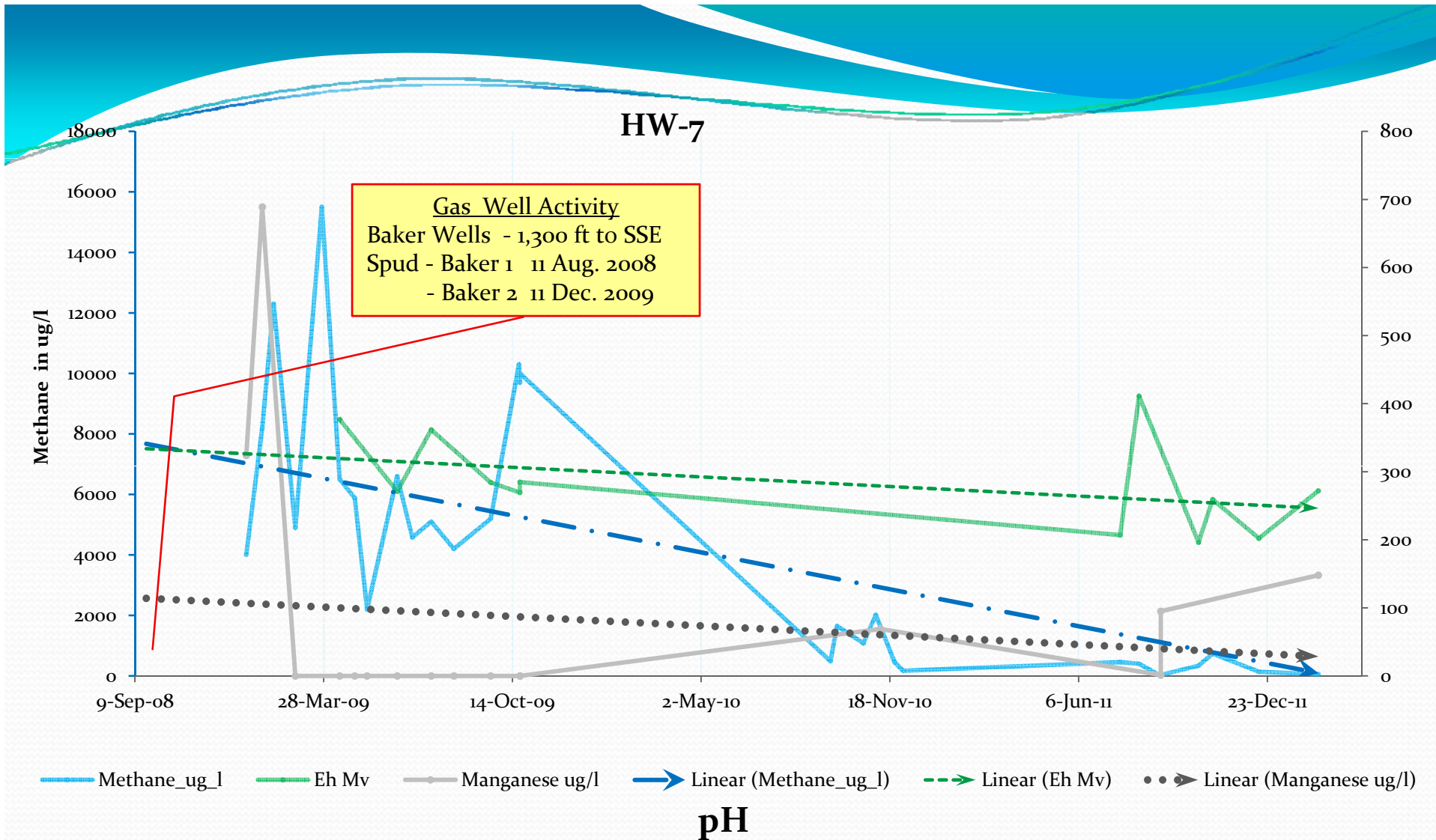
# Three Patterns of Contamination

1. **Short term** (< 1 year) disruption to the aquifer caused by drilling.
2. **Long term** (> 3-4 year) disruption or contamination of the aquifer caused by drilling/fracking, releases or other situations.
3. **Natural Background Conditions** with high levels of metals and anions.



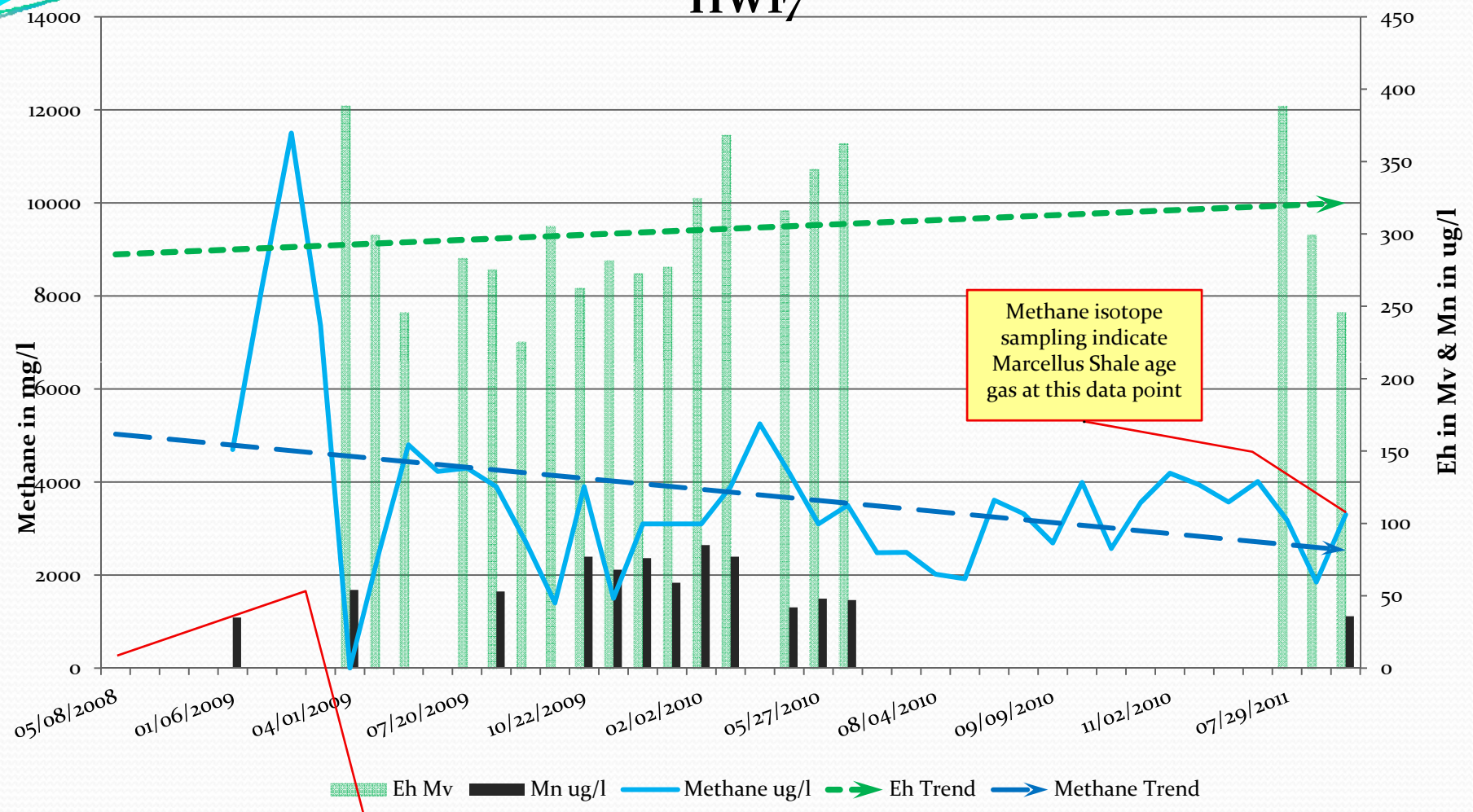
# Type 1: Short Term Disruption







# HW17

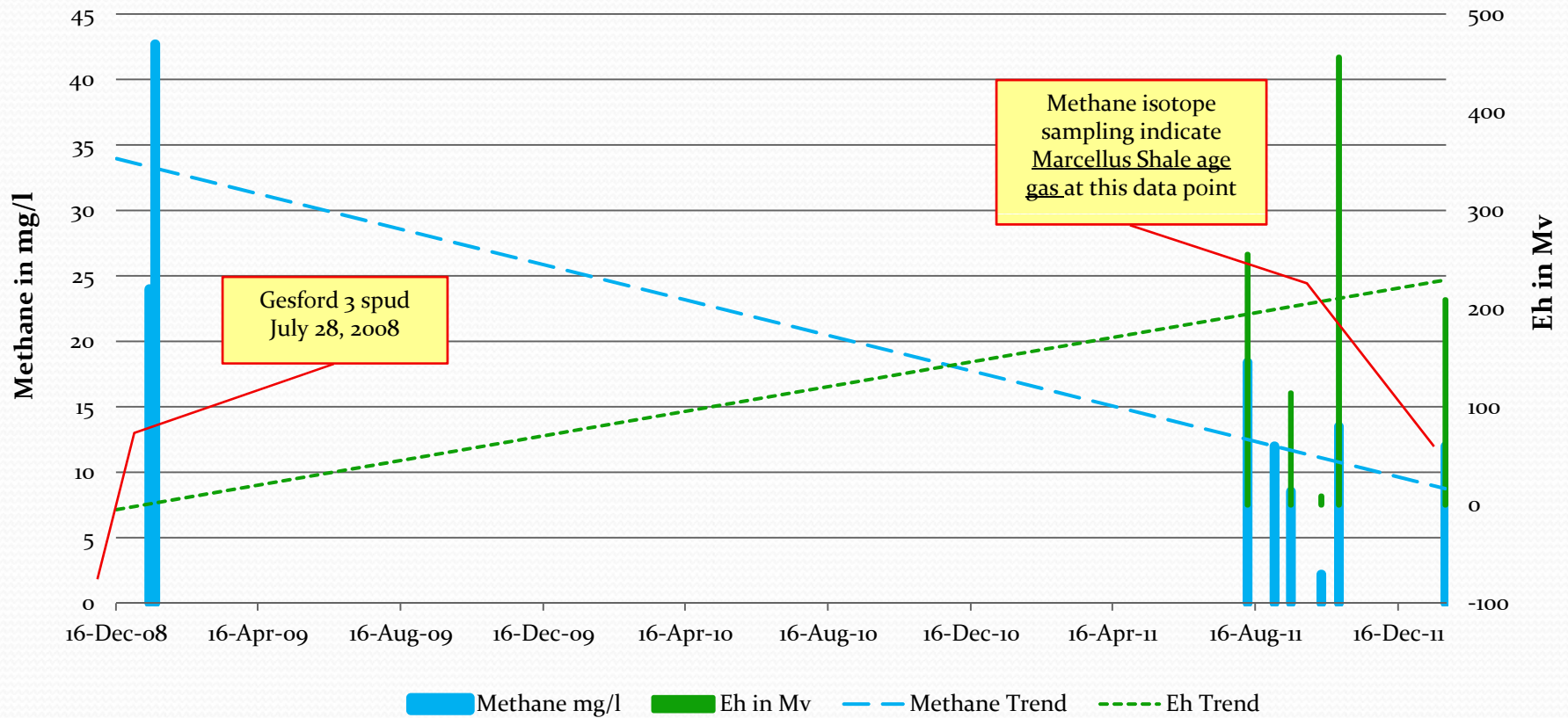


Methane isotope sampling indicate Marcellus Shale age gas at this data point

<u>Gas Well</u>	<u>Date Spud</u>	<u>Distance to HW17</u>
Lewis	5/28/2008	670 ft.
Ely 4H & 6H	3/27/2008	1,360 ft.
Costello 1	7/16/2008	1,350 ft.

Note incomplete data set

# HW<sub>1</sub> - Hubert



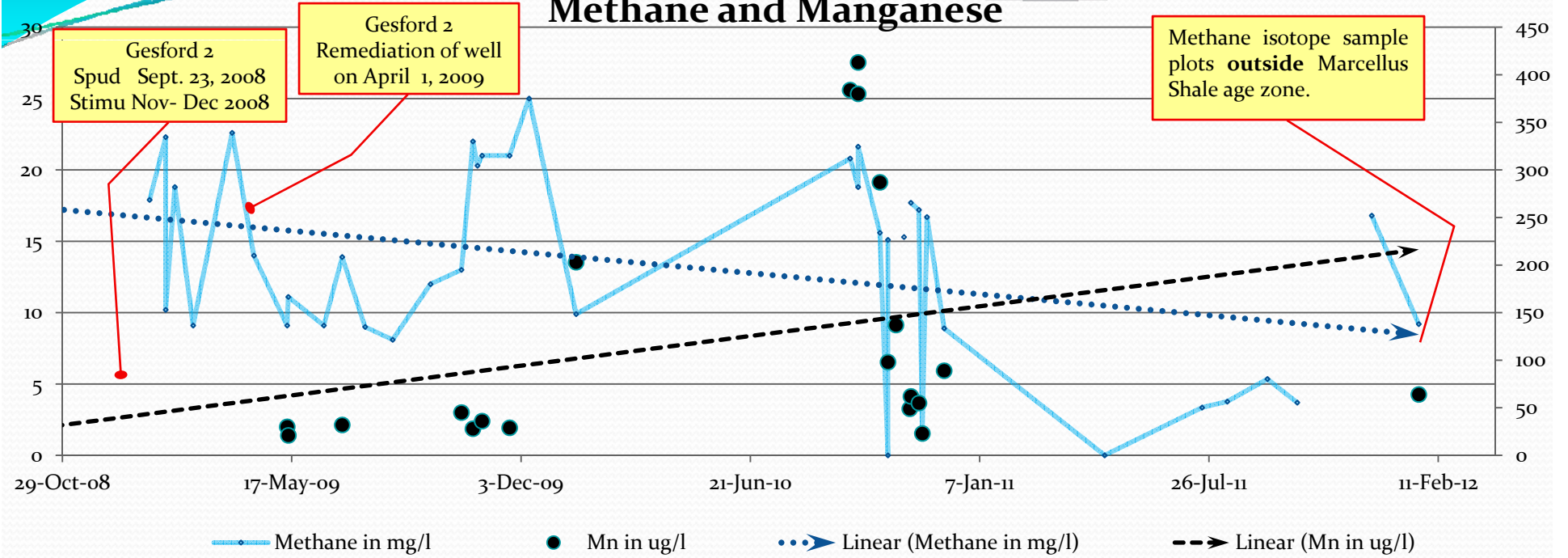
HW<sub>1</sub> lacked data for nearly all constituents, particularly for the years 2009-2010



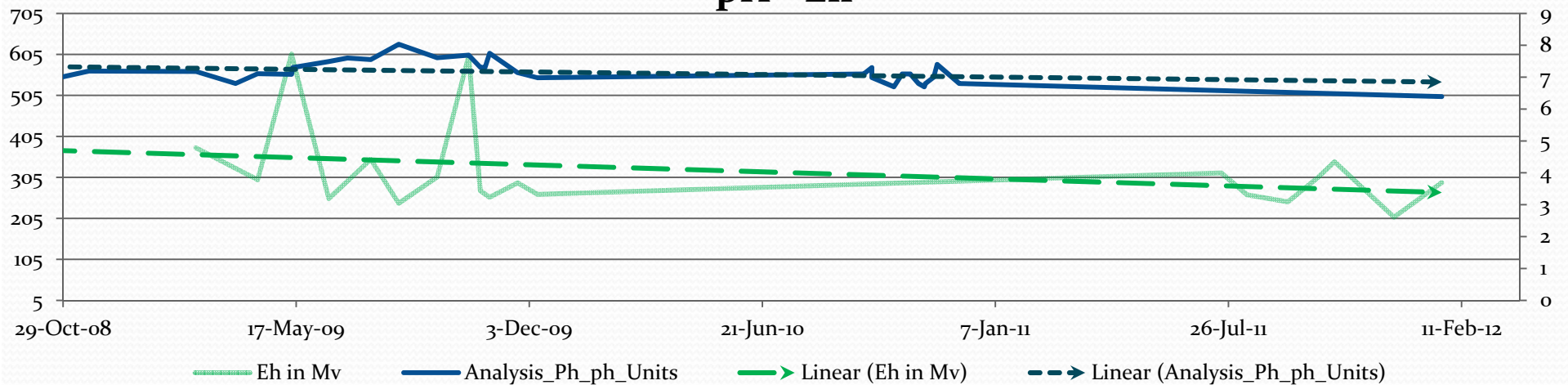
# Type 2: Long Term Disruption

# HW8

## Methane and Manganese



## pH - Eh





Carter Rd

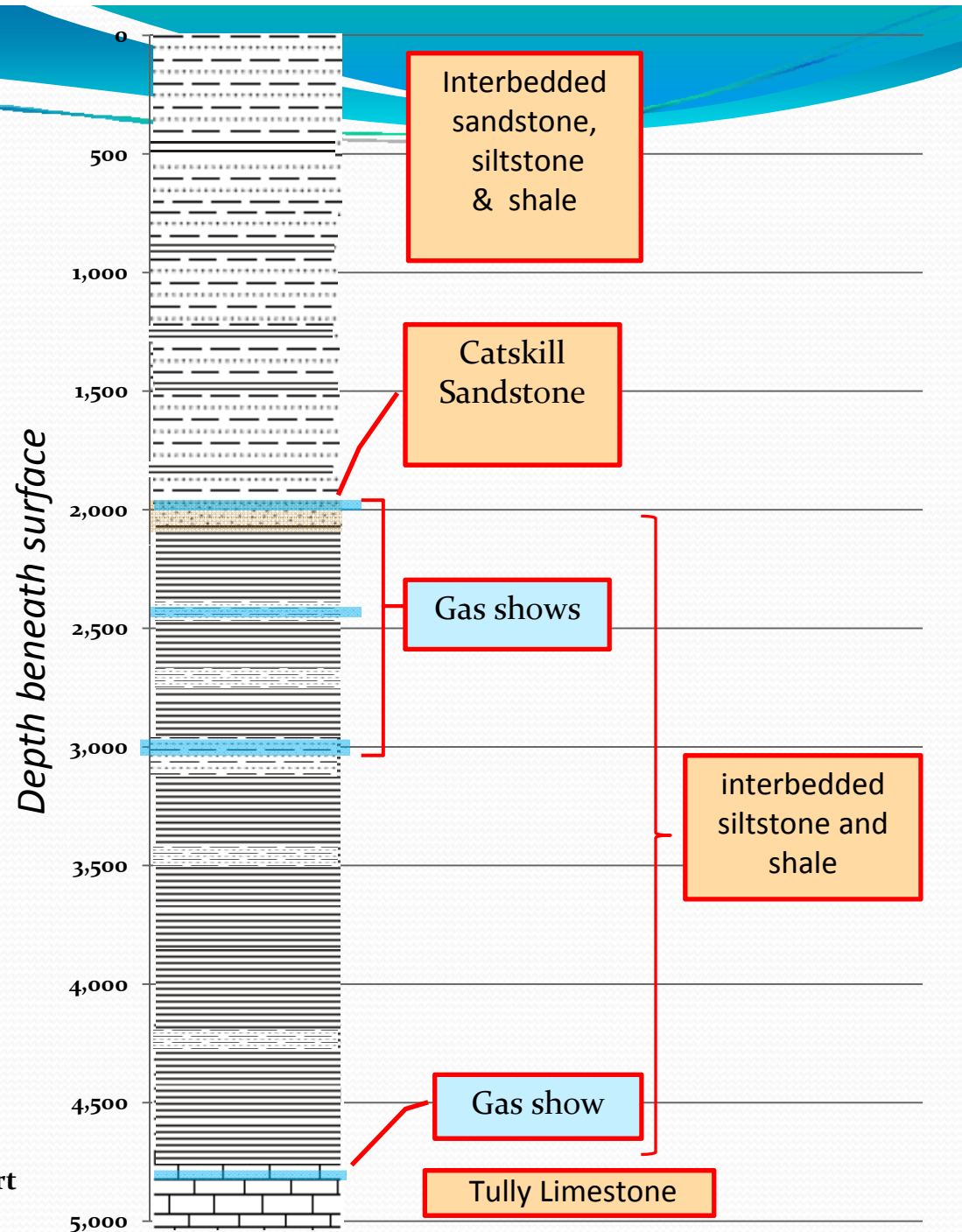
400 ft.

© 2012 Google

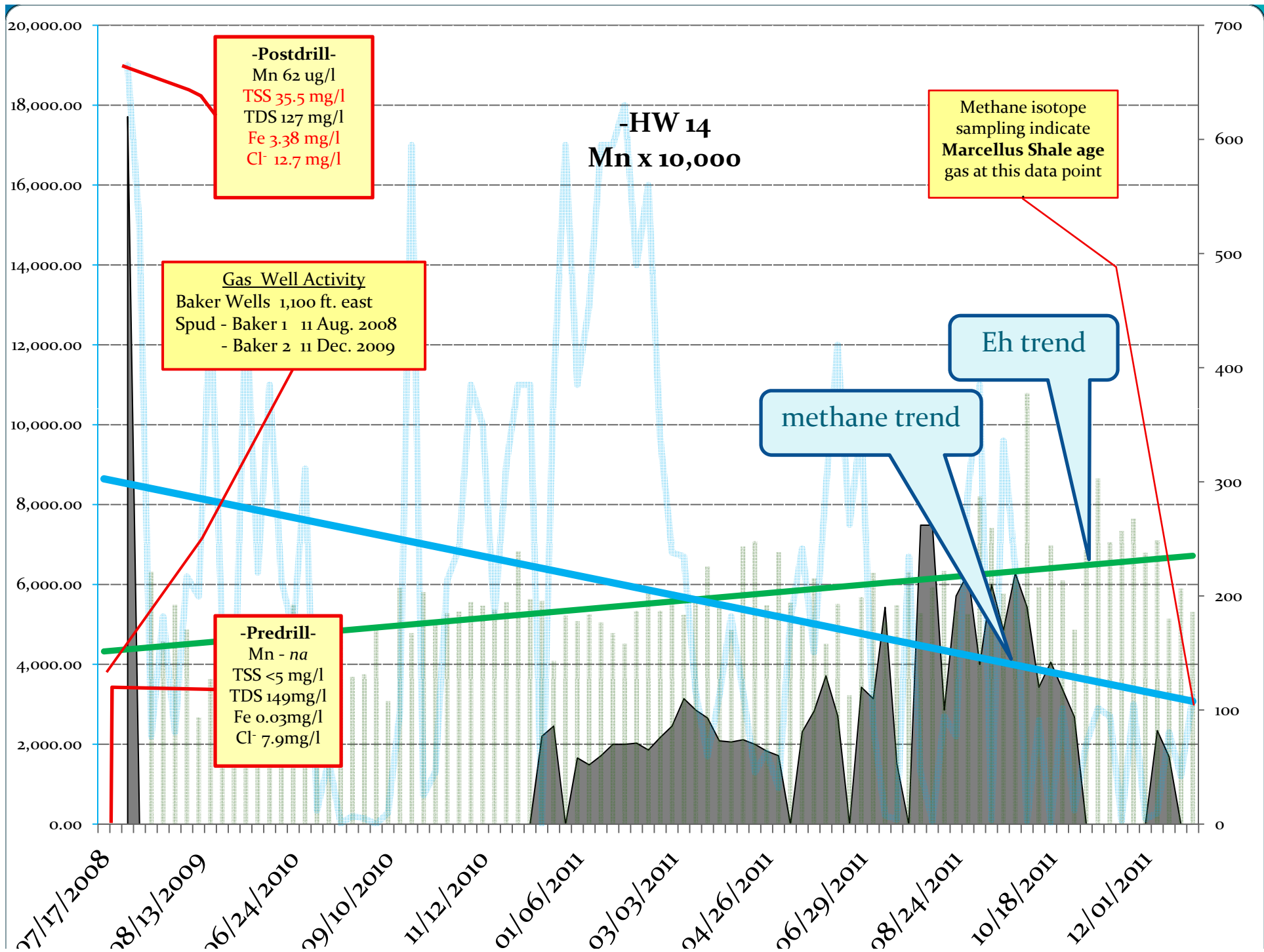
Goog

# Gas is Gas

- Thermogenic gas is present throughout the upper Devonian formations. Drilling creates pathways, either temporary or permanent, that allows gas to migrate to the shallow aquifer near surface.
- Shallower (non Marcellus) gas may also include higher amounts of H<sub>2</sub>S which can have a greater impact on groundwater.
- In some cases, these gases disrupts groundwater quality

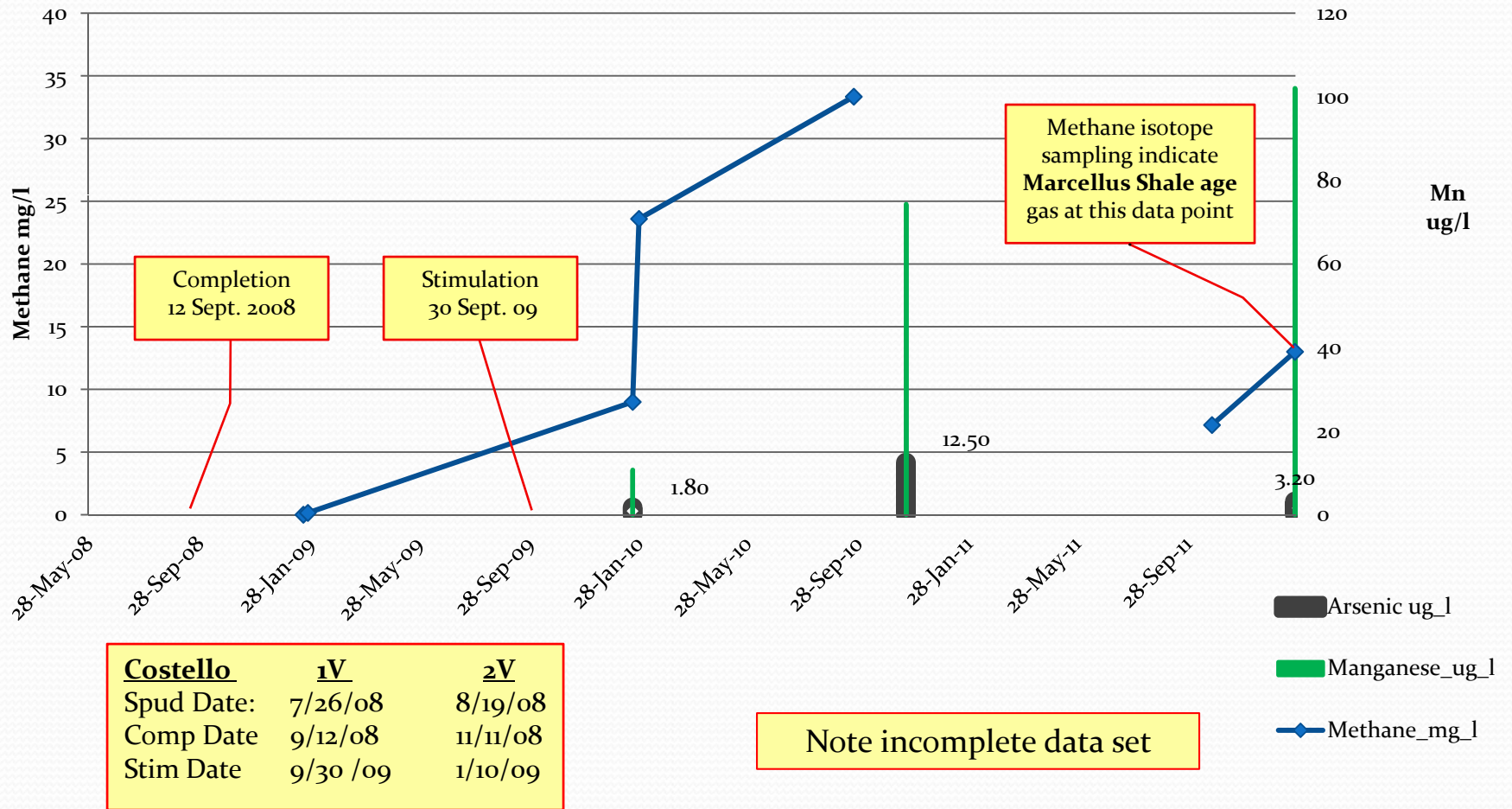


From Gesford 2 Well Record and Completion Report



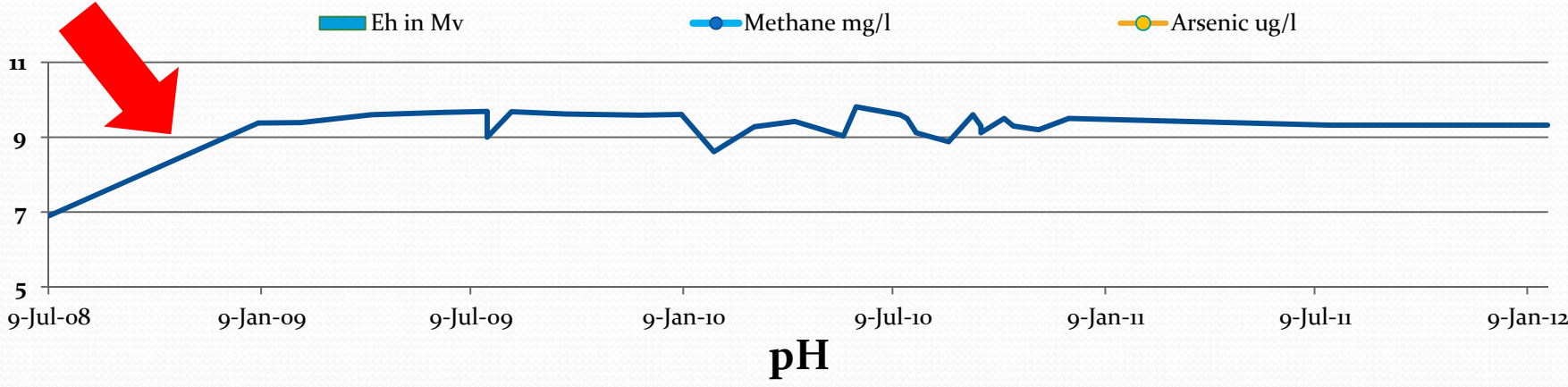
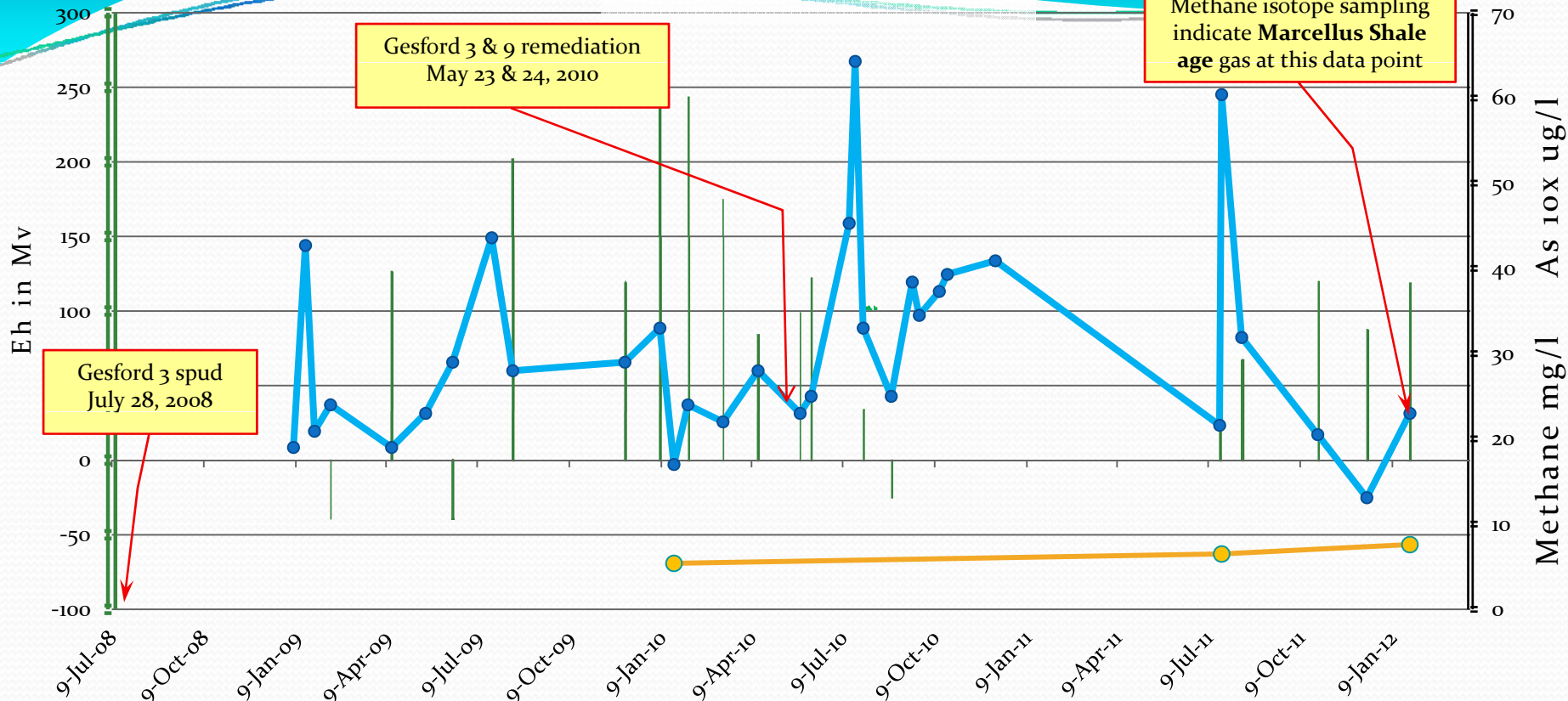


## HW-2

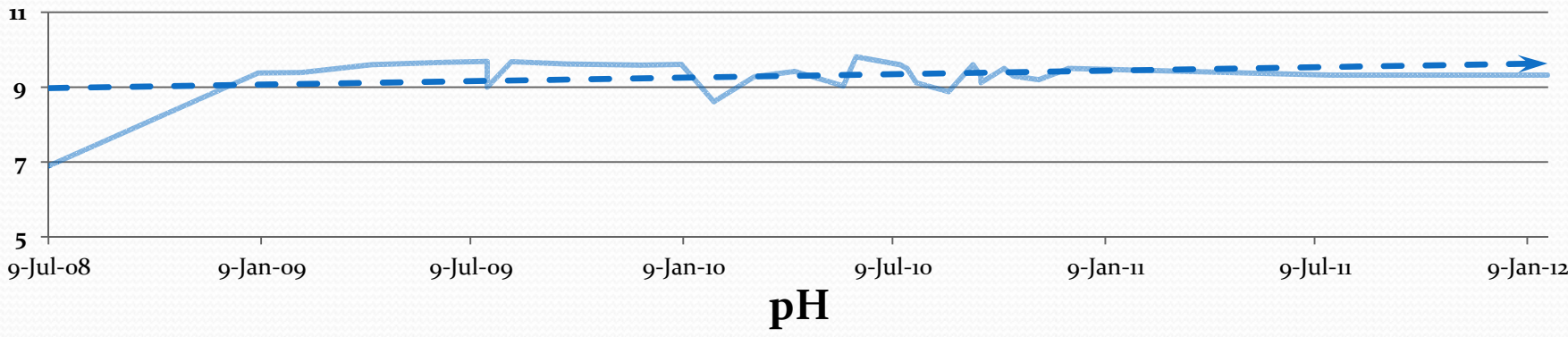
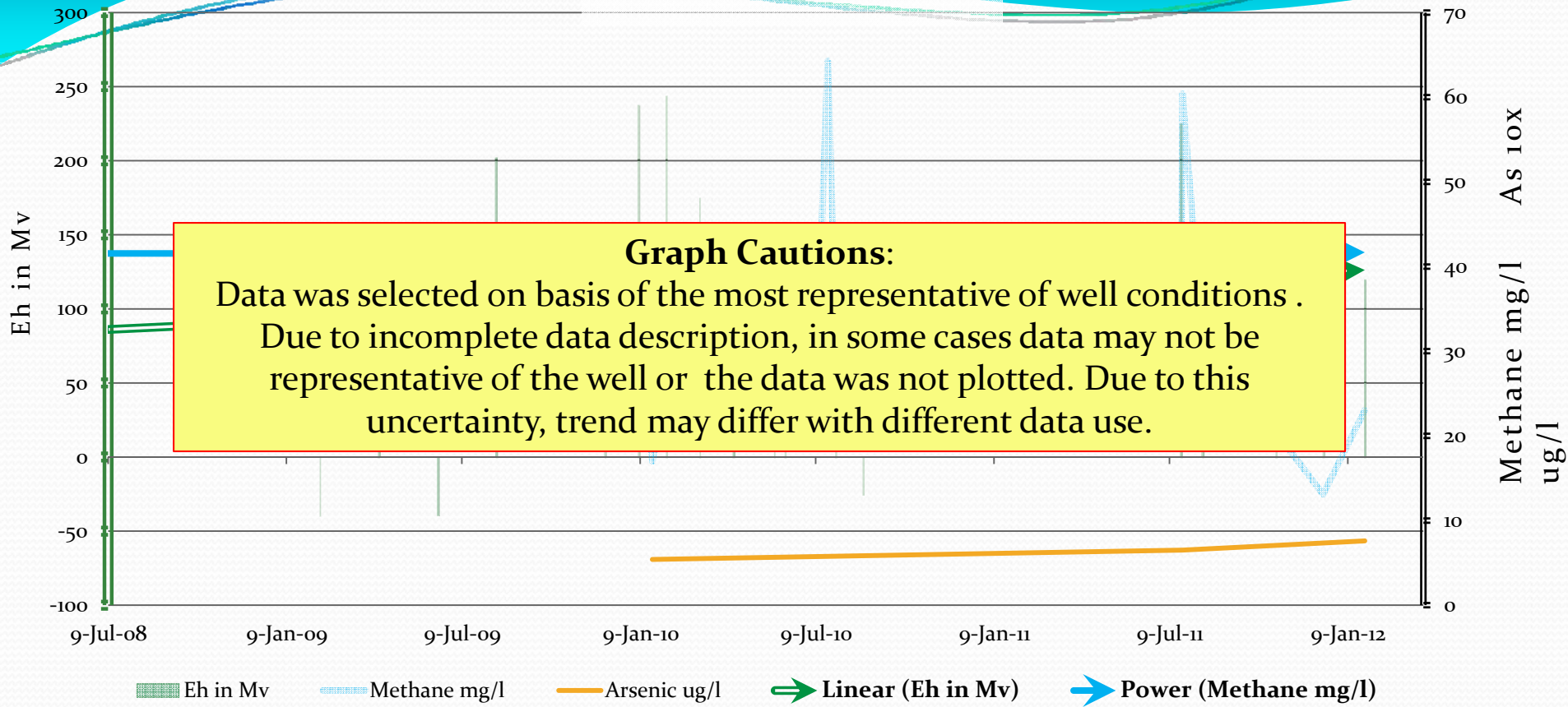




# HW6



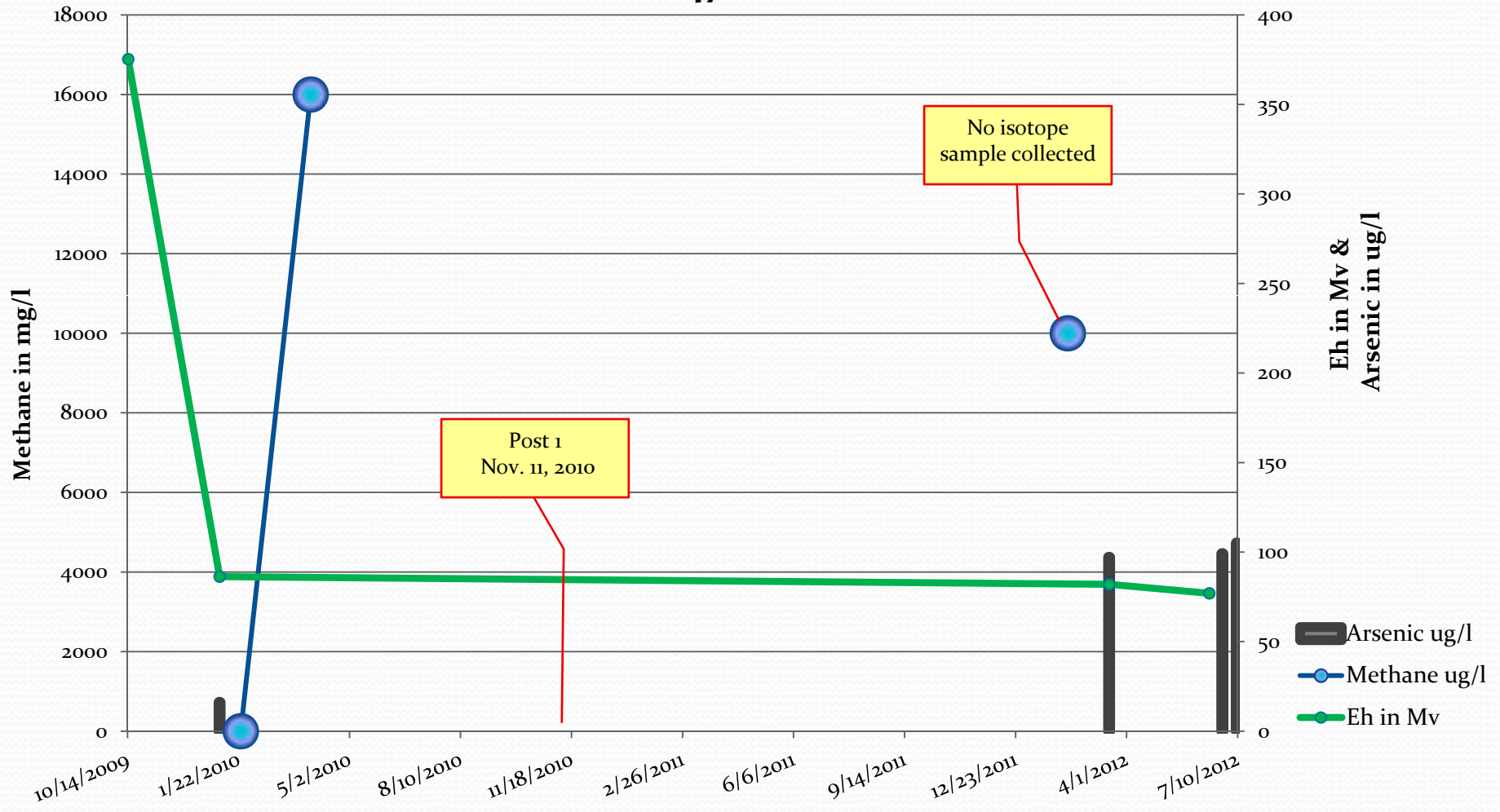
# HW6





# Type 3: Naturally Occurring Contamination

# HW47 -



Post 1  
Nov. 11, 2010

No isotope  
sample collected

When no data is plotted,  
no data was available.

- Arsenic ug/l
- Methane ug/l
- Eh in Mv



# Conclusions

- Methane is released during the drilling and perhaps during the fracking process and other gas well work.
- Methane is at significantly higher concentrations in the aquifers after gas drilling and perhaps as a result of fracking and other gas well work.
- The methane migrating into the aquifer is both from the shallower (younger age) formations and older Marcellus Shale (and perhaps even older formations).
- Methane and other gases released during drilling (including air from the drilling) apparently cause significant damage to the water quality.
- In some cases the aquifers recover (under a year) but, in others cases the damage is long term (greater than 3 years).



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**Socioeconomic Value of the Delaware River Basin  
in Delaware, New Jersey, New York, and Pennsylvania**

*The Delaware River Basin, an economic engine for over 400 years*

October 11, 2011

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## Executive Summary

What do the Guggenheim Museum, New York Yankees, Boeing, Sunoco, Campbell's Soup, DuPont, Wawa, Starbucks, Iron Hill Brewery, Philadelphia Phillies, Camelback Ski Area, Pt. Pleasant Canoe Livery, Salem Nuclear Power Plant, and United States Navy all have in common? They all depend on the waters of the Delaware River Basin to sustain their businesses.

The Delaware River Basin is an economic engine that supplies drinking water to the 1<sup>st</sup> (New York City) and 7<sup>th</sup> (Philadelphia) largest metropolitan economies in the United States and supports the largest freshwater port in the world. The Delaware Basin's water supplies, natural resources, and ecosystems in Delaware, New Jersey, New York, Pennsylvania and a small sliver of Maryland:

- Contribute \$25 billion in annual economic activity from recreation, water quality, water supply, hunting/fishing, ecotourism, forest, agriculture, open space, potential Marcellus Shale natural gas, and port benefits.
- Provide ecosystem goods and services (natural capital) of \$21 billion per year in 2010 dollars with net present value (NPV) of \$683 billion discounted over 100 years.
- Are directly/indirectly responsible for 600,000 jobs with \$10 billion in annual wages.

### The Basin

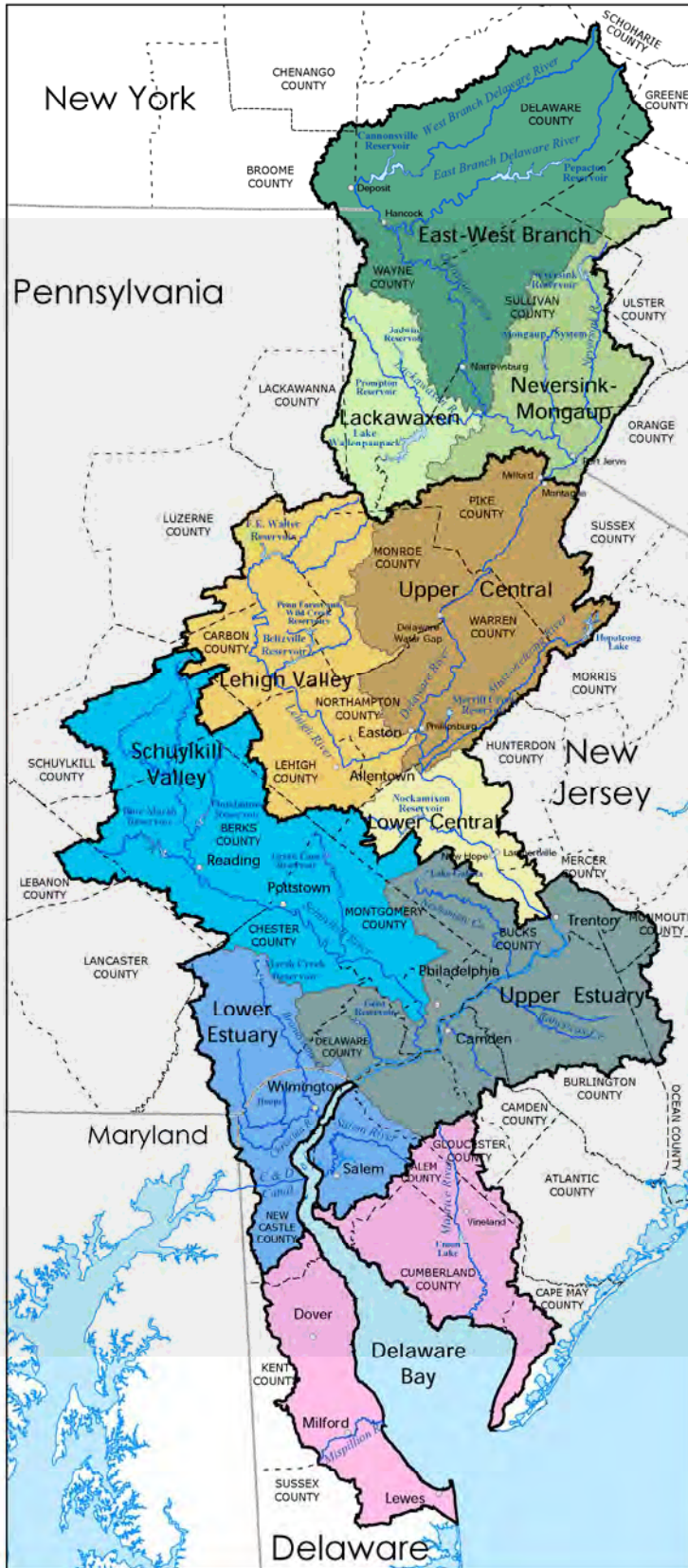
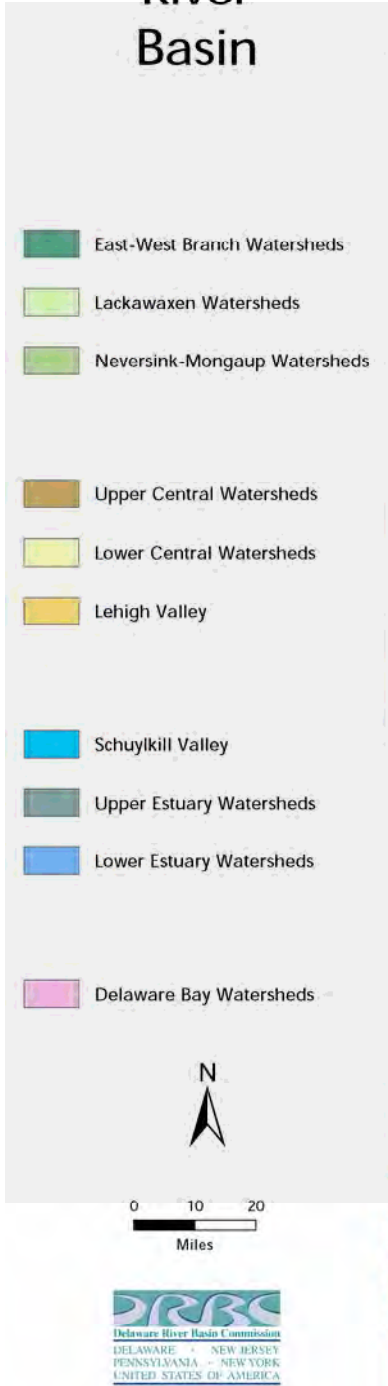
The Delaware River Basin occupies almost 13,000 sq mi (not including the river and bay) in Delaware, Maryland, New Jersey, New York, and Pennsylvania. In 2010, over 8.2 million residents lived in the basin including 654,000 people in Delaware, 2,300 in Maryland, 1,964,000 in New Jersey, 131,000 in New York, and 5,469,000 in Pennsylvania. Nearly 3,500,000 people work in the basin with 316,000 jobs in Delaware, 823,000 jobs in New Jersey, 70,000 jobs in New York, and 2,271,000 jobs in Pennsylvania. An additional 8 million people in New York City and northern New Jersey receive drinking water from the Delaware River via interbasin transfers. The Delaware Basin occupies just 0.4% of the continental U.S. yet supplies drinking water to 5% of the U.S. population.

The Delaware Basin population exceeds 8.2 million which if counted together would be the 12th most populous state after New Jersey but ahead of Virginia. The Delaware Basin occupies:

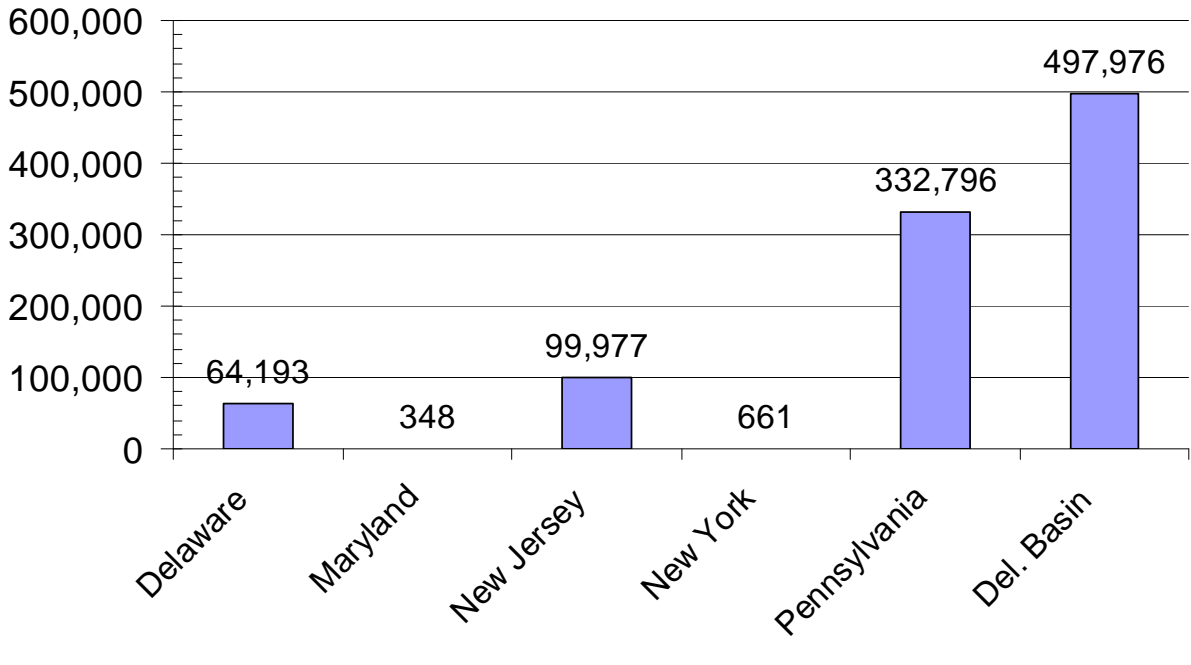
- Delaware (50% of the State's area and 74% of the First State's population)
- New Jersey (40% of the State's area and 22% of the Garden State's population)
- New York (5% of the State's area and 0.7% of the Empire State's population)
- Pennsylvania (14% of the State's area and 43% of the Keystone State's population).

Between 2000 and 2010, the population in the Delaware Basin increased by 6.1% or 472,066 people. Over the last decade, the population increased by 30% in Pike County, Pa.; by over 20% in Kent and Sussex counties, Del. and Monroe County, Pa.; and by over 10% in Gloucester and Ocean counties, NJ, Orange County, NY, and Chester, Lehigh, and Northampton counties, Pa. For the first time in two generations, Philadelphia gained population. Several counties in the basin lost population since 2000: Cape May, NJ; Broome, Delaware, and Greene counties, NY; and Lackawanna, Luzerne, and Schuylkill counties, Pa.

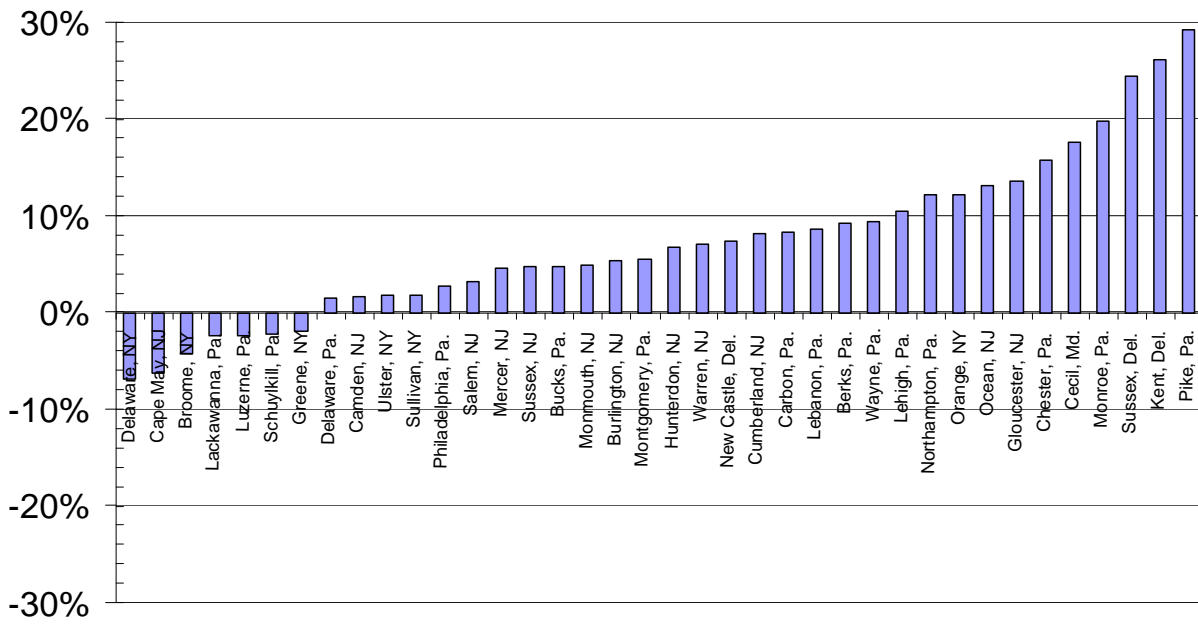
# Watersheds of the Delaware River Basin



## Population Change Delaware Basin, 2000-2010



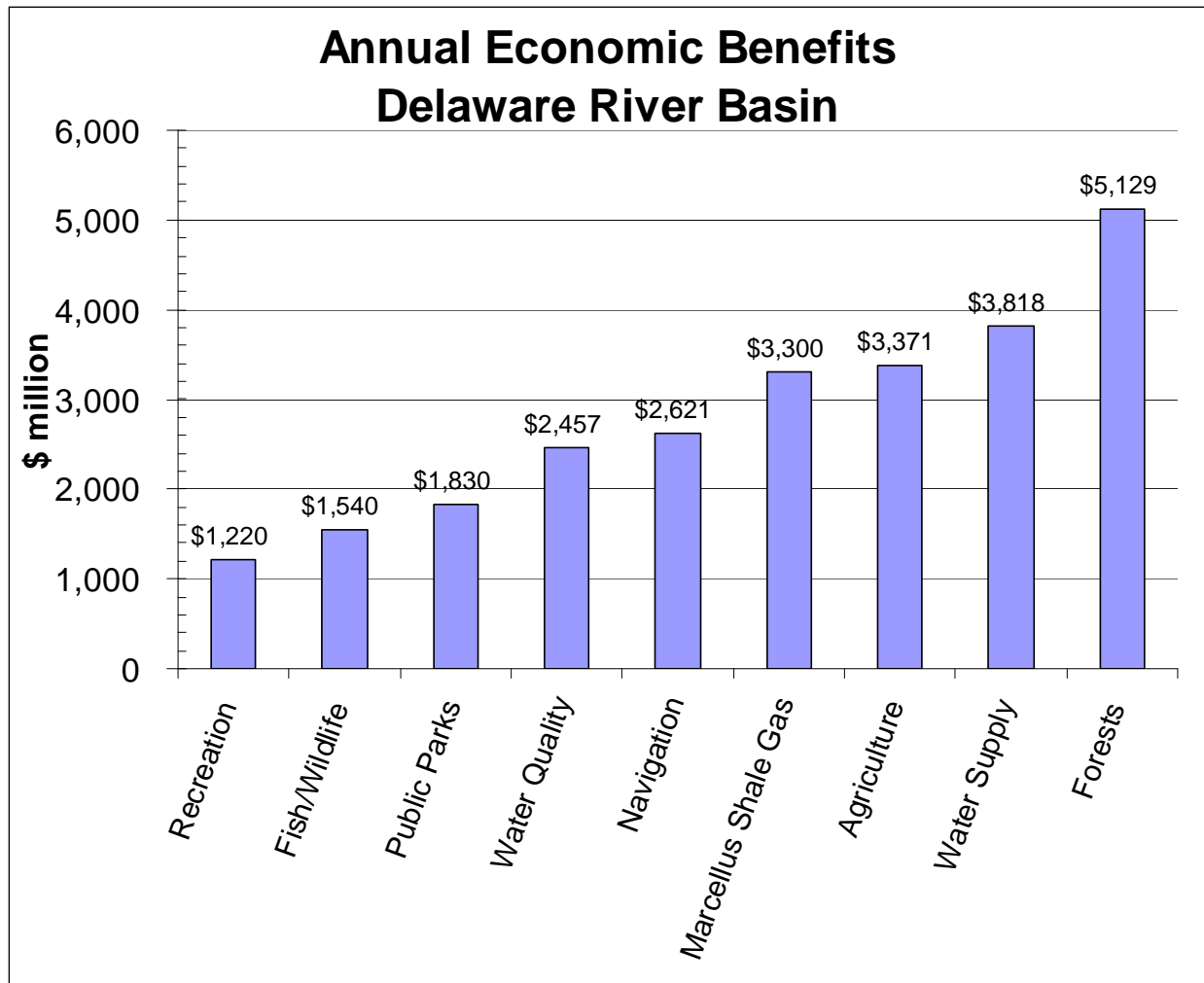
## Population Change by County Delaware Basin, 2000-2010



## Annual Economic Activity

The Delaware Basin contributes over \$25 billion in annual market/non-market value to the regional economy from the following activities:

- Recreation \$1.22 billion
- Fish and Wildlife \$1.55 billion
- Public Parks \$1.83 billion
- Water Quality \$2.46 billion
- Navigation/Ports \$2.62 billion
- Marcellus Shale Natural Gas (potential) \$3.30 billion
- Agriculture \$3.37 billion
- Water Supply \$3.82 billion
- Forests \$5.13 billion



**Table E1.** Annual economic value supported by the Delaware River Basin.

<b>Market Value</b>	<b>2010 (\$ million)</b>	<b>Sources</b>
<b>Recreation (Boating, Fishing, Swimming)</b>		
Skiing (1.9 million ski-days @ \$45/day)	325	Penna Ski Areas Association (2010)
Paddling-based Recreation (620,860 paddlers)	362	Outdoor Industry Association (2006)
Del. Water Gap River Recreation (267,000 visits)	41	U.S. Forest Service, Nat'l Park Service (1990)
Canoe/Kayak/Rafting (225,000 visits)	9	Canoe and Kayak Liveries (2010)
Powerboating (232,000 boat registrations)	395	National Marine Manufacturers Assoc. (2010)
<b>Water Quality</b>		
Water Treatment by Forests (\$96/mgd)	63	Trust for Public Land, AWWA (2004)
Wastewater Treatment (\$4.00/1000 gal)	1,722	DRBC and USEPA
Increased Property Value (+8%, 2000 ft of river)	13	EPA (1973), Brookings Institute (2010)
<b>Water Supply</b>		
Drinking Water Supply (\$4.78/1000 gal)	3,145	UDWRA and DRBC (2010)
Reservoir Storage (\$0.394/1000 gal)	145	UDWRA and DRBC (2010)
Irrigation Water Supply (\$300/ac-ft)	32	Resources for Future (1996), USDA (2007)
Thermoelectric Power Water Supply (\$44/ac-ft)	297	EIA (2002), NETL (2009)
Industrial Water Supply (\$200/ac-ft)	179	Resources for Future (1996), DRBC (2010)
Hydropower Water Supply (\$32/ac-ft)	20	Resources for Future (1996), DRBC (2010)
<b>Fish/Wildlife</b>		
Commercial Fish Landings (\$0.60/lb)	34	NMFS, Nat'l. Ocean Econ. Program (2007)
Fishing (11-18 trips/angler, \$53/trip)	576	U. S. Fish and Wildlife Service (2001)
Hunting (16 trips/hunter, \$50/trip)	340	U. S. Fish and Wildlife Service (2001)
Wildlife/Bird-watching (8-13 trips/yr, \$27/trip)	561	U. S. Fish and Wildlife Service (2001)
Shad Fishing (63,000 trips, \$102/trip)	6	Pennsylvania Fish & Boat Comm. (2011)
Wild Trout Fishing	29	Sportfishing Assn./Trout Unlimited (1998)
<b>Agriculture</b>		
Crop, poultry, livestock value (\$1,180/ac)	3,371	USDA Census of Agriculture 2007 (2009)
<b>Public Parks</b>		
Del. Water Gap Natl. Rec. Area (4.9 million visits)	100	U.S. National Park Service (2002)
<b>Marcellus Shale</b>		
Natural Gas (potential)	3,300	USGS (2011), EIA (2011)
<b>Maritime Transportation</b>		
Navigation (\$15/ac-ft)	220	Resources for the Future (1996)
Port Activity	2,400	Economy League of Greater Phila. (2008)
<b>Delaware Basin Market Value</b>	<b>≈ \$17.7 billion</b>	
<b>Non-Market Value</b>		
<b>Recreation (Boating, Fishing, Swimming)</b>		
Clean Water Act Restoration		
Viewing/Aesthetics (\$0.58/person)	5	University of Delaware (2003)
Boating (\$0.76/person)	6	University of Delaware (2003)
Fishing (\$2.95/person)	24	University of Delaware (2003)
Swimming (\$6.88/person)	57	University of Delaware (2003)
<b>Water Quality</b>		
WTP for Clean Water (\$38/nonuser-\$121/user)	659	University of Maryland (1989)
<b>Forests</b>		
Carbon Storage (\$827/ac)	3,592	U.S. Forest Service, Del. Center Hort. (2008)
Carbon Sequestration (\$29/ac)	126	U.S. Forest Service, Del. Center Hort. (2008)
Air Pollution Removal (\$266/ac)	1,155	U.S. Forest Service, Del. Center Hort. (2008)
Building Energy Savings (\$56/ac)	243	U.S. Forest Service, Del. Center Hort. (2008)
Avoided Carbon Emissions (\$3/ac)	13	U.S. Forest Service, Del. Center Hort. (2008)
<b>Public Parks</b>		
Health Benefits (\$9,734/ac)	1,283	Trust for Public Land (2009)
Community Cohesion (\$2,383/ac)	314	Trust for Public Land (2009)
Stormwater Benefit (\$921/ac)	121	Trust for Public Land (2009)
Air Pollution (\$88/ac)	12	Trust for Public Land (2009)
<b>Delaware Basin Non-Market Value</b>	<b>≈ \$7.6 billion</b>	

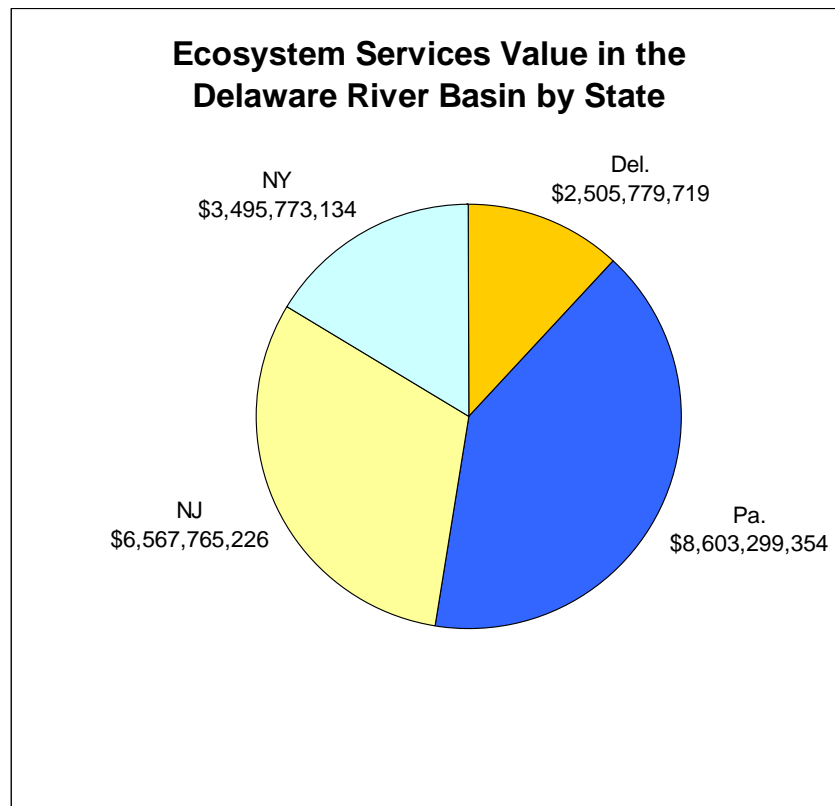
## Ecosystem Services

The value of natural goods and services from ecosystems in the Delaware Basin is \$21 billion (\$2010) with net present value (NPV) of \$683 billion using a discount of 3% over 100 years. The contributions of ecosystem services by state include:

- Delaware (\$2.5 billion, NPV \$81.4 billion)
- New Jersey (\$6.6 billion, NPV \$213.4 billion)
- New York (\$3.5 billion, NPV \$113.6 billion)
- Pennsylvania (\$8.6 billion, NPV \$279.6 billion)

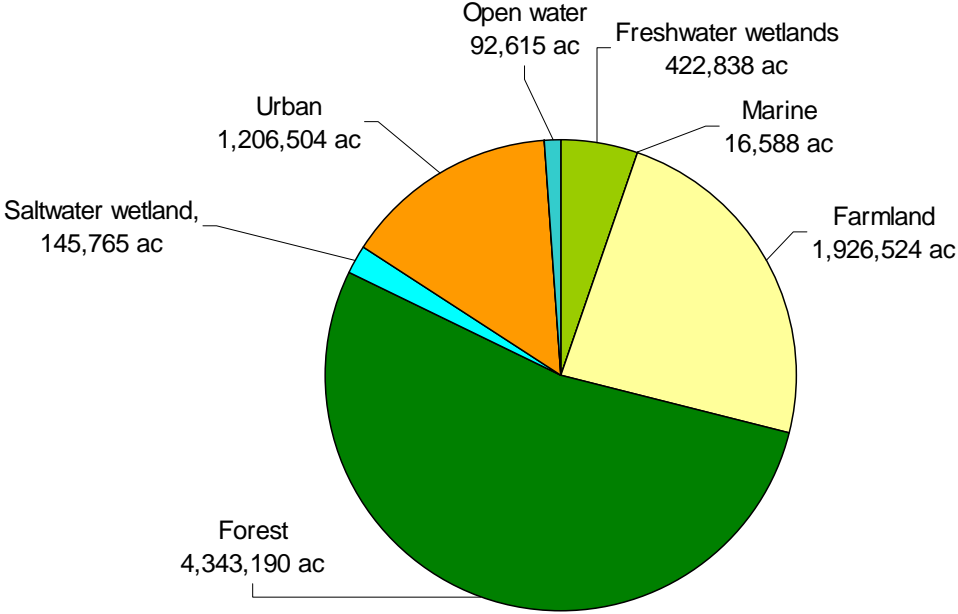
**Table E2.** Ecosystem goods and services provided by the Delaware River Basin

Ecosystem	Area (ac)	\$/ac/yr 2010	\$/yr 2010	NPV \$
Freshwater wetlands	422,838	13,621	5,759,329,048	187,178,194,067
Marine	16,588	10,006	165,982,947	5,394,445,767
Farmland	1,926,524	2,503	4,823,030,404	156,748,488,136
Forest land	4,343,190	1,978	8,591,367,360	279,219,439,184
Saltwater wetland	145,765	7,235	1,054,617,851	34,275,080,170
Urban	1,206,504	342	412,157,579	13,395,121,322
Beach/dune	900	48,644	43,758,633	1,422,155,566
Open water	92,615	1,946	180,210,703	5,856,847,857
<b>Total</b>	<b>8,154,924</b>		<b>\$21,030,454,525</b>	<b>\$683,489,772,069</b>

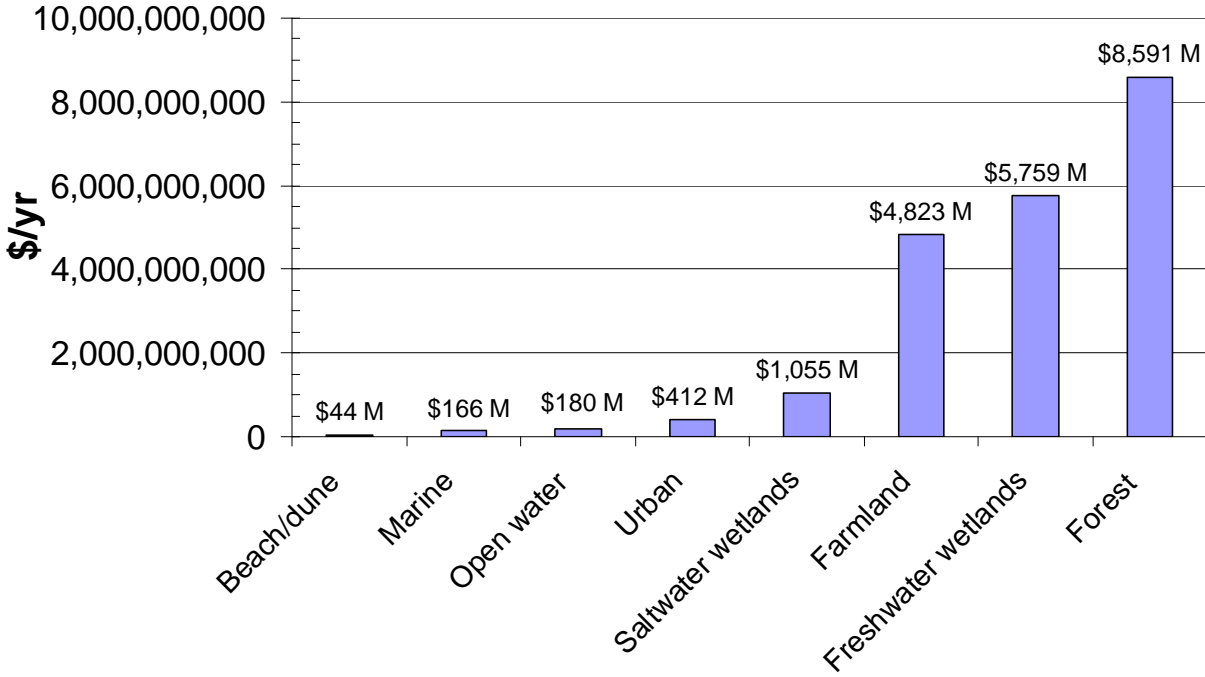


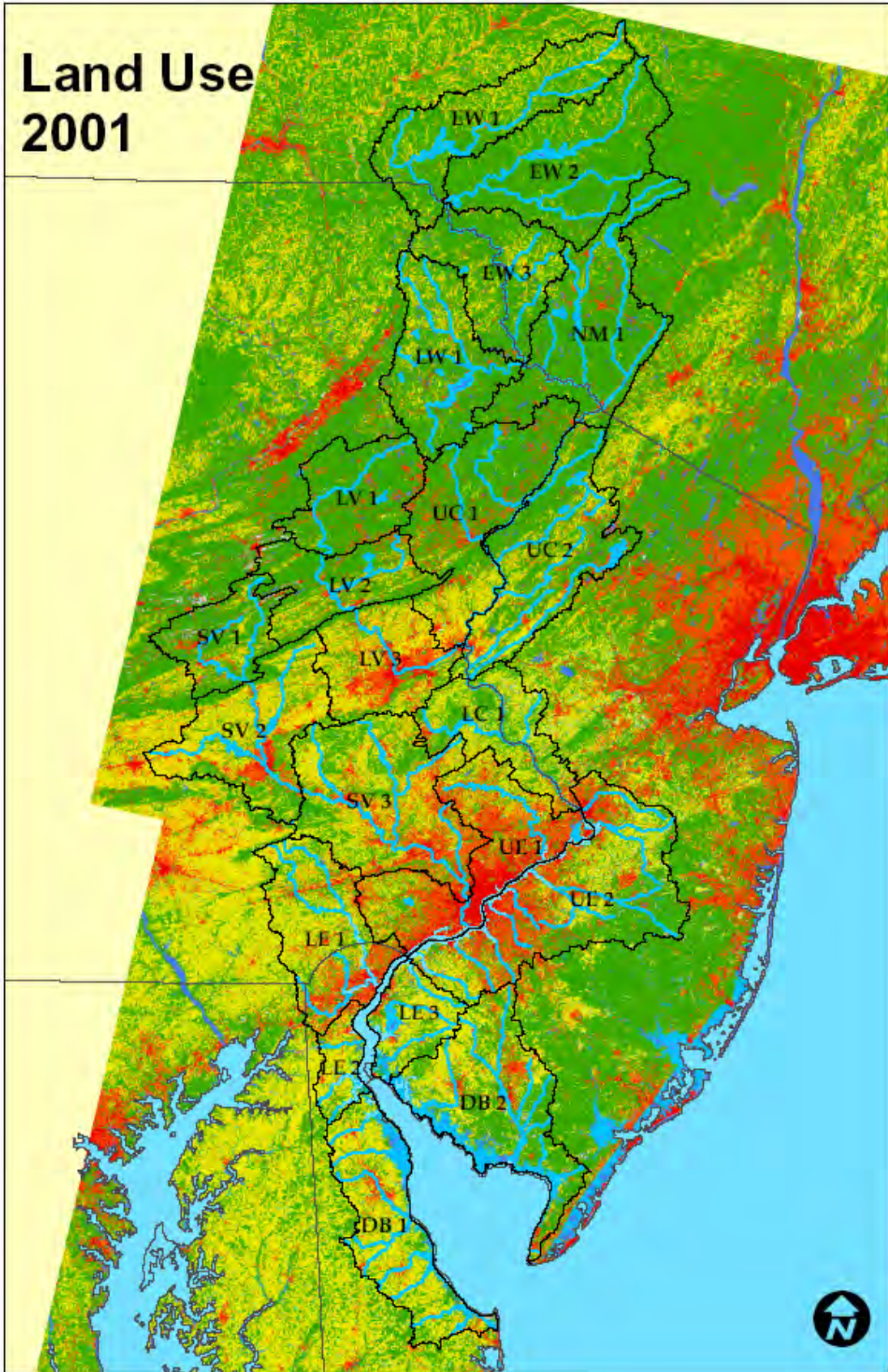


### Ecosystems Area (acres) Delaware River Basin, 2005



### Natural Capital Value of Ecosystems in the Delaware River Basin





## Jobs and Wages

The Delaware River Basin is a jobs engine that supports 600,000 direct/indirect jobs with \$10 billion in annual wages in the coastal, farm, ecotourism, water/wastewater, ports, and recreation industries.

**Table E3.** Jobs and wages directly and indirectly supported by the Delaware River Basin

Sector	Jobs	Wages (\$ million)	Source
Direct Basin Related	240,621	4,900	U.S. Bureau of Labor Statistics, 2009
Indirect Basin Related	288,745	4,000	U.S. Census Bureau, 2009
Coastal	44,658	947	National Coastal Economics Program, 2009
Farm	45,865	1,376	USDA Census of Agriculture, 2007
Fishing/Hunting/Birding	44,941	1,476	U.S. Fish and Wildlife Service, 2008
Water Supply Utilities	8,750	485	UDWRA and DRBC, 2010
Wastewater Utilities	1,298	61	UDWRA and DRBC, 2010
Watershed Organizations	201	10	UDWRA and DRBC, 2010
Ski Area Jobs	1,753	88	Penna. Ski Areas Association
Paddling-based Recreation	4,226		Outdoor Industry Association (2006)
River Recreation	448	9	U. S. Forest Service/Nat'l. Park Service, 1990
Canoe/Kayak/Rafting	225		Canoe Liveries and UDWRA, 2010
Wild Trout Fishing	350	4	Maharaj, McGurrin, and Carpenter, 1998
Del. Water Gap Nat'l. Rec. Area	7,563	101	Stynes and Sun, 2002
Port Jobs	12,121	772	Economy League of Greater Phila., 2008
<b>Delaware Basin Total</b>	<b>&gt; 600,000</b>	<b>&gt;\$10 billion</b>	

Within the Delaware Basin are 3,480,483 jobs earning \$172.6 billion in wages including:

- Delaware (316,014 jobs earning \$16.5 billion in wages)
- New Jersey (823,294 jobs, \$38.1 billion in wages)
- New York (69,858 jobs earning \$2.5 billion in wages)
- Pennsylvania (2,271,317 jobs earning \$115.5 billion in wages)

Jobs directly associated with the Delaware River Basin (such as water/sewer construction, water utilities, fishing, recreation, tourism, and ports) employ 240,621 with \$4.9 billion in wages including:

- Delaware (15,737 jobs earning \$340 million in wages)
- New Jersey (62,349 jobs earning \$1.3 billion in wages)
- New York (32,171 jobs earning \$550 million in wages)
- Pennsylvania (130,364 jobs earning \$2.8 billion in wages)

Jobs indirectly related to the waters of the Delaware Basin (based on multipliers of 2.2 for jobs and 1.8 for salaries) employ 288,745 people with \$4.0 billion in wages including:

- Delaware (18,884 jobs earning \$270 million in wages)
- New Jersey (74,819 jobs earning \$1.0 billion in wages)
- New York (38,605 jobs earning \$400 million in wages)
- Pennsylvania (156,437 jobs earning \$2.2 billion in wages)

According to the National Coastal Economy Report (2009), coastal employment sectors within the Delaware River Basin are responsible for 44,658 jobs earning \$947 million in wages with contributions of \$1.8 billion toward the GDP including:

- Delaware (12,139 jobs, \$214 million in wages, \$392 million toward the GDP)
- New Jersey (4,423 jobs, \$140 million in wages, \$235 million toward the GDP).
- Pennsylvania (28,096 jobs, \$593 million in wages, \$1.2 billion toward the GDP).

Over 21,800 farms provide 45,865 jobs with \$1.9 billion in wages in the Delaware Basin including:

- Delaware (3,140 farm jobs earning \$129 million in wages)
- New Jersey (14,305 farm jobs earning \$587 million in wages)
- New York (2,410 farm jobs earning \$99 million in wages)
- Pennsylvania (26,010 farm jobs earning \$1.1 billion in wages)

Fishing, hunting, and bird watching/wildlife associated recreation employ 44,941 jobs with \$1.5 billion in wages in the Delaware Basin including:

- Delaware (4,080 jobs earning \$134 million in wages)
- New Jersey (17,477 jobs earning \$574 million in wages)
- New York (4,872 jobs earning \$160 million in wages)
- Pennsylvania (18,512 jobs earning \$608 million in wages)
- 

Public and private water utilities that withdraw drinking water from the Delaware River Basin employ 8,750 people with wages of \$485 million including:

- Delaware (141 jobs earning \$7.8 million in wages)
- New Jersey (823 jobs earning \$46 million in wages)
- New York (5,600 jobs earning \$310 million in wages)
- Pennsylvania (2,186 jobs earning \$121 million in wages)

Wastewater utilities that treat and discharge wastewater to the Delaware River Basin employ 1,298 people with wages of \$61 million including:

- Delaware (108 jobs earning \$5 million in wages)
- New Jersey (257 jobs earning \$12 million in wages)
- New York (20 jobs earning \$1 million in wages)
- Pennsylvania (913 jobs earning \$43 million in wages)

Over 100 nonprofit watershed and environmental organizations employ at least 200 staff who earn at least \$9.5 million in wages to restore the watersheds in the Delaware River Basin.

In the Pocono Mountains of Pennsylvania, 9 ski resorts support 1,753 direct jobs in the Delaware Basin from aggregate annual revenues of \$87,655,063 from 1,908,228 skier visits.

Paddling-based recreation in the Delaware Basin is responsible for 620,860 participants and 4,226 jobs according to data prorated from the Outdoor Industry Association (2006).

The U. S. Forest Service and U.S. National Park Service estimated river recreation along the Upper Delaware River and Delaware Water Gap was responsible for 448 jobs with wages of \$8.8 million in 1986.

The 37 canoe/kayak liveries along the Delaware, Lehigh, and Schuylkill, and Brandywine Rivers have earnings of \$9 million per year and employ 225 people to lease watercraft to 225,000 visitors.

Along the Beaverkill, East Branch, West Branch, and upper main stem of the Delaware River in New York, wild trout fishing provides for 350 jobs with \$3.6 million in wages.

The Delaware Water Gap National Recreation Area recorded 4,867,272 recreation visits in 2001 that generated \$106 million in sales and 7,563 direct/indirect jobs with \$100 million in wages.

Delaware River ports from Wilmington to Philadelphia to Trenton are collectively the 5<sup>th</sup> largest port in the U.S. based on imports and the 20 largest U.S. port based on exports. These ports:

- Employ 4,056 workers who earn \$326 million in wages.
- Provide port jobs that support an additional two jobs each in port activity and employee spending for a total of 12,121 port related jobs with \$772 million in wages.
- Most of the 4,056 direct port jobs are in cargo handling and warehousing with petroleum port jobs adding up to less than 10% of employment
- Provides good jobs, the average salary of a port employee (with benefits) is over \$80,000.

# 1. Introduction

## Objectives

This report summarizes the socioeconomic value of water, natural resources and ecosystems in the Delaware River Basin in Delaware, New Jersey, New York, and Pennsylvania estimated as:

- Economic activity including market use and nonuse value of water supply, fishing, hunting, recreation, boating, ecotourism, agriculture, and navigation/port benefits in the basin.
- Natural capital or ecosystem services value of natural goods and services provided by habitat such as wetlands, forests, farms and open water.
- Jobs and wages directly and indirectly associated with the Delaware River Basin.

Two decades ago, researchers conducted a series of studies that indicated the Delaware River and Bay was worth hundreds of millions if not billions of dollars. Latham and Stapleford (1990) from the University of Delaware estimated total contributions of Delaware Estuary (the tidal river and bay) activities within the State of Delaware accounted for 10,500 jobs with \$222 million in annual wages, each direct estuary job created 2.2 indirect jobs, and the multiplier of direct/indirect wages was 1.8. The Greeley-Polhemus Group (1993) estimated the Delaware Estuary supported 123,000 jobs, \$4.3 billion in wages, \$24 billion in sales, \$25 million in sport fishing non-market value, \$1 million in commercial fish landings, and wetlands replacement values up to \$638 million.

This report is designed to update economic analyses for the Delaware River and Bay conducted 20 years ago and incorporate more recent valuation data from the emerging fields of ecological economics and ecosystem services.

## The Value of a Watershed

Studies for the Chesapeake Bay, Great Lakes, and Florida Everglades conclude that watersheds have significant economic value and restoration can result in green jobs and favorable cost-benefit investment ratios. The University of Maryland reported in 1988 that the Chesapeake Bay was worth \$678 billion and the Chesapeake Blue Ribbon Panel (2003) reported with inflation the present value of the bay would exceed \$1 trillion.

The Brookings Institution (Austin et al. 2007) found restoration of the Great Lakes would cost \$26 billion in present value and aggregate economic benefits would exceed \$50 billion (2:1 B/C ratio). Great Lakes benefits include \$6.5-11.8 billion in tourism, fishing, and recreation dollars, \$12-19 billion increase in property values from contaminated sediment cleanup, \$50-125 million in reduced municipal water treatment costs, and \$30 billion in short time multiplier benefits. The Great Lakes Coalition (2010) concluded investment in watershed restoration creates good paying jobs and leads to economic benefits while restoring the environment (Table 1).

The Everglades Foundation estimated that the Comprehensive Everglades Restoration Plan (CERP) would result in \$6 billion in benefits and 443,000 jobs over 50 years (McCormick 2010). Net present

value of the Everglades’s restoration benefits would be \$46 billion resulting from investments of \$11.5 billion or a benefit to cost ratio of 4:1.

**Table 1.** Jobs and salaries created by watershed restoration work  
(Great Lakes Coalition (2010) from U. S. Bureau of Labor Statistics)

Job	Mean Salary	Job	Mean Salary
Wetland scientist	\$45,730	Fisheries Biologist	\$60,670
Research scientist	\$45,730	Archeologist	\$57,230
Construction manager	\$93,290	Operating Engineer	\$44,180
Biologist	\$69,430	Environmental Engr.	\$80,750
Toxicologist	\$70,000	Hydrogeologist	\$92,710
Chemist	\$72,740	Environmental Planner	\$64,680
Geologist	\$58,000	Plumber/Pipefitter	\$9,870
Helicopter Pilot	\$90,000	Carpenter	\$43,640
Info. Technology	\$70,930	Electrician	\$50,850
Admin. Staff	\$32,990	Truck Driver	\$39,260
Mechanics	\$37,000	Concrete Workers	\$39,410
Excavator	\$38,540	Dredge Operator	\$38,330
Landscape Architect	\$65,910	Conservation Scientist	\$61,180
Civil Engineer	\$81,180	Biological technician	\$41,140
General Laborer	\$33,190	Pile Drive Operator	\$51,410

## An Economic Engine

What do the Guggenheim Museum, Boeing, Sunoco, Campbell’s Soup, DuPont, Wawa, Starbucks, Iron Hill Brewery, Philadelphia Philadelphia Phillies, New York Yankees, Camelback Ski Area, Pt. Pleasant Canoe Livery, Salem Nuclear Power Plant, and the United States Navy have in common? They all depend on the waters of the Delaware River Basin to sustain their businesses.

Most economists agree that water is an undervalued resource. The astronomer Copernicus and Adam Smith of the invincible hand of the economy fame both considered the “diamond-water paradox”. If water is more valuable to society than a precious gem, then why is water sold for a fraction of a penny per gallon for drinking water or not even valued at all as an ecological resource in the river or bay? Just as under-compensated police officers or teachers are more valuable to society than multimillion dollar movie stars, perhaps the value of water is just as marginalized. We tend to underprice water based on its marginal value for single uses (i.e. drinking water) and not consider the full value of water for all its myriad uses. This report attempts to quantify the highest multiobjective value of water *in toto* for its wide range of habitat, recreation, ecological, and industrial benefits in the Delaware River Basin.

If water is society’s most valuable chemical, then the Delaware River with a mean annual flow of 2.7 trillion gallons per year at Trenton is the Delaware Valley’s (and by aqueduct Manhattan Island’s) most invaluable economic asset. For 400 years, the Delaware River has been an economic engine ever since Henry Hudson discovered the bay off Cape May in August 1609 for commerce and the Dutch East India Company during his unsuccessful quest for an inner trade route to Asia.

When William Penn founded the City of Brotherly Love in 1681 seeking refuge from religious persecution in Europe, he also found a safe harbor between the Delaware and the Schuylkill in a colony rich with lumber, fertile land, beaver pelts, and in later centuries coal and oil reserves. By the 18<sup>th</sup> century frugal yet prosperous Philadelphia Quaker merchants established triangle trade route connections to Europe and the Caribbean from their home port along the Delaware. During the American Revolution, Philadelphia was the largest city in the colonies and the 3<sup>rd</sup> largest port in the British Empire after London and Liverpool. In 1790 Ben Franklin, America's first environmentalist, was so concerned about pollution in the river that he willed funds to build the first municipal water system in the United States at Philadelphia to tap the Delaware and Schuylkill for drinking water.

The economic engine kicked into high gear during the 19<sup>th</sup> century with hydropower and steam power during the Industrial Revolution. In 1802, the DuPont family searched up and down the Atlantic Seaboard and established gunpowder mills along the falls of the Brandywine River above Wilmington as one of the first industries in the Delaware Valley. Delaware River ports grew when anthracite coal was discovered in the Lehigh Valley in 1792 and steam railroads were built in the 1830s. By the Gay Nineties, every Philadelphia wharf had railroad access and the advent of steam ships made for faster transatlantic shipping. In 1895, the Corps of Engineers dredged the Delaware River to 26 feet from the natural depth of 17 feet (Economy League 2008).

By the end of the 19<sup>th</sup> century, the Delaware River supported the largest commercial American shad and sturgeon fishery along the Atlantic coast. The sturgeon was such a lucrative fish that boom town Caviar (Bayside) near Greenwich, New Jersey was founded to process the roe for worldwide export. By the 1880s, 1,400 sailing vessels harvested 22 million pounds of oysters from the Delaware Bay. In 1886, nationally famous hotels in Gloucester, N. J. served 10,000 planked shad dinners at events that resembled modern day blue crab feasts. In 1896 over 14 million pounds of shad were caught with a value of \$400,000 (\$10 million in 2008 dollars). In 1896, a fisheries report to the governor of Pennsylvania listed the catch of a 76-pound striped bass above Gloucester, NJ.

At the turn of the 20<sup>th</sup> century, Delaware River ports supported a premier ship building industry. By the First World War the Delaware was known as the "Clyde of America" with ship building and repair production that rivaled its Scottish cousin. By 1912, Philadelphia and environs built and manufactured 5% of all goods in the United States. Export markets included coal, iron, cotton, leather, grain, lumber and tobacco, and gunpowder from Wilmington. By 1914, the Panama Canal opened access from the East Coast to Hawaii sugar cane fields and Philadelphia refined and shipped 500,000 tons of raw sugar or 1/6 of all sugar refined in the United States.

After the Delaware River ship channel was deepened to 41 feet in 1941, the port economy boomed during World War II as the Philadelphia Navy Yard employed 40,000 workers who built 53 ships and repaired over 500 vessels. After the war, the "Arsenal of America" manufacturing and export base declined due to decreased demand for Pennsylvania coal and decline of Lehigh Valley steel industries. In 1995, the Department of the Navy closed the Philadelphia Navy Yard and decommissioned the ghost fleet due to decreased ship building needs in the "New Navy."

During the 19<sup>th</sup> Century, the Delaware Water Gap along the Blue Mountain near Stroudsburg, Pa. was a resort that grew with the railroads from Philadelphia and New York City. In 1965, Congress authorized the National Park Service to form the Delaware Water Gap National Recreation Area that now receives 5 million visits per year, the 8<sup>th</sup> most visited unit in the National Park System.



In 1931 and amended in 1954, the U. S. Supreme Court issued a decree authorizing New York City to divert 800 mgd of water from three Catskill Mountain reservoirs in the Delaware Basin to the Hudson River Basin. The Delaware River delivers over half the drinking water to New York City.

By 1986, the Salem and Hope Creek nuclear power plants were built on Artificial Island in Salem County, New Jersey that pump 3 billion gallons per day of cooling water to provide 3,500 megawatts of electricity to the tri-state region. In 2010, a billion gallons per day of drinking water and industrial process water were withdrawn from streams and aquifers in the Delaware Basin to sustain the region's jobs and domestic, commercial, and industrial economy. The river, bay, beaches, wetlands, and forests support a billion dollar tourism, recreation, and hunting/fishing/birding economy.

After the turn of the 21<sup>st</sup> Century, new horizontal drilling and hydraulic fracturing technology kicked off the Marcellus Shale natural gas drilling boom in a 50,000 square mile basin stretching from Kentucky to Pennsylvania and New York. The Marcellus Shale occupies about 36% or 4700 square miles under the upper Delaware Basin. A 2011 USGS report indicates 7 trillion cubic feet of natural gas may be recoverable under the Delaware Basin, a potential multi-billion dollar natural resource.

The Delaware River Basin supplies drinking water to the 1<sup>st</sup> (New York City) and 5<sup>th</sup> (Philadelphia) largest metropolitan economies in the United States. The following report tabulates the substantial economic value and worth of this irreplaceable asset for over 8 million residents in Delaware, New Jersey, New York, and Pennsylvania who live in the basin and an additional 8 million people in New York City and northern New Jersey who receive drinking water from the Delaware River.

## **Governance**

For the last fifty years, Federal, state, and local governments, nonprofits, and the private sector have focused efforts on restoring the Delaware River Basin. In 1961, JFK signed the Delaware River Basin Compact that appointed the Governors of Delaware, New Jersey, New York, and Pennsylvania as Commissioners as the first ever Federal-state watershed accord. In 1968 a full four years before the Clean Water Act was passed by Congress, the DRBC issued waste load allocations to reduce pollutant discharges from over 80 wastewater treatment plants. In 1988, the Delaware Estuary was nominated by the Governors of Delaware, New Jersey, and Pennsylvania for the National Estuary Program per Section 320 of the Federal Clean Water Act. In 1996, the Delaware Estuary was designated by Congress as one of only 28 National Estuary Programs in the United States and is now the only tri-state estuary program in the nation. In 1996, the nonprofit Partnership for the Delaware Estuary was established to implement a Comprehensive Conservation and Management Plan (CCMP). In 2011, the DRBC celebrates the 50<sup>th</sup> anniversary of its founding by JFK, Congress, and the Governors of Delaware, New Jersey, New York, and Pennsylvania.

## **The Watershed**

The Delaware River Basin (Figure 1 and Table 2) occupies 12,769 sq mi (not including the river and bay) in Delaware (8%), New Jersey (23%), New York (20%), and Pennsylvania (49%). In 2010, 8,255,013 residents lived in the basin including 643,418 people in Delaware (9%), 2,324 in Maryland, 1,951,047 in New Jersey (24%), 124,969 in New York (2%), and 5,533,254 in Pennsylvania (66%). In 2009, nearly 3,500,000 people worked in the Delaware Basin with 316,014 jobs in Delaware (9%), 1,172 jobs in Maryland, 823,294 jobs in New Jersey (24%), 69,858 jobs in New York (2%), and 2,271,317 jobs in Pennsylvania (65%).

# Watersheds of the Delaware River Basin

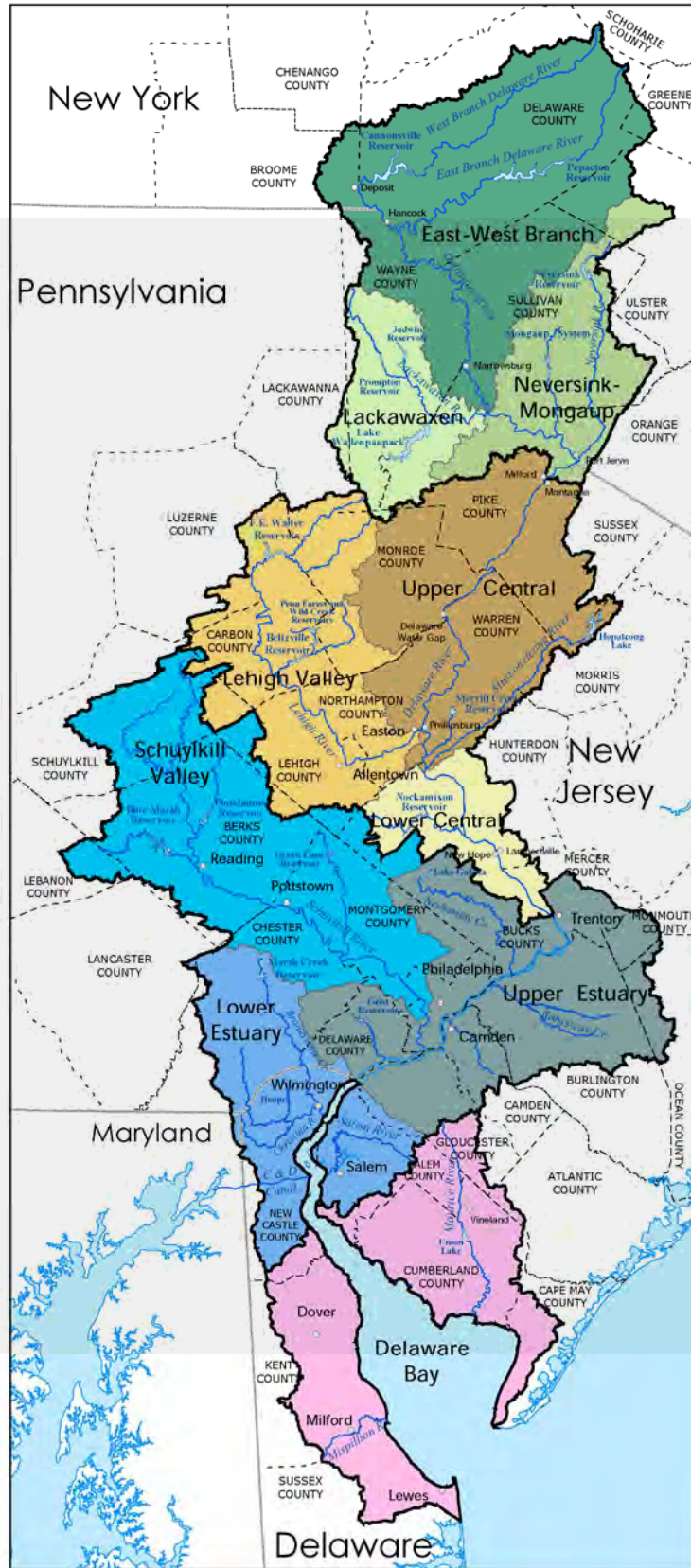
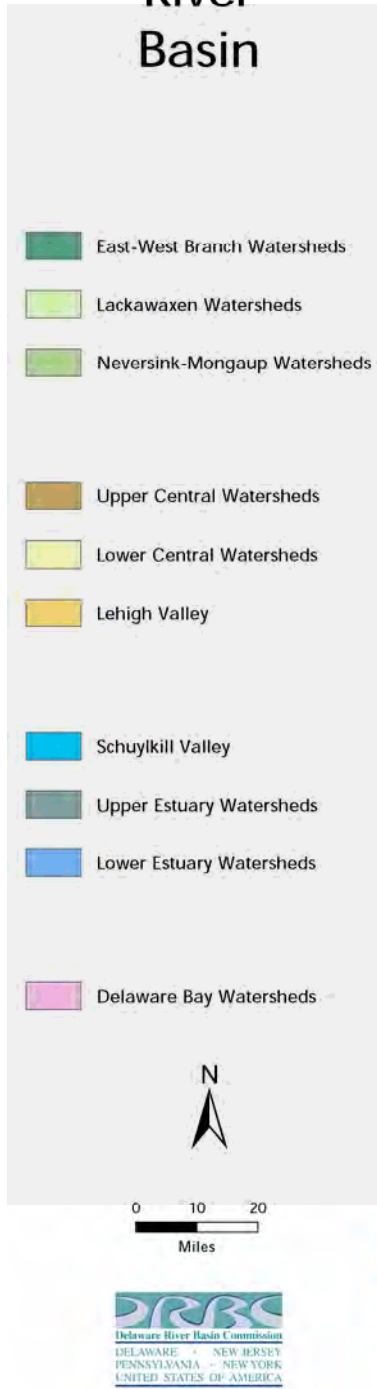


Figure 1. The Delaware River Basin. (DRBC)

**Table 2.** Land area, population, and employment in the Delaware River Basin

State	Area (sq mi)	Population <sup>1</sup> 2010	Employment <sup>2</sup> 2009
Delaware	965	643,418	316,014
Maryland	8	2,324	1,172
New Jersey	2,961	1,951,047	823,294
New York	2,555	124,969	69,858
Pennsylvania	6,280	5,533,254	2,271,317
Total	12,769	8,255,013	3,481,655

1. U.S. Census Bureau 2009. 2. U.S. Bureau of Labor Statistics

Table 3 summarizes the area, population, and employment by state and county in the Delaware Basin. In Delaware, the basin covers 50% of the land area yet includes 74% of the First State's population. The New Jersey portion of the basin covers 40% of the State's land area and includes 22% of the Garden State's population. New York State covers 5% of the State's land area and the basin includes 0.7% of the Empire State's population. The Pennsylvania part of the basin covers just 14% of the State's area yet includes 43% of the Keystone State's population.

The population of the Delaware Basin now exceeds 8.2 million which if considered as a single jurisdiction, it would be the 12th most populous state in the U.S. after North Carolina and New Jersey but ahead of Virginia and Massachusetts. Between 2000 and 2010, the population in the Delaware Basin increased by 6.1% or 472,066 people (Table 4 and Figure 2). Over the last decade, population increased by 30% in Pike County, Pa.; by over 20% in Kent and Sussex counties, Del. and Monroe County, Pa.; and by over 10% in Gloucester and Ocean counties, NJ, Orange County, NY, and Chester, Lehigh, and Northampton counties, Pa (Figure 3). For the first time in two generations, Philadelphia gained population. Several counties in the basin lost population since 2000: Cape May, NJ; Broome, Delaware, and Greene counties, NY; and Lackawanna, Luzerne, and Schuylkill counties, Pa.

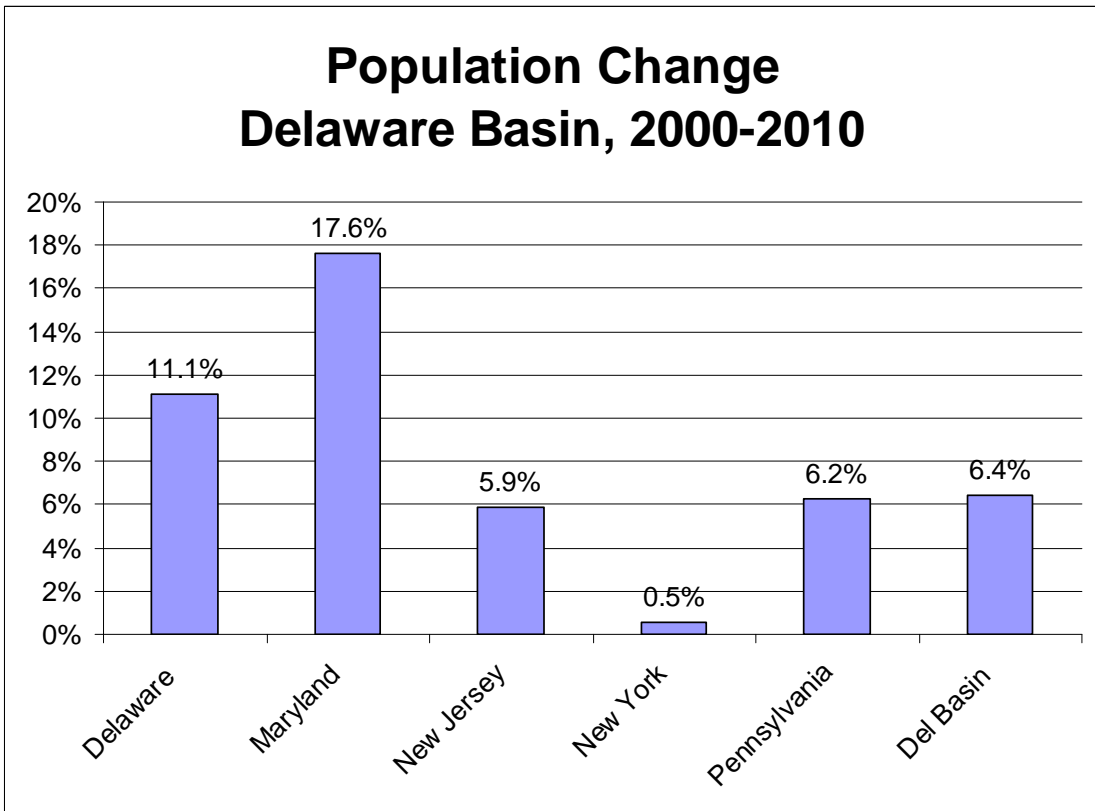
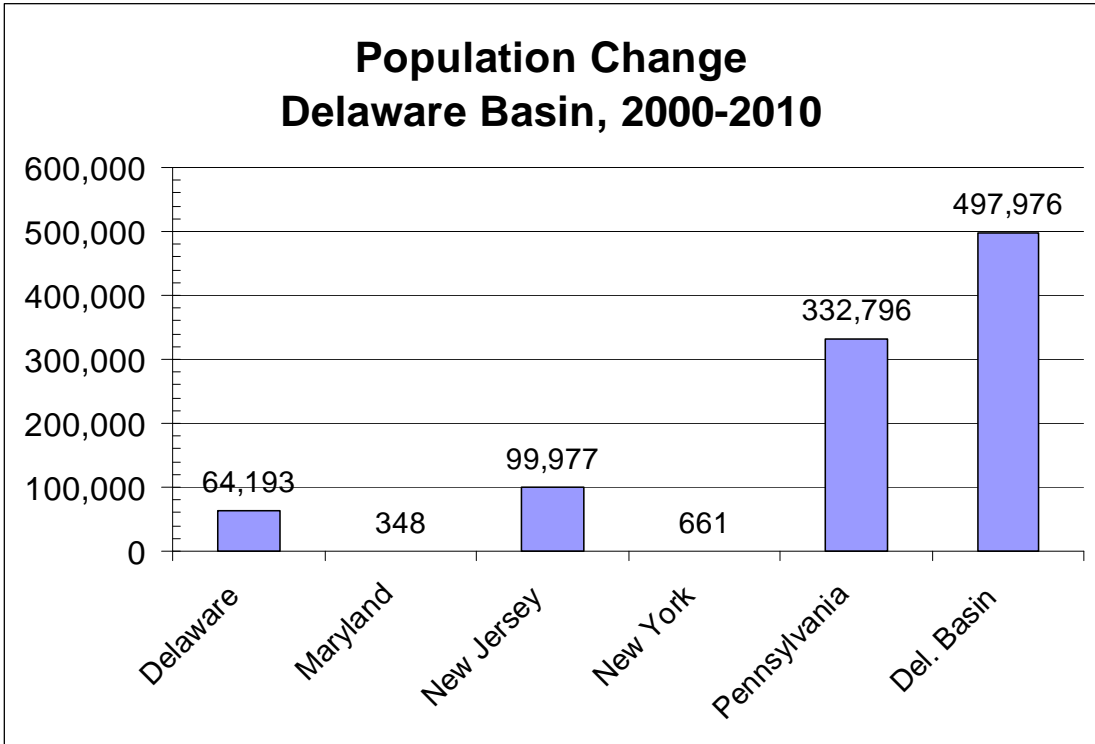
**Table 3.** Land area, population, and employment by county in the Delaware River Basin

State/county	Area 2005 <sup>1</sup> (sq mi)	Population <sup>2</sup> 2010	Employment <sup>3</sup> 2009
Kent	389	108,025	50,412
New Castle	381	493,428	252,534
Sussex	195	41,965	13,068
<b>Delaware</b>	<b>965</b>	<b>643,418</b>	<b>316,014</b>
Cecil	8	2,324	1,172
<b>Maryland</b>	<b>8</b>	<b>2,324</b>	<b>1,172</b>
Burlington	495	367,157	187,758
Camden	123	432,315	169,909
Cape May	104	52,209	14,545
Cumberland	490	158,289	61,868
Gloucester	279	271,332	89,183
Hunterdon	215	65,132	23,650
Mercer	180	287,685	178,320
Monmouth	20	24,620	9,864
Ocean	30	23,616	7,495
Salem	347	66,342	21,900
Sussex	320	92,689	23,302
Warren	358	109,662	35,500
<b>New Jersey</b>	<b>2,961</b>	<b>1,951,047</b>	<b>823,294</b>
Broome	85	15,038	11,292
Delaware	1,295	26,111	14,240
Greene	25	1,207	572
Orange	65	19,887	10,456
Sullivan	940	47,563	25,511
Ulster	145	15,162	7,787
<b>New York</b>	<b>2,555</b>	<b>124,969</b>	<b>69,858</b>
Berks	777	407,843	150,665
Bucks	607	626,280	244,453
Carbon	381	63,640	16,730
Chester	616	491,070	212,996
Delaware	184	559,776	201,208
Lackawanna	25	11,335	4,830
Lebanon	20	7,221	2,750
Lehigh	347	344,571	166,932
Luzerne	50	17,491	8,074
Monroe	609	166,209	56,025
Montgomery	483	789,862	453,771
Northampton	374	299,646	96,536
Philadelphia	135	1,558,613	619,396
Pike	547	59,859	9,874
Schuylkill	420	79,358	27,077
Wayne	705	50,480	14,114
<b>Pennsylvania</b>	<b>6,280</b>	<b>5,533,254</b>	<b>2,271,317</b>
<b>Delaware Basin</b>	<b>12,761</b>	<b>8,255,013</b>	<b>3,481,655</b>

1. NOAA CSC 2005. 2. U. S. Census Bureau 2010. 3. U. S. Bureau of Labor Statistics 2009.

**Table 4.** Population change in the Delaware River Basin, 2000-2010 (U. S. Census)

State/ County	Population 2000	Population 2010	Change	%
Kent	85,680	108,025	22,345	26.1%
New Castle	459,829	493,428	33,599	7.3%
Sussex	33,716	41,965	8,249	24.5%
<b>Delaware</b>	<b>579,225</b>	<b>643,418</b>	<b>64,193</b>	<b>11.1%</b>
Cecil	1,976	2,324	348	17.6%
<b>Maryland</b>	<b>1,976</b>	<b>2,324</b>	<b>348</b>	<b>17.6%</b>
Burlington	348,729	367,157	18,428	5.3%
Camden	425,646	432,315	6,669	1.6%
Cape May	55,679	52,209	-3,470	-6.2%
Cumberland	146,442	158,289	11,847	8.1%
Gloucester	239,012	271,332	32,320	13.5%
Hunterdon	60,995	65,132	4,137	6.8%
Mercer	274,945	287,685	12,740	4.6%
Monmouth	23,465	24,620	1,155	4.9%
Ocean	20,887	23,616	2,729	13.1%
Salem	64,285	66,342	2,057	3.2%
Sussex	88,547	92,689	4,142	4.7%
Warren	102,438	109,662	7,224	7.1%
<b>New Jersey</b>	<b>1,851,070</b>	<b>1,951,047</b>	<b>99,977</b>	<b>5.9%</b>
Broome	15,713	15,038	-675	-4.3%
Delaware	28,030	26,111	-1,919	-6.8%
Greene	1,231	1,207	-24	-1.9%
Orange	17,722	19,887	2,165	12.2%
Sullivan	46,712	47,563	851	1.8%
Ulster	14,900	15,162	262	1.8%
<b>New York</b>	<b>124,308</b>	<b>124,969</b>	<b>661</b>	<b>0.5%</b>
Berks	373,638	407,843	34,205	9.2%
Bucks	597,632	626,280	28,648	4.8%
Carbon	58,795	63,640	4,845	8.2%
Chester	424,241	491,070	66,829	15.8%
Delaware	551,976	559,776	7,800	1.4%
Lackawanna	11,617	11,335	-282	-2.4%
Lebanon	6,648	7,221	573	8.6%
Lehigh	312,090	344,571	32,481	10.4%
Luzerne	17,916	17,491	-425	-2.4%
Monroe	138,690	166,209	27,519	19.8%
Montgomery	748,987	789,862	40,875	5.5%
Northampton	267,077	299,646	32,569	12.2%
Philadelphia	1,517,542	1,558,613	41,071	2.7%
Pike	46,303	59,859	13,556	29.3%
Schuylkill	81,159	79,358	-1,801	-2.2%
Wayne	46,147	50,480	4,333	9.4%
<b>Pennsylvania</b>	<b>5,200,458</b>	<b>5,533,254</b>	<b>332,796</b>	<b>6.2%</b>
<b>Delaware Basin</b>	<b>7,757,037</b>	<b>8,255,013</b>	<b>497,976</b>	<b>6.4%</b>



**Figure 2.** Population change in the Delaware River Basin, 2000-2010 (U.S. Census)

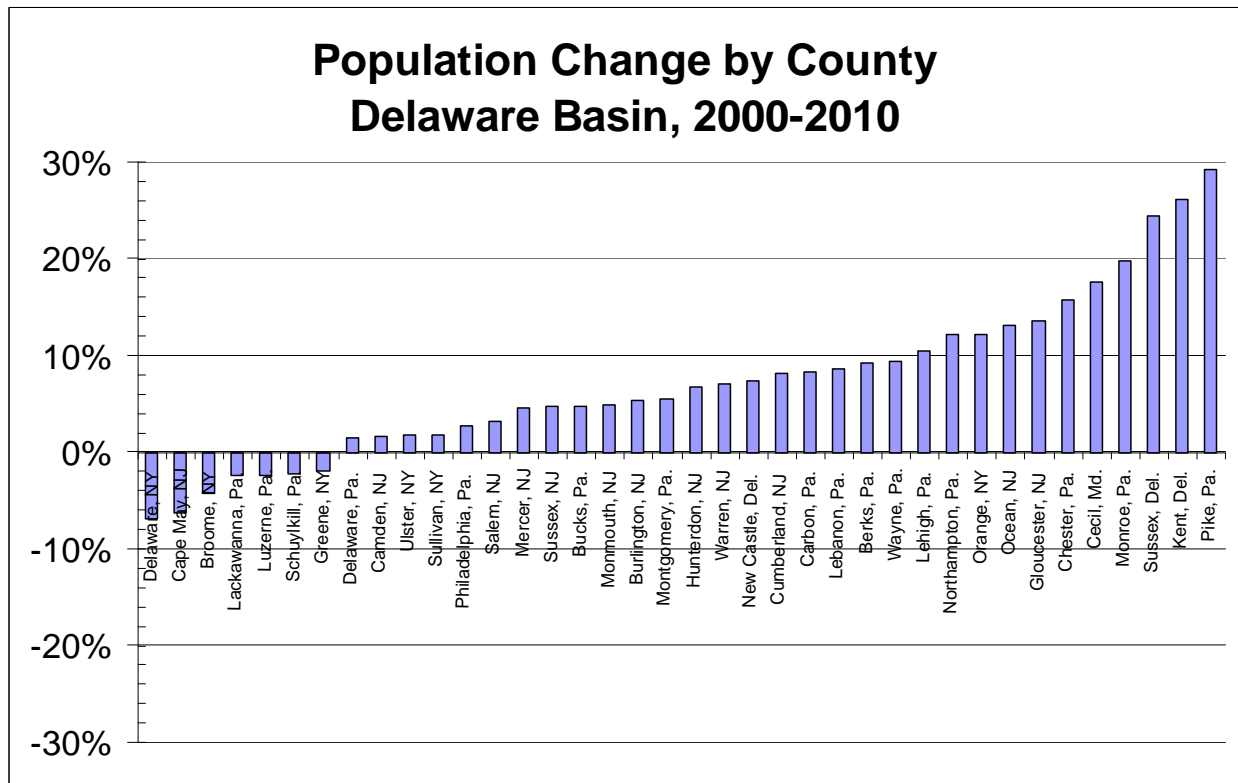
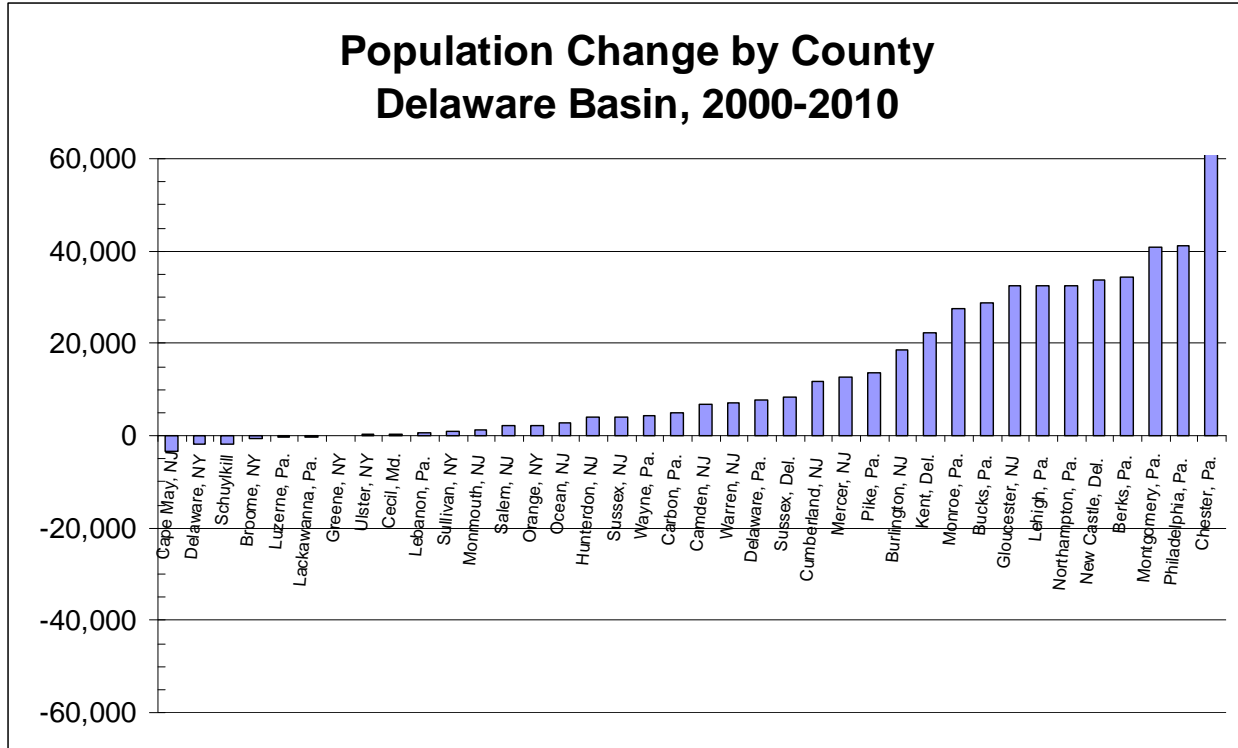


Figure 3. Population change in Delaware River Basin counties, 2000-2010 (U.S. Census)

The Delaware Basin includes 21 watersheds that flow to the river and bay (Table 5 and Figure 4).

**Table 5.** Watersheds in the Delaware River Basin

<b>Watershed</b>	<b>Area (sq mi)</b>	<b>Population 2000</b>	<b>Pop. Density (pop./sq mi)</b>
LE1 Brandywine/Christina	187	382,703	2,047
LE2 C&D Canal	152	54,960	362
DB1 Delaware Bay	626	141,562	226
<b>Delaware</b>	<b>965</b>	<b>579,225</b>	<b>600</b>
UC2 NJ Highlands	745	218,638	293
LC1 Del. R. above Trenton	159	55,880	351
UE2 New Jersey Coastal Plain	1,021	1,287,810	1,261
LE3 Salem River	254	54,290	214
DB2 Delaware Bay	782	234,480	300
<b>New Jersey</b>	<b>2,961</b>	<b>1,851,098</b>	<b>625</b>
EW1 East Branch Del. R.	666	23,040	35
EW2 West Branch Del. R.	841	19,263	23
EW3 Del. R. above Pt. Jervis	314	11,840	38
NM1 Neversink R.	734	70,164	96
<b>New York</b>	<b>2,555</b>	<b>124,307</b>	<b>49</b>
EW3 Del. R. above Pt. Jervis	210	7,894	38
NM1 Neversink R.	82	7,796	95
LW1 Lackawaxen R.	598	49,734	83
UC1 Pocono Mt.	779	208,478	268
LV1 Lehigh River above Lehighton	451	37,622	83
LV2 Lehigh River above Jim Thorpe	430	88,349	205
LV3 Lehigh River above Bethlehem	480	478,278	996
LC1 Del. R. above Trenton	295	103,771	352
SV1 Schuylkill above Reading	338	88,681	262
SV2 Schuylkill above Valley Forge	649	321,066	495
SV3 Schuylkill above Philadelphia	874	952,560	1,090
UE1 Penna Fall Line	693	2,579,100	3,722
LE1 Brandywine/Christina	401	277,129	691
<b>Pennsylvania</b>	<b>6,280</b>	<b>5,200,458</b>	<b>828</b>
<b>Delaware Basin</b>	<b>12,761</b>	<b>7,755,088</b>	<b>608</b>



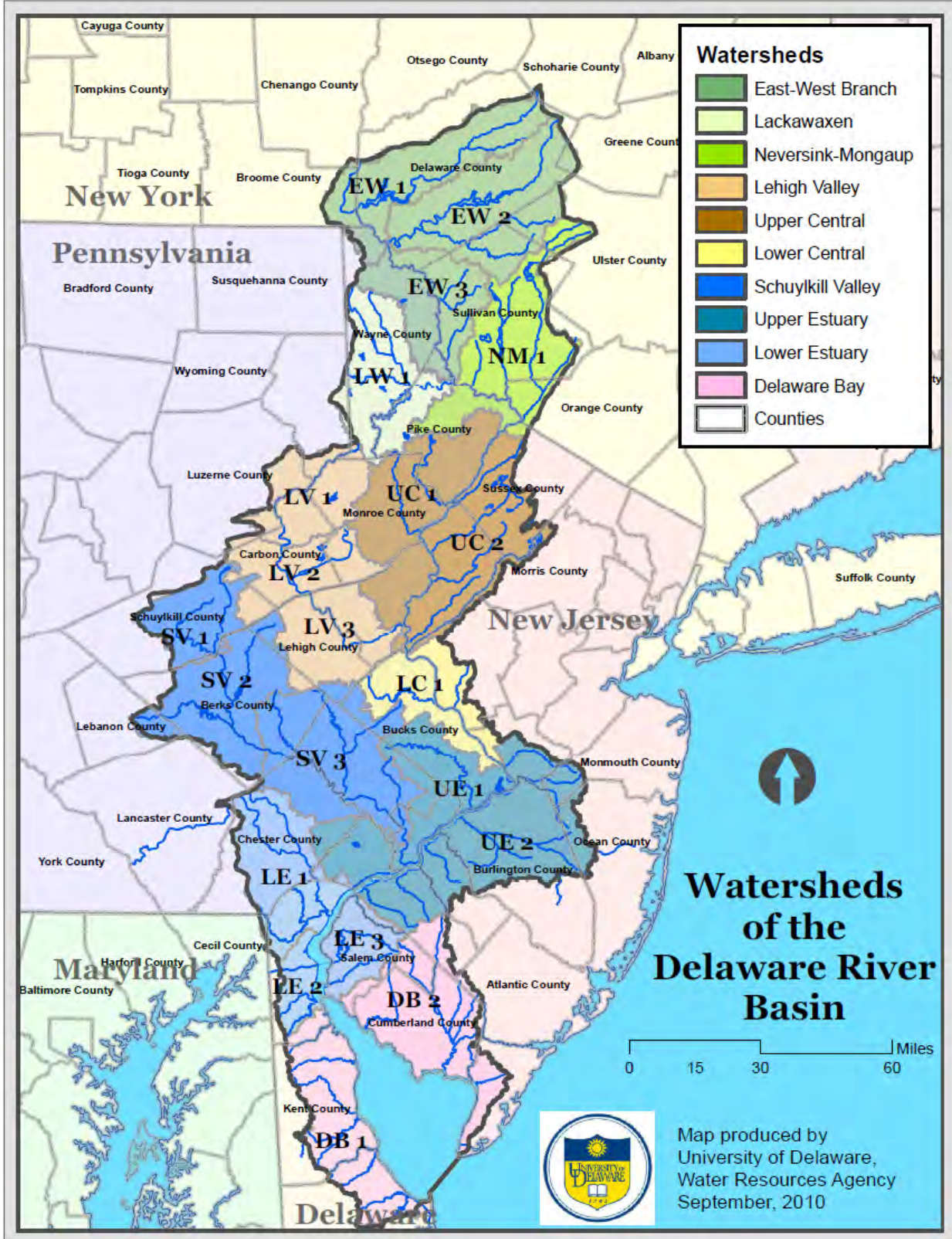


Figure 4. Watersheds in the Delaware River Basin (UDWRA 2010)

## 2. Methods

### Valuation Techniques

The economic value of the Delaware River Basin in Delaware, New Jersey, New York, and Pennsylvania is derived from published studies and valuation methods such as:

**Avoided Cost:** Society sustains costs if certain ecosystems are not present or lost. For instance, the loss of wetlands may increase economic flood damages.

**Replacement Cost:** Natural services are lost and replaced by more expensive manmade systems, i.e. forests provide water filtration benefits that are replaced by costly water filtration plants.

**Net Factor Income by Enhancement of Income:** Improved water quality water enhances fisheries and crabbing industries and, in turn, boosts jobs and wages.

**Travel Cost:** Visitors are willing to pay to travel and visit ecosystems and natural resources for hunting, fishing, and birding.

**Hedonic Pricing Process:** Residents may be willing to pay more for property values that are higher along scenic bay and river coastlines.

**Contingent Valuation:** Valuation by survey of individual different preferences to preserve ecosystems. People may be willing to pay more in fees to preserve bay water quality.

### Scope of Work

The socioeconomic value of the Delaware Basin was established by the following scope of work.

- 1. Define and map area of interest:** The area of interest is defined as the Delaware River Basin from the headwaters in the Catskill Mountains of New York to the mouth of the bay at Cape Henlopen, Delaware. ArcGIS map layers of population census blocks, watershed boundaries, and land use/land cover were developed to perform the analysis.
- 2. Literature review:** Gather a database of published literature and socioeconomic data relevant to the Delaware River Basin from the U. S. Census Bureau, U. S. Bureau of Labor Statistics, U.S. Department of Agriculture, U. S. Forest Service, and U. S. Fish and Wildlife Service.
- 3. Economic activity:** Estimate the direct/indirect value of agriculture, water quality, water supply, fishing, hunting, recreation, boating, ecotourism, and navigation in the watershed from population, employment, industrial activity, and land use data. Total economic activity is defined as the sum of direct/indirect use, option, and non use values (Ingraham and Foster 2008). Direct use values are from natural goods such as drinking water, boating, recreation, and commercial fishing. Indirect values are benefits from ecosystems such as water filtration by forests and flood control/habitat protection from wetlands. Option demand is public willingness to pay for benefits from water quality or scenic value of the bay. Nonuse (existence) values accrue to a public who may never visit the resource but are willing to pay to preserve the existence of the resource.

**4. Ecosystem Services:** Tabulate the market value of natural resources (ecosystem services value) in the watershed for habitat such as wetlands, forests, farmland, and open water. Prepare GIS based data sets and mapping. Ecosystem services (ecological services) are provided by nature and represent benefits such as water filtration, flood reduction, and drinking water supply.

Using GIS, define ecosystem areas using 2006 NOAA Coastal Services Center land cover data in the following classifications: (a) Freshwater wetlands, (b) Marine, (c) Farmland, (d) Forest, (e) Barren, (f) Saltwater wetland, (g) Urban, (h) Beach/dune, (i) Open freshwater, and (j) Riparian buffer.

Search research studies and gather value (\$/acre) data for ecosystem services: (a) carbon sequestration, (b) flood control, (c) drinking water supply, (d) water quality filtration, (e) waste treatment and assimilation, (f) nutrient regulation, (g) fish and wildlife habitat, (h) recreation and aesthetics. Ecosystem services were estimated using value (benefits) transfer where published data and literature are reviewed and applied in the context of the resource in question. Value transfer is used to estimate ecosystem goods and services for the Delaware River Basin.

Compute ecosystem services value by multiplying land use area (acres) by ecosystem value (\$/ac). The value transfer techniques employed here involves selecting data from published literature from another watershed or study area and applying the \$ per ac values to land use areas computed by GIS. While primary research data from the watershed in question (the Delaware Basin) is preferable and is used in this report, value transfer is the next best practical way to value ecosystems especially when in the absence of such data the worth of ecosystems have previously been deemed zero. Future economic valuation survey research is recommended to develop primary ecosystem service values for the Delaware Basin in particular.

**4. Jobs and salaries:** Obtain employment and wage data from the U. S. Department of Labor, U. S. Census Bureau, and National Ocean Economics Program. Calculate direct/indirect jobs in the Delaware Basin by North American Industry Classification System (NAICS) codes such as shipbuilding, marine transportation/ports, fisheries, recreation, minerals, trade, agriculture, and others. Total jobs and salaries were summarized for each county within the watershed based on population census block data. NAICS data were supplemented with farm jobs data from the USDA Agricultural Statistics Bureau, U. S. Fish and Wildlife Service ecotourism jobs data, and jobs provided by water purveyors and wastewater treatment utilities.

**5. Report:** Prepare a report and GIS mapping summarizing the direct and indirect economic values of goods and services provided by the Delaware River Basin updated to 2010 dollars.

### 3. Annual Economic Activity

Estimated annual economic value of the Delaware River Basin from recreation, fish and wildlife, public parks, water quality, navigation/ports, potential Marcellus Shale natural gas, agriculture, water supply, and forest activities is over \$25 billion (Table 6 and Figure 5).

- Recreation \$1.22 billion
- Fish and Wildlife \$1.55 billion
- Public Parks \$1.83 billion
- Water Quality \$2.46 billion
- Navigation/Ports \$2.62 billion
- Marcellus Shale Natural Gas (potential) \$3.30 billion
- Agriculture \$3.37 billion
- Water Supply \$3.82 billion
- Forests \$5.13 billion

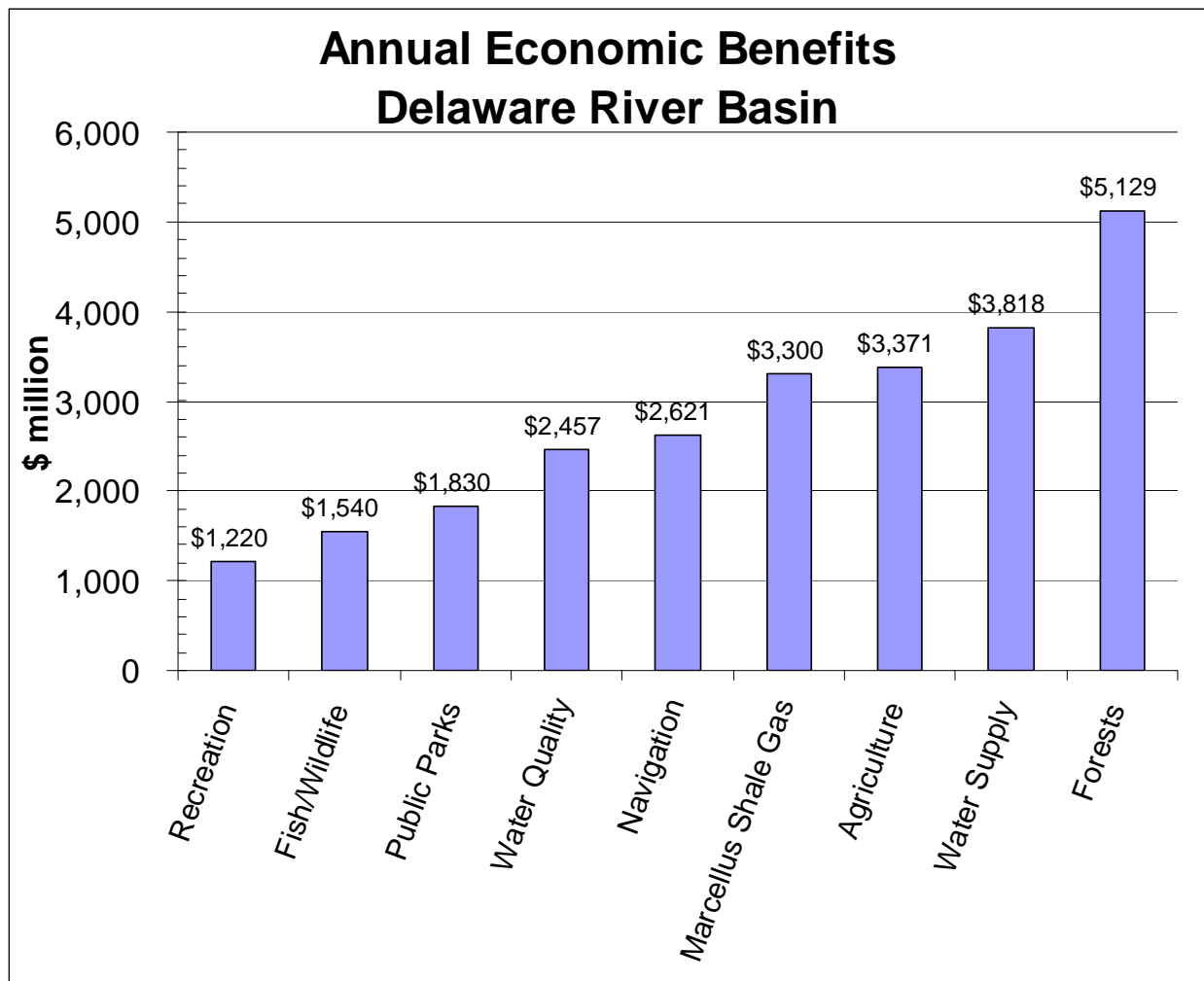


Figure 5. Annual economic activity related to the Delaware River Basin

**Table 6.** Annual economic activity in the Delaware River Basin, 2010

Activity	2010 (\$ million)	Value Transfer Sources
<b>Recreation (Boating, Fishing, Swimming)</b>		
Clean Water Act Restoration		
Viewing/Aesthetics (\$0.58/person)	5	University of Delaware (2003)
Boating (\$0.76/person)	6	University of Delaware (2003)
Fishing (\$2.95/person)	24	University of Delaware (2003)
Swimming (\$6.88/person)	57	University of Delaware (2003)
<b>Water Quality Based Recreation</b>		
Swimming (\$13.40/trip)	9	University of Rhode Island (2002)
Boating (\$30/trip)	47	University of Rhode Island (2002)
Fishing (\$62.79/trip)	52	University of Rhode Island (2002)
Wildlife/bird watching (\$77.73/trip)	104	University of Rhode Island (2002)
Skiing (1.9 million ski-days @\$45/day)	325	Pennsylvania Ski Areas Association (2010)
Paddling-based Recreation (620,860 paddlers)	362	Outdoor Industry Association(2006)
Del. Water Gap River Recreation (267,000 visitors)	41	U.S. Forest Service, U.S. Nat'l Park Service (1990)
Canoe/Kayak/Rafting (225,000 visits)	9	Canoe and Kayak Liveries (2010)
Powerboating (232,000 boat registrations)	395	National Marine Manufacturers Association (2010)
<b>Water Quality</b>		
Willing to Pay for Clean Water (\$38-\$121/user)	659	University of Maryland (1989)
Water Treatment by Forests (\$96/mgd)	63	Trust for Public Land, AWWA (2004)
Wastewater Treatment (\$4.00/1000 gal)	1,722	DRBC and USEPA
Increased Property Value (+8%)	13	EPA (1973), Brookings Institute (2010)
<b>Water Supply</b>		
Drinking Water Supply (\$4.78/1000 gal)	3,145	UDWRA and DRBC (2010)
Reservoir Storage (\$0.394/1000 gal)	145	UDWRA and DRBC (2010)
Irrigation Water Supply (\$300/ac-ft)	32	Resources for the Future (1996), USDA (2007)
Thermoelectric Power Water Supply (\$44/ac-ft)	297	EIA (2002), NETL (2009)
Industrial Water Supply (\$200/ac-ft)	179	Resources for the Future (1996), DRBC (2010)
Hydropower Water Supply (\$32/ac-ft)	20	Resources for the Future (1996), DRBC (2010)
<b>Fish/Wildlife</b>		
Commercial Fish Landings (\$0.60/lb)	34	NMFS, Nat'l. Ocean Economics Program (2007)
Fishing (11-18 trips/angler, \$17-\$53/trip))	576	U. S. Fish and Wildlife Service (2001)
Hunting (16 trips/hunter, \$16-50/trip)	340	U. S. Fish and Wildlife Service (2001)
Wildlife/Bird-watching (8-13 trip/yr, \$15-\$27/trip)	561	U. S. Fish and Wildlife Service (2001)
Shad Fishing (63,000 trips, \$102/trip)	6	Pennsylvania Fish and Boat Commission (2011)
Wild Trout Fishing	29	Amer. Sportfishing Assn./Trout Unlimited (1998)
<b>Agriculture</b>		
Crop, poultry, livestock value (\$1,180/ac)	3,371	USDA Census of Agriculture 2007 (2009)
<b>Forests</b>		
Carbon Storage (\$827/ac)	3,592	U.S. Forest Service, Del. Ctr. Horticulture (2008)
Carbon Sequestration (\$29/ac)	126	U.S. Forest Service
Air Pollution Removal (\$266/ac)	1,155	U.S. Forest Service
Building Energy Savings (\$56/ac)	243	U.S. Forest Service
Avoided Carbon Emissions (\$3/ac)	13	U.S. Forest Service
<b>Public Parks</b>		
Health Benefits (\$9,734/ac)	1,283	Trust for Public Land
Community Cohesion (\$2,383/ac)	314	Trust for Public Land
Stormwater Benefit (\$921/ac)	121	Trust for Public Land
Air Pollution (\$88/ac)	12	Trust for Public Land
Del. Water Gap Natl. Rec. Area (4.9 million visits)	100	U.S. National Park Service (2002)
<b>Marcellus Shale</b>		
Natural Gas (7.3 trillion cf @ \$11.21/1000 cf)	3,300	USGS (2011), EIA (2011)
<b>Maritime Transportation</b>		
Navigation (\$15/ac-ft)	220	Resources for the Future (1996)
Port Activity	2,400	Economy League of Greater Philadelphia (2008)
<b>Delaware River Basin</b>	<b>≈\$25 billion</b>	

## Recreation

### Clean Water Act Restoration

Parsons, Helm, and Bondelid (2003) from the University of Delaware measured the economic benefits of water quality improvements to recreational users in the northeastern states and found annual per person benefits for improvements due to the Clean Water Act ranged from \$0.47 for viewing, \$0.62 for boating, \$2.40 for fishing, to \$5.59 for swimming. Table 7 summarizes total water quality benefits to recreational users in the Delaware River Basin by transferring the benefits in \$2003 to \$2010 assuming an annual rate of 3% and then multiplying the \$2010 benefits by the basin population. Total 2010 recreation benefits due to Clean Water Act water quality improvements in the Delaware Basin are \$92 million per year or \$11.17 per person. Swimming (62%) and fishing (26%) are the highest valued recreational benefits followed by boating (7%) and viewing (5%).

**Table 7.** Water quality benefits from Clean Water Act improvements in the Delaware River Basin

Recreational Benefit	\$2003 <sup>1</sup> (per person)	\$2010 <sup>2</sup> (per person)	Del. Basin Pop. 2010	Benefit/yr	% of Benefit
Viewing	\$0.47	\$0.58	8,255,013	\$4,787,908	5%
Boating	\$0.62	\$0.76	8,255,013	\$6,273,810	7%
Fishing	\$2.40	\$2.95	8,255,013	\$24,352,288	26%
Swimming	\$5.59	\$6.88	8,255,013	\$56,794,489	62%
<b>Total</b>	<b>\$9.08</b>	<b>\$11.17</b>	<b>8,255,013</b>	<b>\$92,208,495</b>	<b>100%</b>

1. Parsons et al. 2003. 2. \$2010 transferred from \$2003 at annual rate of 3%.

### Water Quality Based Recreation

Using travel cost demand methods, Johnston et al. (2002) from the University of Rhode Island computed the consumer surplus (economic use value per person) for swimming, boating, recreational fishing, and bird watching/wildlife viewing in the Peconic Estuary watershed on Long Island, New York. Swimming, boating, fishing, and wildlife viewing were valued at \$8.59, \$19.23, \$40.25, and \$49.83 per trip in \$1995, respectively. Table 8 summarizes water quality benefits to recreational users of \$211 million per year in the Delaware Basin (estuary only) by transferring unit values from the Peconic Estuary, converting \$1995 to \$2010 by an annual rate of 3%, and multiplying \$2010 benefits by trips per year.

**Table 8.** Total annual value of recreational benefits in the Delaware River Basin

Recreational Benefit	\$1995 Consumer surplus/trip <sup>1</sup>	\$2010 Consumer surplus/trip <sup>2</sup>	Trips/year to Del. Estuary	Annual Value	% of Benefit
Swimming	\$8.59	\$13.40	670,000 <sup>3</sup>	\$8,978,000	4%
Boating	\$19.23	\$30.00	1,568,473 <sup>4</sup>	\$47,054,190	22%
Fishing	\$40.25	\$62.79	824,249 <sup>4</sup>	\$51,754,595	24%
Wildlife/bird watching	\$49.83	\$77.73	3,336,440 <sup>5</sup>	\$103,700,000	49%
<b>Total</b>				<b>\$211,486,785</b>	<b>100%</b>

1. Johnston et al. 2002. 2. \$2010 transferred from \$1995 at 3%. 3. 10% of Delaware Estuary population swims. 4. NOEP 2009 for boating (16.8% of pop. and 1.4 trips/p./yr) and fishing (10.3% of pop. and 1.2 trips/p./yr). 5. USFWS 2006 wildlife/bird watching (Del. 427,500, NJ 2,070,900, & Pa. 838,000 trips/yr).

## Skiing

In the Pocono Mountains of Pennsylvania, nine ski areas draw approximately 1 mgd from Delaware Basin water supplies for snowmaking on 1,005 skiable acres. The Pennsylvania Ski Areas Association (2009) estimated the economic value at 23 ski resorts statewide was \$832,000,000. Prorating from PSAA statewide estimates, the economic value for 9 resorts in the Delaware Basin is \$325,000,000. The nine ski resorts in the Delaware Basin have aggregate annual revenues of \$87,655,063 from 1,908,228 skier visits based on a mid-week lift ticket rate of \$45/day (Table 9).

**Table 9.** Revenues from ski resorts in the Delaware River Basin

Ski Resort	Ski Area (ac)	Annual Ski Visits	Lift Ticket (\$/day)	Revenue (\$)
Elk Mountain	235	446,203	\$48	\$21,417,722
Ski Big Bear	26	49,367	42	2,073,418
Ski Shawnee	125	237,342	43	10,205,696
Alpine Mountain	60	113,924	37	4,215,190
Camelback	160	303,797	48	14,582,278
Jack Frost	100	189,873	44	8,354,430
Big Boulder	55	104,430	44	4,594,937
Blue Mountain	158	300,000	49	14,700,000
Bear Creek	86	163,291	46	7,511,392
<b>Total</b>	<b>1,005</b>	<b>1,908,228</b>	<b>\$45</b>	<b>\$87,655,063</b>

## Paddling-based Recreation

Canoeing, kayaking, and rafting are key drivers to the local economy along the Brandywine, Lehigh, Schuylkill, and middle/upper Delaware rivers in the Delaware Basin (Van Rossum, Carluccio, and Blankinship 2010). In the Mid-Atlantic census division (NY, NJ, PA), the Outdoor Industry Association (2006) estimates paddling-based recreation is practiced by 11% of the population and is responsible for 3,356,000 participants, \$356 million in gear retail sales, \$1.6 billion in trip related sales, and 22,844 jobs. Given the Delaware Basin is the home of 7,611,595 people in NJ, NY, and Pa. or 22% of New Jersey's population (1,951,047), 0.7% of New York State's population (124,969), and 43% of Pennsylvania's population (5,533,254) or 18.5% of the three state's total population of 40,800,000 people, then prorated paddling-based recreation in the basin is responsible for 620,860 participants, \$96 million in gear retail sales, \$296 million in trip sales, and 4,226 jobs (Table 10).

**Table 10.** Economic value of paddling-based recreation in the Delaware River Basin

Paddling Based Recreation	States of NJ, NY, PA <sup>1</sup>	Del. Basin NJ, NY, PA <sup>2</sup>
Population	40,800,000	7,563,762
Participants	3,356,000	620,860
Gear retail sales	\$356 million	\$66 million
Trip related sales	\$1.600 billion	\$296 million
Total Sales	\$1.956 billion	\$362 million
Jobs	22,844	4,226

1. Outdoor Industry Association 2006. 2. Prorated by 18.5% given 40,800,000 people live in NJ, NY, and PA and 7,611,595 people live in these states in the Delaware Basin.

## River Recreation

Cordel et al. (1990) from the U. S. Forest Service and U.S. National Park Service estimated river recreation along the Upper Delaware River and Delaware Water Gap was responsible for \$13.3 million and \$6.9 million in total economic output, respectively, in \$1986 (Table 11). Adjusting for 3% annually, river recreation economic output along the Upper Delaware River and Delaware Water Gap is roughly \$27.1 million and \$14.1 million, respectively, or \$41.2 million total in \$2010.

**Table 11.** Economic impacts of river recreation along Upper Delaware and Delaware Water Gap

River	Participants	Jobs	Wages (\$1986)	Economic Output (\$1986)	Wages (\$2010)	Economic Output (\$2010)
Upper Delaware	232,000	292	5,582,800	13,351,000	11,408,000	\$27,100,000
Del. Water Gap	135,400	156	3,246,300	6,929,000	6,633,743	\$14,100,000
<b>Total</b>	<b>367,400</b>	<b>448</b>	<b>8,829,100</b>	<b>20,280,000</b>	<b>18,041,743</b>	<b>41,200,000</b>

1. Cordel et al. 1990. 2. Adjusted to \$2010 at 3% annually.

## Canoe/Kayak/Rafting

Thirty seven (37) canoe and kayak liveries along the Delaware, Lehigh, and Schuylkill, and Brandywine Rivers lease watercraft to approximately 225,000 visitors with earnings of \$9 million per year assuming a daily rental fee of \$40 per person (Table 12).



**Table 12.** Annual revenue from canoe and kayak liveries in the Delaware River Basin

Canoe/Kayak Livery	Address	Daily Rate (\$)	Annual Visitors	Revenue (\$)
<b>Delaware River</b>				
Adventure Sports Canoe/Raft	Marshalls Creek, PA	\$40	9,000	\$360,000
Bucks County River Country	Point Pleasant, PA	\$40	13,500	\$540,000
Catskill Mountain Canoe Rentals	Hankins, NY	\$40	7,000	\$280,000
Cedar Rapids Kayak/Canoe	Barryville, NY	\$40	5,000	\$200,000
Chamberlain Canoes Inc	Minisink Hills, PA	\$40	5,000	\$200,000
Delaware River Rafting/Canoeing	Delaware, NJ	\$40	9,000	\$360,000
Delaware River Tubing	Frenchtown, NJ	\$40	7,000	\$280,000
Driftstone on the Delaware	Mount Bethel, PA	\$40	5,000	\$200,000
GreenWave Paddling	Yardville, New Jersey	\$40	3,000	\$120,000
Indian Head Canoes & Rafts	Barryville, NY	\$40	5,000	\$200,000
Jerrys Three River Canoes	Pond Eddy, NY	\$40	4,000	\$160,000
Kayak East	East Stroudsburg, PA	\$40	4,000	\$160,000
Kittatinny Canoes, Inc.	Dingmanns Ferry, PA	\$40	4,000	\$160,000
Landers River Trips	Narrowsburg, NY	\$40	15,000	\$600,000
Lazy River Outpost	Phillipsburg, NJ	\$40	4,000	\$160,000
Pack Shack Adventures Inc	Delaware Water Gap, PA	\$40	5,000	\$200,000
Paint Island Canoe & Kayak	Bordentown, NJ	\$40	4,000	\$160,000
Portland Outfitters	Portland, PA	\$40	5,000	\$200,000
River Country	Point Pleasant, PA	\$40	9,000	\$360,000
Shawnee Canoe Trips	Shawnee on Delaware, PA	\$40	12,000	\$480,000
Silver Canoe Rentals	Port Jervis, NY	\$40	4,000	\$160,000
Upper Delaware Campgrounds	Callicoon, NY	\$40	5,000	\$200,000
Whitewater Willies Canoe Rentals	Pond Eddy, NY	\$40	4,000	\$160,000
Wild & Scenic River Tours/Rentals	Barryville, NY	\$40	5,000	\$200,000
<b>Lehigh River</b>				
Jim Thorpe River Adventures	Jim Thorpe, PA	\$40	9,000	\$360,000
Lehigh Rafting Rentals Inc	White Haven, PA	\$40	9,000	\$360,000
Lehigh River Bait and Bow	Allentown, PA	\$40	3,000	\$120,000
Northeast PA Kayak School	Lehighon, PA	\$40	3,000	\$120,000
Pocono Whitewater	Jim Thorpe, PA	\$40	8,000	\$320,000
Whitewater Challengers, Inc.	White Haven, PA	\$40	9,000	\$360,000
Whitewater Rafting Adventures Inc.	Nesquehoning, PA	\$40	6,000	\$240,000
<b>Schuylkill</b>				
Schuylkill River Outfitters	Birdsboro, PA	\$40	4,500	\$180,000
<b>Brandywine River</b>				
Brandywine Outfitters	Coatesville, PA	\$40	3,000	\$120,000
Northbrook Canoe	West Chester, PA	\$40	9,000	\$360,000
Wilderness Canoe Trips	Wilmington, DE	\$40	9,000	\$360,000
<b>Total</b>			<b>225,000</b>	<b>9,000,000</b>

## Powerboating

The National Marine Manufacturers Association (2010) announced that New York, Delaware, Pennsylvania, and New Jersey ranked 3<sup>rd</sup>, 7<sup>th</sup>, 17<sup>th</sup>, and 23<sup>rd</sup> in the U.S. respectively in total expenditures for new powerboats, outboard engines, boat trailers, and accessories. Table 13 summarizes powerboat expenditures by state and then prorated by percent population of each state within the Delaware Basin. Powerboat expenditures due to boating within the waters of the Delaware Basin are estimated at about \$395 million/year

**Table 13.** Recreational powerboat expenditures in the Delaware River Basin  
(NMMA 2010)

State	Rank Expenditures	Total Powerboat Expenditures (\$)	% Pop. of State in Basin	Del. Basin Powerboat Expenditures (\$)
Delaware	7	343,743,963	74%	254,370,533
New Jersey	23	183,044,985	22%	40,269,897
New York	3	401,353,400	0.70%	2,809,474
Pennsylvania	17	226,281,490	43%	97,301,041
<b>Total</b>		<b>1,154,423,838</b>		<b>394,750,944</b>

New York, Pennsylvania, New Jersey, and Delaware are ranked 7<sup>th</sup>, 13<sup>th</sup>, 28<sup>th</sup>, and 40<sup>th</sup> in number of recreational boat registrations in 2009. The four states combined had just over \$1 million boat registrations in 2009 with 232,000 registrations for boating in the Delaware River Basin (Table 14).

**Table 14.** Recreational boat registrations in the Delaware River Basin  
(NMMA 2010)

State	Rank Registrations	Total Boat Registrations	% Pop. of State in Basin	Del. Basin Boat Registrations
Delaware	40	61,523	0.74	45,527
New Jersey	28	173,994	0.22	38,279
New York	7	479,161	0.007	3,354
Pennsylvania	13	337,747	0.43	145,231
<b>Total</b>		<b>1,052,425</b>		<b>232,391</b>

## Water Quality

### Willingness to Pay for Clean Water

Bockstael, McConnell, and Strand (1989) from the University of Maryland estimated public annual willingness to pay for a moderate improvements in water quality of the Chesapeake Bay to be \$10 to \$100 million in 1984 dollars (\$21.6 to \$216 million in \$2010 at 3% annually). The study found 43% of the respondents were users or visitors (boaters, fishermen) to the Chesapeake Bay and were willing to pay \$121 per year to make the bay water quality “acceptable”. About 57% of respondents were nonusers, those who do not visit or use the bay’s resources but were willing to pay \$38 per year to restore the bay. Transferring these values to the estuary watershed portion of the Delaware Basin

(pop. 6,700,000) and using proportions of 10% users or visitors to the estuary and 90% nonusers, aggregate willingness to pay to make the Delaware Estuary water quality acceptable to the public is \$658 million in \$2010 or \$99 per person.

Total willingness to pay for acceptable Delaware Estuary water quality  
 = (0.10)(6,700,000)(\$121/yr) + (0.90)(6,700,000)(\$38/yr)  
 = \$310 million (\$1984) = \$659 million (\$2010 at 3% annually).

### Water Treatment

The Trust for Public Land and American Water Works Association (2004) found for every 10% increase in forested watershed land, drinking water treatment and chemical costs are reduced by approximately 20% (Table 15). The public drinking water supply is 1,803 mgd and forests cover 6,786 sq mi or 53% of the Delaware River Basin. Loss of these forests would increase drinking water treatment costs by \$96 per mil gal (\$139 per mil gal @ 0% forested minus \$43 per mil gal @ 53% forested) or \$173,088 per day for 1,803 mgd = \$63,177,120 per year.

**Table 15.** Drinking water treatment and chemical costs based on percent of forested watershed (Trust for Public Land and AWWA 2004)

% of Watershed Forested	Water Treatment/ Chemical Costs (per mil gal)	% Change in Costs
0%	\$139	21%
10%	\$115	19%
20%	\$93	20%
30%	\$73	21%
40%	\$58	21%
50%	\$46	21%
60%	\$37	19%

### Wastewater Treatment

The waters of the Delaware Basin provide significant wastewater treatment, discharge, and assimilation services. In accordance with Federal Clean Water Act, DRBC, and state water quality regulations, NPDES municipal wastewater dischargers hold permits to discharge up to 1,180 million gallons per day to the Delaware River Basin or 106 mgd in Delaware, 218 mgd in New Jersey, 7 mgd in New York, and 849 mgd in Pennsylvania (Table 16). The average wastewater rate in the basin is \$4.00 per 1000 gal. The fee for an average residence of 4 people @ 50 gpcd is \$290 per year. The value of treated wastewater in the Delaware Basin is \$4.7 million per day or \$1.7 billion per year.

**Table 16.** Value of NPDES wastewater treatment discharges in the Delaware River Basin

NPDES ID	Facility	Location	State	Flow <sup>1</sup> (mgd)	Value <sup>2</sup> (\$/day)	Wastewater Value (\$/year)
DE0020338	Kent Co. Levy Court WWTR	Frederica	DE	15.0	60000	21900000
DE0021512	Lewes City POTW	Lewes	DE	0.8	3,200	1,168,000
DE0020320	Wilmington Wastewater Plant	Wilmington	DE	90.0	360,000	131,400,000
<b>Delaware</b>			<b>DE</b>	<b>105.8</b>	<b>423,200</b>	<b>154,468,000</b>

NJ0027481	Beverly City Sewer Auth. STP	Beverly	NJ	1.0	4,000	1,460,000
NJ0024678	Bordentown Sewerage Auth.	Bordentown	NJ	3.0	12,000	4,380,000
NJ0024651	Cumberland Co. Auth. WWTP	Bridgeton	NJ	7.0	28,000	10,220,000
NJ0024660	Burlington City STP	Burlington	NJ	2.7	10,800	3,942,000
NJ0021709	Burlington Twp. DPW	Burlington	NJ	1.6	6,400	2,336,000
NJ0026182	Camden County MUA	Camden	NJ	80.0	320,000	116,800,000
NJ0021601	Carneys Point Twp. WWTP	Carneys Point	NJ	1.3	5,200	1,898,000
NJ0024007	Cinnaminson Sewerage Auth.	Cinnaminson	NJ	2.0	8,000	2,920,000
NJ0023701	Florence Twp. DPW Sewer Auth.	Florence	NJ	2.5	10,000	3,650,000
NJ0026301	Hamilton Twp. DPW	Hamilton Twp.	NJ	16.0	64,000	23,360,000
NJ0020915	Lambertville City Sewer Auth.	Lambertville	NJ	1.5	6,000	2,190,000
NJ0024759	Ewing Lawrence Sewer WWTP	Lawrenceville	NJ	16.0	64,000	23,360,000
NJ0069167	Maple Shade Twp. Util. Authority	Maple Shade	NJ	3.4	13,600	4,964,000
NJ0026832	Medford Twp. Sewer Auth. STP	Medford	NJ	1.8	7,200	2,628,000
NJ0029467	Millville City Sewer Auth.	Millville	NJ	5.0	20,000	7,300,000
NJ0024996	Moorestown Twp. WWTP	Moorestown	NJ	3.5	14,000	5,110,000
NJ0024015	Mount Holly Twp. MUA	Mount Holly	NJ	7.7	30,800	11,242,000
NJ0020184	Newton Town DPW	Newton	NJ	1.4	5,600	2,044,000
NJ0024821	Pemberton Twp. MUA STP	Pemberton	NJ	2.5	10,000	3,650,000
NJ0024023	Penns Grove Sewerage Auth.	Penns Grove	NJ	0.8	3,200	1,168,000
NJ0021598	Pennsville Twp. Sewer Auth.	Pennsville	NJ	1.9	7,600	2,774,000
NJ0024716	Phillipsburg Town STP	Phillipsburg	NJ	3.5	14,000	5,110,000
NJ0022519	Riverside Twp. DPW	Riverside	NJ	1.0	4,000	1,460,000
NJ0024856	Salem WWTP Facility	Salem	NJ	1.4	5,600	2,044,000
NJ0024686	Gloucester Co. Util. Auth. STP	Thorofare	NJ	24.1	96,400	35,186,000
NJ0020923	Trenton City DPW Sewer Auth.	Trenton	NJ	20.0	80,000	29,200,000
NJ0023361	Willingboro Twp. MUA	Willingboro	NJ	5.2	20,800	7,592,000
<b>New Jersey</b>				<b>217.8</b>	<b>871,200</b>	<b>317,988,000</b>
NY0020265	Delhi WWTP	Delhi	NY	0.8	3,200	1,168,000
NY0030074	Liberty WWTF	Liberty	NY	1.6	6,400	2,336,000
NY0022454	Monticello STP	Monticello	NY	3.1	12,400	4,526,000
NY0029271	Sidney WWTP	Sidney	NY	1.7	6,800	2,482,000
<b>New York</b>				<b>7.2</b>	<b>28,800</b>	<b>10,512,000</b>
PA0026867	Abington Twp. STP	Abington	PA	3.9	15,600	5,694,000
PA0026000	Allentown City WWTP	Allentown	PA	40.0	160,000	58,400,000
PA0026042	Bethlehem City STP	Bethlehem	PA	90.0	360,000	131,400,000
PA0021181	Bristol Borough Water and Sewer	Bristol	PA	1.2	4,800	1,752,000
PA0027103	Delaware Co. Reg. Water Auth.	Chester	PA	44.0	176,000	64,240,000
PA0026859	Coatesville WWTP	Coatesville	PA	3.8	15,200	5,548,000
PA0026794	Conshohocken Borough Auth.	Conshohocken	PA	2.3	9,200	3,358,000
PA0026531	Downingtown Regional WPCC	Downingtown	PA	7.1	28,400	10,366,000
PA0026549	Borough of Doylestown WWTP	Doylestown	PA	28.5	114,000	41,610,000
PA0027235	Easton Area Joint Auth. WWTP	Easton, PA	PA	10.0	40,000	14,600,000
PA0029441	Upper Dublin Twp. MS4 UA	Ft. Washington	PA	1.1	4,400	1,606,000
PA0051985	Horsham Twp. STP	Horsham	PA	1.0	4,000	1,460,000
PA0024058	Kennett Square Borough WWTP	Kennett Square	PA	1.1	4,400	1,606,000
PA0026298	Whitemarsh STP	Lafayette Hill	PA	2.0	8,000	2,920,000
PA0026182	Lansdale Borough STP	Lansdale	PA	2.6	10,400	3,796,000
PA0039004	U. Gwynedd/Towamencin STP	Lansdale	PA	6.5	26,000	9,490,000
PA0026468	Morrisville Municipal Authority	Morrisville	PA	10.0	40,000	14,600,000
PA0027421	Norristown Borough WWTP	Norristown	PA	9.8	39,200	14,308,000
PA0020532	Upper Montgomery Joint Sewer	Pennsburg	PA	2.0	8,000	2,920,000

PA0026689	Northeast WPCP	Philadelphia	PA	210.0	840,000	306,600,000
PA0026662	Philadelphia Southeast POTW	Philadelphia	PA	112.0	448,000	163,520,000
PA0026671	SW Water Pollution Control	Philadelphia	PA	200.0	800,000	292,000,000
PA0020460	Quakertown WWTP	Quakertown	PA	4.3	17,200	6,278,000
PA0026549	Reading WWTP	Reading	PA	28.5	114,000	41,610,000
PA0020168	East Stroudsburg Filtration Plant	Stroudsburg	PA	2.3	9,200	3,358,000
PA0029289	Stroudsburg STP	Stroudsburg	PA	2.5	10,000	3,650,000
PA0027031	Goose Creek STP	West Chester	PA	1.7	6,800	2,482,000
PA0026018	West Chester Taylor Run STP	West Chester	PA	1.8	7,200	2,628,000
PA0028584	West Goshen STP	West Chester	PA	6.0	24,000	8,760,000
PA0023256	Upper Gwynedd Twp. WWTP	West Point	PA	5.7	22,800	8,322,000
PA0025976	Upper Moreland Hatboro Sewer	Willow Grove	PA	7.2	28,800	10,512,000
<b>Pennsylvania</b>			<b>PA</b>	<b>848.9</b>	<b>3,395,600</b>	<b>1,239,394,000</b>
<b>Delaware Basin</b>			<b>Basin</b>	<b>1,179.7</b>	<b>4,718,800</b>	<b>1,722,362,000</b>

1. DRBC and USEPA. 2. Value at @ \$4.00/1000 gal

### Increased Property Values

Several studies along rivers, estuaries, and coasts throughout the United States indicate that improved water quality can increase shoreline property values by 6% to 25% (Table 17). The EPA (1973) estimated that improved water quality can raise property values by up to 18% next to the water, 8% at 1000 feet from the water, 4% at 2000 feet from the water, and 1.5% at 3000 feet from the water. Leggett, et al. (2000) estimated that improved bacteria levels to meet state water quality standards along the western shore of the Chesapeake Bay in Maryland raised shoreline property values by 6%. The Brookings Institution (2007) projected that investments of \$26 billion to restore the Great Lakes would increase shoreline property values by up to 10%. For this analysis, shoreline property values within 2000 feet of the waterways are estimated to increase by an average of 8% due to improved water quality in the Delaware Estuary.

Shoreline property values within 2000 feet of the water due to water quality improvements in the Delaware Estuary watershed will increase by \$256 million (Table 18). The average riverfront property value in Philadelphia is \$92,000 per acre. Multiply this value by the area of property within a 2,000 feet corridor along the Delaware Estuary shore between the C&D Canal and head of tide at Trenton. Multiply by increased property value of 8% due to improved water quality in the Delaware Estuary. Since the increase in property value is a one time benefit, the annual value over a 20 year period where water quality has improved in the Delaware Estuary is estimated as \$13 million.

**Table 17.** Increased property values resulting from improved water quality

Study	Watershed	Increased Value
EPA (1973)	San Diego Bay, CA Kanawha, OH Willamette R., OR	
Next to water		18%
1000 ft from water		8%
2000 ft from water		4%
3,000 ft from water		1.5%
Leggett, et al. (2000)	Chesapeake Bay	6%
Brookings Institution (2007)	Great Lakes	10%

**Table 18.** Increased shore property value due to improved water quality in the Delaware Basin

State	Length of shoreline (ft)	Area 2000 ft of water (sf)	Area 2000 ft of water (ac)	Property Value @ \$92,000/ac (\$)	Increased Property Value @ 8% (\$)
Delaware	114,048	228,096,000	5,236	481,745,455	38,539,636
New Jersey	357,456	714,912,000	16,412	1,509,915,152	120,793,212
Pennsylvania	285,648	571,296,000	13,115	1,206,593,939	96,527,515
Delaware Estuary	757,152	1,514,304,000	34,764	3,198,254,545	255,860,364

## Water Supply

### Drinking Water Supply

The Delaware Basin covers just 0.4% of the continental United States (12,769 sq mi/3,000,000 sq mi) yet supplies drinking water to 5% of the U.S. population (16,000,000/309,000,000 people). Delaware Basin aquifers and streams supply drinking water to over 8 million people within the basin to cities like Wilmington, Philadelphia, Allentown, Camden, and Trenton, NJ. Through interbasin transfers, the Delaware Basin also supplies drinking water to an additional 8 million people who live outside the basin by allocated diversions through the New York City Catskill Reservoir system (800 mgd) and the Delaware & Raritan Canal in New Jersey (100 mgd). Table 19 summarizes the economic benefits of groundwater reserve stock to generate ecosystem services (USEPA 1995).

**Table 19.** Groundwater services and effects (USEPA 2005)

Services	Effects
Drinking Water	Increase or decrease in availability of drinking water Change in human health or health risks
Water for Crop Irrigation	Change in value of crops or production costs Change in human health or health risks
Water for Livestock/Poultry	Change in Value of livestock products or production Change in human health or health risks

The Delaware Basin provides significant public drinking water supplies (1,804 mgd) with 44% in NY (800 mgd), 38% from Pa. (679 mgd), 16% from NJ (284 mgd), and 2% from Del. (40 mgd), Figure 6. The largest public water supply allocations in the Delaware Basin include United Water Delaware and Wilmington in Del.; Delaware & Raritan Canal diversion, New Jersey American, Trenton, and Camden in NJ; New York City, and Philadelphia and Aqua Pennsylvania in Pa. (Table 20). Figure 7 depicts public water supply service areas in the Delaware River Basin.

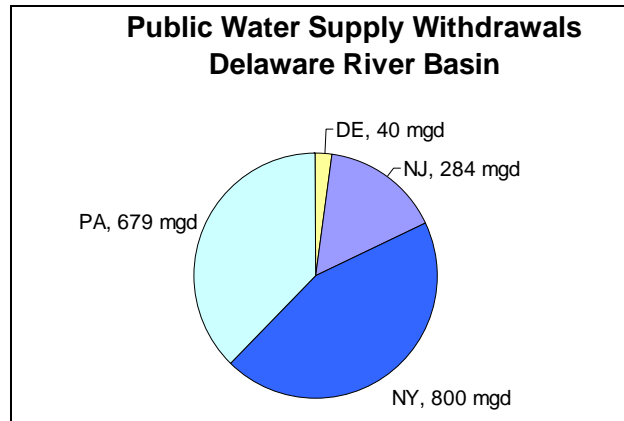
The annual value of raw (untreated) public water supply allocations in the Delaware Basin (1,803 mgd) is \$658 million. When treated and delivered to customers the annual value of drinking water supplies is \$3.14 billion (Table 21). Water purveyors in Delaware estimate the value of raw water supply is \$1.00/1000 gallons according to cost of services studies for rate setting by the Public Service Commission. In FY13, the New Jersey Water Supply Authority plans to sell raw water supplies from the Manasquan Reservoir system for \$1.02/1000 gallons (NJWSA 2011). The average value of treated drinking water based on rates set by public/private water purveyors in Del., NJ, Pa., and Md. is \$4.78/1000 gallon (Corrozi and Seymour 2008).

**Table 20.** Public water supply allocations in the Delaware River Basin (DRBC 2010)

Water Purveyor	Supply (mgd)	Water Purveyor	Supply (mgd)	Water Purveyor	Supply (mgd)
<b>Delaware</b>	<b>40.10</b>				
United Water Del.	18.46	Harrington	0.36	Frederica Perkiomen	0.05
Wilmington	10.40	Camden-Wyoming	0.31		
Dover	4.74	Milton	0.17		
Newark	2.22	Milford	0.17		
Lewes BPW	0.98	Georgetown	0.13		
Tidewater Utilities	0.64	Frederica	0.08		
Dover AFB	0.44	Felton	0.08		
New Castle MSC	0.41	Delaware State Fair	0.05		
Smyrna	0.37	Magnolia	0.05		
<b>New Jersey</b>	<b>284.19</b>				
Del. & Raritan Canal	100.00	Hackettstown MUS	2.57	Medford Twp.	1.29
NJ American Western	39.37	Millville Water Dept	2.55	NJ American Oxford	1.20
Trenton	26.10	Moorestown	2.51	Florence Twp.	1.17
Camden	10.89	Bordentown	2.21	Salem City	1.12
Vineland	8.33	Burlington Twp.	2.00	Mantua Twp.	1.04
Merchant.-Pennsauken	6.05	Mt. Laurel	1.96	Pennsville Twp.	1.04
Washington Twp.	4.79	Glassboro	1.95	Pemberton Twp.	1.01
Willingboro MUA	4.65	Collingswood	1.93	Gloucester City	0.95
NJ American Mt. Holly	4.48	Maple Shade	1.64	Lower Twp MUA	0.95
Bridgeton	3.63	West Deptford	1.57	Sparta Twp.	0.94
Wildwood	3.59	Woodbury	1.55	Audubon Twp.	0.91
Aqua NJ Phillipsburg	3.46	Burlington City	1.47	Haddon Twp.	0.90
Aqua NJ Hamilton Sq.	3.39	Pennsgrove	1.42	Bellmawr Twp.	0.86
Aqua NJ Blackwood	2.96	Deptford Twp.	1.38	Haddonfield	0.82
Evesham MUA	2.82	Nesquehoning Boro	1.30	Greenwich Twp	0.82
				Misc. Water Purveyors	16.65
<b>New York State</b>	<b>800.03</b>				
New York City	800.00				
<b>Pennsylvania</b>	<b>679.30</b>				
Philadelphia	287.77	Easton Suburb.Water	4.47	Falls Twp.	2.66
Aqua PA Main System	102.18	Schuylkill Co. Auth.	4.36	Northampton Bucks	2.55
Forest Park	20.16	Muhlenberg Twp.	4.31	Warminster Twp.	2.54
Bethlehem	15.69	Lehigh County	4.22	Horsham Water/Sewer	2.30
Allentown	15.46	PA American Nazareth	4.13	Newtown Artesian	2.24
North Wales Water	15.09	Hazleton	4.12	Milford	1.88
Bucks Co. Water	14.99	PA Amer. Coatesville	4.07	Tamaqua MWA	1.87
Reading Area Auth.	14.31	Allentown City	4.02	Lehighton MWA	1.77
Bucks County SW	13.79	Northampton Boro.	3.74	Ambler Boro	1.75
PA Amer. Norristown	10.10	East Stroudsburg	3.69	Brodhead Cr. Auth.	1.73
Lower Bucks County	8.66	PA American Yardley	3.20	South Whitehall Twp.	1.71
North Penn Water	8.59	Phoenixville	3.01	Emmaus Munic. Water	1.49
Easton	7.13	Morrisville	2.89	Warrington Twp.	1.45
Schuylkill Co. Auth.	5.15	PA American Home	2.88	Wyomissing Boro	1.44
Pottstown Water Auth.	4.64	PA American Penn	2.76	Schuylkill Haven Boro.	1.42
				Misc. Water Purveyors	50.93

**Table 21.** Value of public drinking water supply allocations in the Delaware River Basin

State	Withdrawal (mgd)	Value/day untreated (\$1.00/1000 gal)	Value/year untreated (\$1.00/1000 gal)	Value/year treated (\$4.78/1000 gal)
Delaware	40	40,000	14,600,000	69,788,000
New Jersey	284	284,000	103,660,000	495,494,800
New York	800	800,000	292,000,000	1,395,760,000
Pennsylvania	679	679,000	247,835,000	1,184,651,300
<b>Delaware Basin</b>	<b>1,803</b>	<b>1,803,000</b>	<b>658,095,000</b>	<b>3,145,694,100</b>



**Figure 6.** Public water supply withdrawals in the Delaware River Basin (DRBC)

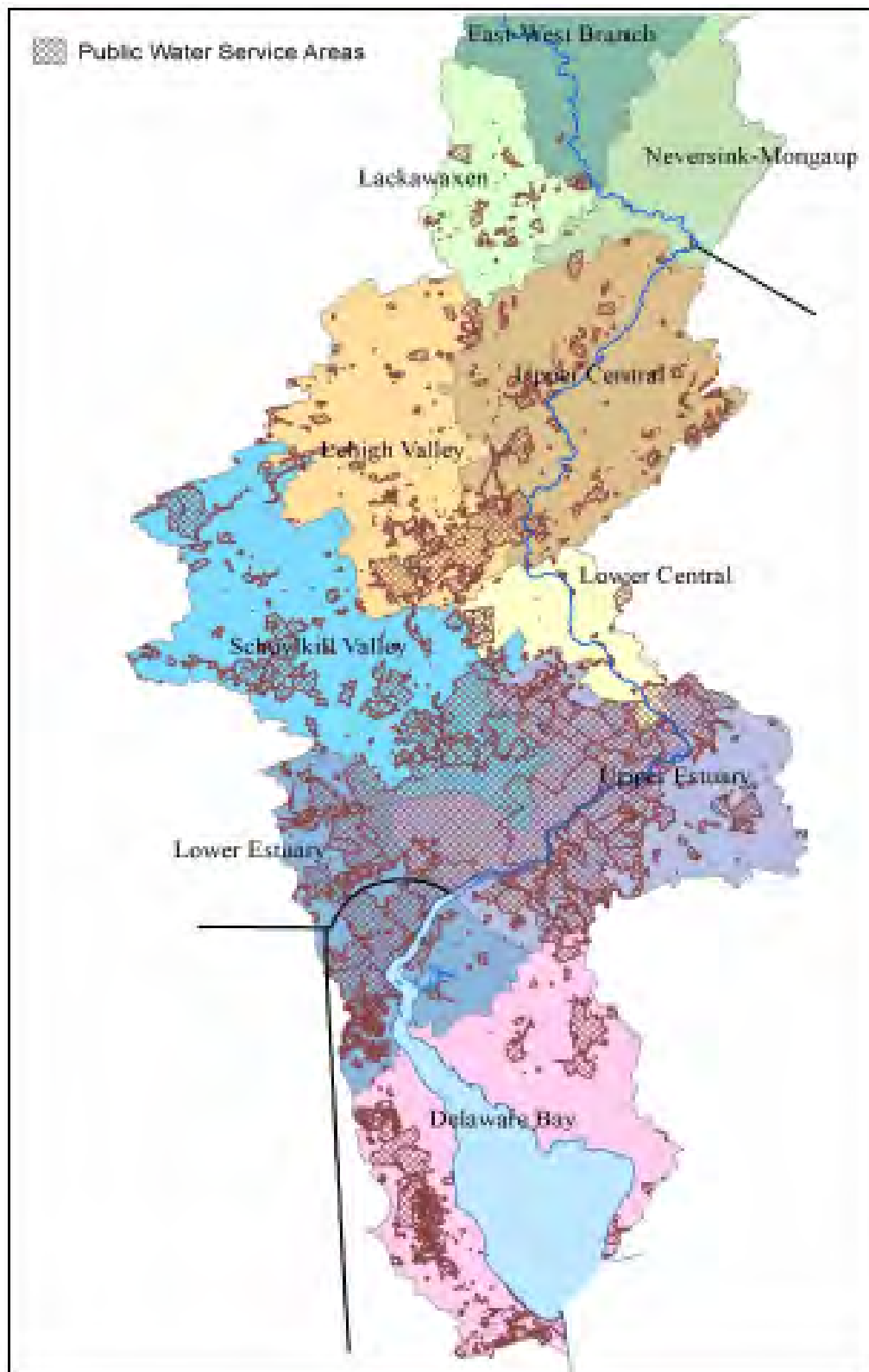
#### Reservoir Storage

Almost 369 billion gallons of water is stored in reservoirs for interstate flow management and drinking water supply in the Delaware Basin (Table 22). The New Jersey Water Supply Authority operates a reservoir system and Delaware & Raritan Canal diversion from the Delaware River to New Jersey. The NJWSA delivers untreated water to public water purveyors from the Raritan River reservoir system at an estimated market price of \$0.394/1,000 gallons (NJWSA 2011). Given the raw water value of drinking water before treatment) is \$0.394/1000 gallons, the annual value of reservoir storage for flow management purposes in the Delaware Basin is \$145 million.

**Table 22.** Economic value of reservoir storage in the Delaware River Basin

Reservoir	Storage (BG)	Value (\$0.394/1000 gal)
Pepacton	140	55,160,000
Cannonsville	96	37,824,000
Neversink	35	13,790,000
Mongaup	15	5,910,000
Merrill Creek	16	6,304,000
Hoopes	2	788,000
Marsh Creek	4	1,576,000
Blue Marsh	6	2,561,000
Beltzville	13	5,122,000
F. E. Walter	11	4,334,000
L.Waullenpaupack	30	11,820,000
<b>Total</b>	<b>368</b>	<b>145,189,000</b>





**Figure 7.** Public water supply service areas in the Delaware River Basin (DRBC 2011)

## Irrigation Water Supply

Agricultural irrigation withdrawals allocated by DRBC total 36.5 mgd. The DRBC allocates groundwater withdrawals over 100,000 gpd therefore many small irrigation wells are not included in this total. Resources for the Future studied the economic value of freshwater in the U.S. estimated the median value of irrigation water withdrawals is \$198/ac-ft in \$1996 (Frederick et al. 1996) or \$300/ac-ft (\$0.92/1000 gal) in \$2010 adjusting for 3% annually (Table 23). The value of irrigation withdrawals based on DRBC allocations is \$33,630 per day or \$12,275,000 per year (Table 24).

**Table 23** Freshwater values in the United States by use

Use	2006 Median <sup>1</sup> (\$/ac-ft)	2010 Median <sup>2</sup> (\$/ac-ft)	2010 Median (\$/1000 gal)
Hydropower	21	32	0.10
Industrial Process	132	200	0.61
Irrigation	198	300	0.92
Navigation	10	15	0.02
Thermoelectric Power	29	44	0.14

1. Frederick et al. 1996. 2. Adjusted to \$2010 at 3% annually.

**Table 24.** Value of agricultural irrigation supply in the Delaware River Basin

Watershed	Withdrawal (mgd)	Irrigation Value/day (\$0.92/1000 gal)	Irrigation Value/year (\$0.92/1000 gal)
Upper Region	0.65	597	217,731
Upper Central	4.91	4,515	1,647,916
Lehigh Valley	0.20	184	67,118
Lower Central	1.51	1,389	507,084
Schuylkill Valley	0.02	23	8,358
Upper Estuary	4.15	3,819	1,394,036
Lower Estuary	7.58	6,976	2,546,164
Delaware Bay	17.53	16,128	5,886,540
Delaware Basin	<b>36.55</b>	<b>33,630</b>	<b>12,274,946</b>

Over 209,882 acres or 7% of cropland are irrigated in Delaware Basin counties (USDA 2009). About 1,926,524 acres or 24% of the basin is farmland, therefore, by proportion about 141,138 acres are irrigated (Table 25). Annual irrigation water needs from June - September are 9 inches for corn, soybeans, and grain (2,600 gpd/ac, 366 mgd). The economic value of water to irrigate 141,138 acres is \$31.8 million, or \$13.8 million in Del., \$14.3 million in NJ, 0.9 million in NY, and \$2.7 million in Pa.. The value of irrigation water demand = (9 in/12 in/ft)(141,138)(\$300/ac-ft) = \$31,756,104/yr.

**Table 25.** Value of agriculture irrigation water demand in the Delaware River Basin

County	Cropland by county <sup>1</sup> (ac)	Irrigation by county <sup>1</sup> (ac)	Farmland in basin (ac)	Irrigated land in basin (ac)	Value of irrigation <sup>2</sup> @ \$300/ac-ft
New Castle	51,913	2,711			
Kent	146,536	29,066			
Sussex	234,324	72,785			
<b>Delaware</b>	<b>432,773</b>	<b>104,562</b>	<b>254,143</b>	<b>61,403</b>	<b>\$13,815,748</b>
Burlington	85,790	12,620			
Camden	8,760	2,647			
Cape May	7,976	2,342			
Cumberland	69,489	18,357			
Gloucester	46,662	12,891			
Hunterdon	100,027	1,501			
Mercer	21,736	1,028			
Monmouth	44,130	5,976			
Ocean	9,833	1,090			
Salem	96,530	18,001			
Sussex	65,242	454			
Warren	74,975	2,426			
<b>New Jersey</b>	<b>631,150</b>	<b>79,333</b>	<b>505,507</b>	<b>63,540</b>	<b>\$14,296,541</b>
Broome	86,613	150			
Delaware	165,572	65			
Greene	44,328	735			
Orange	80,990	4,560			
Sullivan	50,443	75			
Ulster	75,205	4,707			
<b>New York</b>	<b>503,151</b>	<b>10,292</b>	<b>187,561</b>	<b>3,837</b>	<b>\$863,230</b>
Berks	170,760	1,260			
Bucks	58,012	1,421			
Carbon	20,035	132			
Chester	117,145	1,659			
Delaware	1,646	36			
Lackawanna	39,756	258			
Lancaster	326,648	5,366			
Lebanon	89,566	1,276			
Lehigh	72,737	1,189			
Luzerne	66,577	60			
Monroe	29,165	97			
Montgomery	28,563	668			
Northampton	68,252	247			
Philadelphia	150	0			
Pike	27,569	12			
Schuylkill	81,276	1,896			
Wayne	99,939	118			
<b>Pennsylvania</b>	<b>1,297,796</b>	<b>15,695</b>	<b>979,313</b>	<b>11,843</b>	<b>\$2,664,765</b>
<b>Total</b>	<b>2,864,870</b>	<b>209,882</b>	<b>1,926,524</b>	<b>141,138</b>	<b>\$31,756,104</b>

1. Census of Agriculture 2007 (USDA 2009). 2. Frederick, VandenBerg, and Hansen 1996.

### Thermoelectric Power Water Supply

Cooling water withdrawals for thermoelectric power plants in the Delaware Basin provide significant economic value. Over 89% of the energy in the United States is produced by thermoelectric power plants which evaporate water during cooling of condensate. The Delaware Basin provides 5,809

mgd of cooling water to run nuclear, coal, and gas fired power plants to generate 13,458 megawatts of electricity along the Delaware, Schuylkill, and Lehigh. About 95% of the cooling water returns to the river or bay (nonconsumptive use) and 5% evaporates (consumptive use). Table 26 lists power plants and associated cooling water withdrawals within the Delaware Basin obtained from U. S. Energy Information Administration (2002) and U.S. National Energy Technology Laboratory (2009) inventories of electric utility power plants and DRBC water allocation dockets.

Resources for the Future in a study of the economic value of freshwater in the United States estimated the median \$1996 value of thermoelectric power water withdrawals is \$29/ac-ft (\$0.09/1000 gal) with a range of \$9 to \$63/ac-ft (Frederick et al. 1996). Adjusting for 3% annually, the median \$2010 value of thermoelectric plant water withdrawals is \$44 per ac-ft or \$0.14/1000 gal. At \$0.14/1000 gal, the value of thermoelectric water withdrawals in the Delaware Basin is \$297 million/yr or \$24 million/yr in Delaware, \$196 million/yr in New Jersey, and \$77 million/yr in Pennsylvania (Table 27).

**Table 26.** Thermoelectric power plant water withdrawals in the Delaware River Basin

State/Power Plant	Type	Capacity <sup>1</sup> (megawatts)	Withdrawal (mgd)	Value/day <sup>2</sup> (\$0.14/1000 gal) <sup>1</sup>	Value/year (\$0.14/1000 gal)
<b>Delaware</b>		<b>1,009</b>	<b>479</b>	<b>67,060</b>	<b>24,476,900</b>
Delmarva Delaware City		9	9		
Conectiv Edgemoor	Coal/Gas	1,000	470		
<b>New Jersey</b>		<b>4,920</b>	<b>3,830</b>	<b>536,200</b>	<b>195,713,000</b>
PSEG Salem 1 and 2	Nuclear	2,275	2,643		
PSEG Hope Creek	Nuclear	1,268	52		
Chambers Cogen. Salem	Coal	285			
Deepwater Station	Coal	82	219		
Logan Generating	Coal	242	38		
PSEG Mercer Trenton	Coal	768			
<b>Pennsylvania</b>		<b>7,529</b>	<b>1,500</b>	<b>210,000</b>	<b>76,650,000</b>
PECO Chester	Coal	56			
PECO Cromby	Coal	417			
PECO Croyden	Coal	546			
PECO Delaware (Phila.)	Coal	392			
PECO Eddystone	Coal	1,448			
PECO Fairless Hills	Coal	75			
PECO Falls	Coal	64			
PECO Limerick	Nuclear	2,230			
PECO Moser	Coal	64			
PECO Richmond (Phila.)	Coal	132			
PECO Schuylkill (Phila.)	Oil	233			
PECO Southwark (Phila.)	Coal	74			
PGE Northamp. Lehigh	Coal	134			
PPL Martins Creek	Coal	1,664	Shut 2007		
<b>Delaware Basin</b>		<b>13,458</b>	<b>5,809</b>	<b>813,260</b>	<b>296,839,900</b>

1. EIA 2002, NETL 2009, and DRBC. 2. Frederick et al. 1996 adjusted to \$2010 at 3% annually.

**Table 27.** Value of thermoelectric power withdrawals in the Delaware River Basin

Watershed	Withdrawal <sup>1</sup> (mgd)	Value/day <sup>2</sup> (\$0.14/1000 gal)	Value/year (\$0.14/1000 gal)
Upper Region	0	0	0
Upper Central	394	55,160	20,133,400
Lehigh Valley	2	280	102,200
Lower Central	24	3,360	1,226,400
Schuylkill Valley	232	32,480	11,855,200
Upper Estuary	1,461	204,540	74,657,100
Lower Estuary	3,696	517,440	188,865,600
Delaware Bay	0	0	0
<b>Delaware Basin</b>	<b>5,809</b>	<b>813,260</b>	<b>296,839,900</b>

1. DRBC. 2. Frederick et al. 1996 adjusted to \$2010 at 3% annually)

### Industrial Water Supply

Industrial water withdrawals allocated by DRBC total 804 mgd in the Delaware River Basin (Table 28). A study of the economic value of freshwater in the U.S. indicates the median value of industrial withdrawals is \$132/ac-ft in \$1996 (Frederick et al. 1996) or \$200/ac-ft (\$0.61/1000 gal) in \$2010 adjusting for 3% annually. The value of industrial withdrawals based on DRBC allocated supplies is \$490,684 per day or \$179,099,660 per year.

**Table 28.** Value of industry process water withdrawals in the Delaware River Basin

Watershed	Withdrawal <sup>1</sup> (mgd)	Industry Value/day <sup>2</sup> (\$0.61/1000 gal)	Industry Value/year (\$0.61/1000 gal)
Upper Region	0	0	0
Upper Central	31	18,727	6,835,355
Lehigh Valley	73	44,591	16,275,715
Lower Central	71	43,188	15,763,620
Schuylkill Valley	40	24,583	8,972,795
Upper Estuary	132	80,703	29,456,595
Lower Estuary	446	271,877	99,235,105
Delaware Bay	12	7,015	2,560,475
<b>Delaware Basin</b>	<b>804</b>	<b>\$490,684</b>	<b>\$179,099,660</b>

1. DRBC water allocations. 2. Frederick et al. 1996 adjusted to \$2010 at 3% annually

### Hydropower Water Supply

Hydropower water supply withdrawals allocated by DRBC total 539 mgd in the upper Delaware Basin at the Delaware Water Gap at Yards Creek and above Pt. Jervis (Table 29). A study of the economic value of freshwater in the U.S. indicates the median value of hydropower withdrawals is \$21/ac-ft in \$1996 (Frederick et al. 1996) or \$32/ac-ft (\$0.10/1000 gal) in \$2010 adjusting for 3%

annually. The value of hydropower water withdrawals based on DRBC allocated supplies is \$53,879 per day or \$19,662,550 per year.

**Table 29.** Value of hydroelectric water supplies in the Delaware River Basin

<b>Watershed</b>	<b>Withdrawal<sup>1</sup> (mgd)</b>	<b>Hydropower Value/day<sup>2</sup> (\$0.10/1000 gal)</b>	<b>Hydropower Value/year (\$0.10/1000 gal)</b>
Upper Region	393	39,330	14,355,450
Upper Central	145	14,540	5,307,100
Lehigh Valley	0	0	0
Lower Central	0	0	0
Schuylkill Valley	0	0	0
Upper Estuary	0	0	0
Lower Estuary	0	0	0
Delaware Bay	0	0	0
<b>Delaware Basin</b>	<b>539</b>	<b>53,870</b>	<b>19,662,550</b>

1. DRBC water allocations. 2. Frederick et al. 1996 adjusted to \$2010 at 3% annually

## Fish/Wildlife

### Fish Landings

The annual value of fish landings (Table 30) in the tidal Delaware River and Bay is \$25.4 million in \$2000 or \$34.1 million in \$2010 as reported to the National Marine Fisheries Service and tabulated by the National Ocean Economics Program (2007). Table 31 ranks the most lucrative fisheries in the Delaware Estuary as blue crab (\$14.4 million/yr), summer flounder (\$5.3 million/yr), Atlantic menhaden (\$4.3 million/yr), eastern oyster (\$3.7 million/yr), striped bass (\$2.3 million/yr), and American eel (\$0.8 million/yr). Figure 8 charts fish landings for Delaware Estuary species.

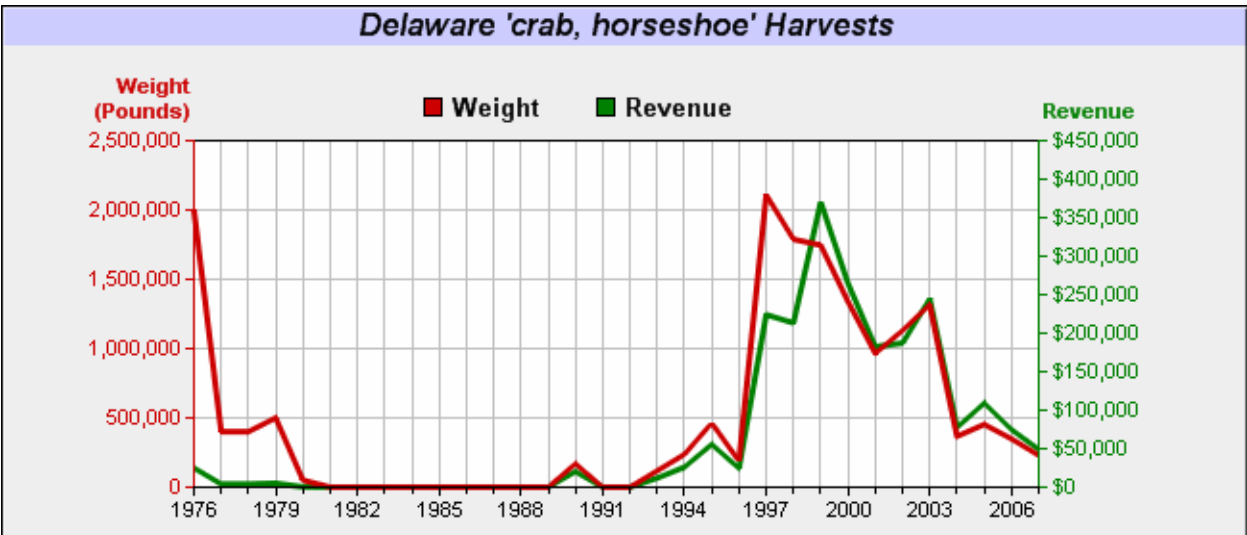
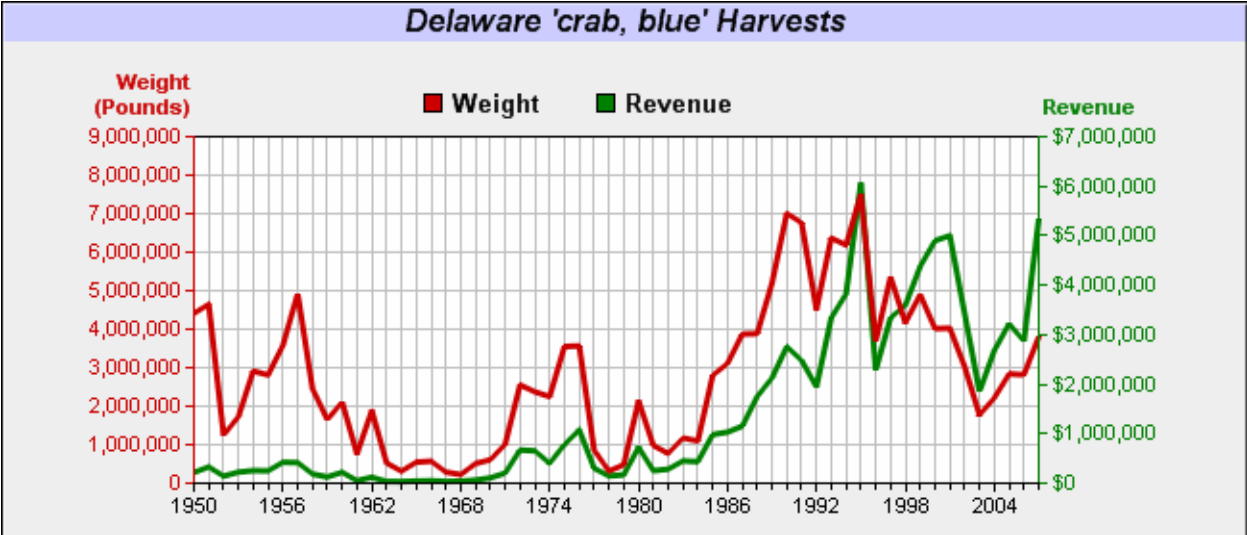
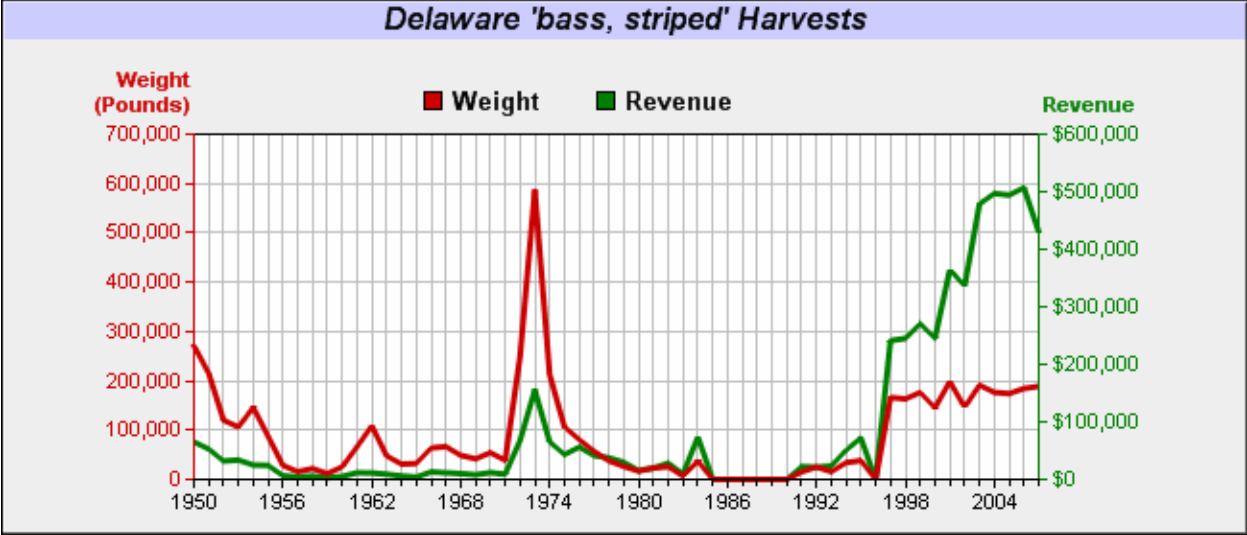
**Table 30.** Fish landings and landed value in the Delaware Estuary in \$2000

Delaware Estuary Species <sup>1</sup>	Delaware		New Jersey		Pennsylvania		Delaware Estuary	
	Pounds	Value (\$2000)	Pounds	Value (\$2000)	Pounds	Value (\$2000)	Pounds <sup>2</sup>	Value <sup>2</sup> (\$2000)
Bass, Striped	188,671	\$429,994	564,000	\$1,287,000	211	\$378	752,882	\$1,717,372
Bluefish	19,565	\$8,075	1,403,717	\$500,053			1,423,282	\$508,128
Carp, Common	3,764	\$865			6,724	\$26,805	10,488	\$27,670
Catfish, Channel	6,922	\$3,929					6,922	\$3,929
Crab, Blue	3,799,820	\$5,329,182	4,636,368	\$5,471,115			8,436,188	\$10,800,297
Crab, Horseshoe	229,602	\$48,978					229,602	\$48,978
Drum, Black	37,712	\$21,867	1,518	\$444			39,230	\$22,311
Eel, American	139,648	\$315,094	159,292	\$310,417			298,940	\$625,511
Flounder, Summer	5,464	\$11,119	1,697,513	\$3,988,869			1,702,977	\$3,999,988
Herring, Blueback	1,434	\$609					1,434	\$609
Herring, Atlantic			6,039,473	\$563,083			6,039,473	\$563,083
Menhaden, Atlantic	85,080	\$6,635	37,634,929	\$3,193,724			37,720,009	\$3,200,359
Oyster, Eastern	79,933	\$490,465	444,227	\$2,230,835			524,160	\$2,721,300
Perch, White	55,973	\$46,865	27,527	\$29,654	4,560	\$7,981	88,060	\$84,500
Perch, Yellow					20,527	\$71,847	20,527	\$71,847
Shad, American	71,445	\$42,408	58,981	\$77,015			130,426	\$119,423
Shellfish	30,130	\$76,119					30,130	\$76,119
Snails (Conchs)			30,250	\$59,016			30,250	\$59,016
Weakfish	24,604	\$36,177	164,506	\$225,051			189,110	\$261,228
Whelk, Chan'd/Knob	277,217	\$511,172					277,217	\$511,172
<b>Total</b>	<b>5,056,984</b>	<b>\$7,379,553</b>	<b>52,862,301</b>	<b>\$17,936,276</b>	<b>32,022</b>	<b>\$107,011</b>	<b>57,951,307</b>	<b>\$25,422,840</b>

1. Dove and Nyman 1995. 2. NMFS and National Ocean Economics Program 2007.

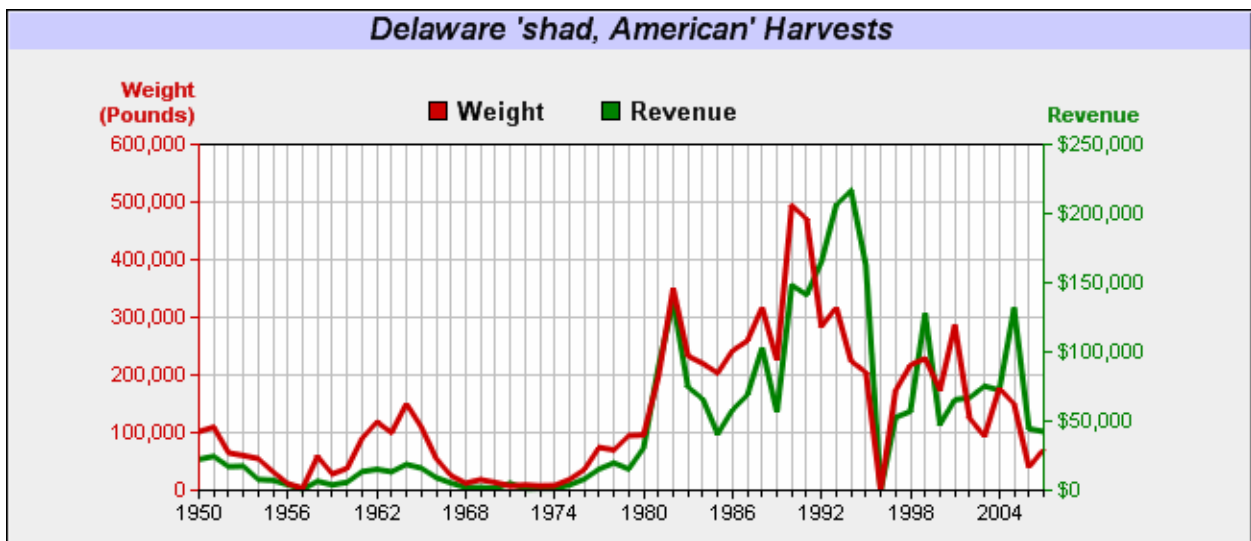
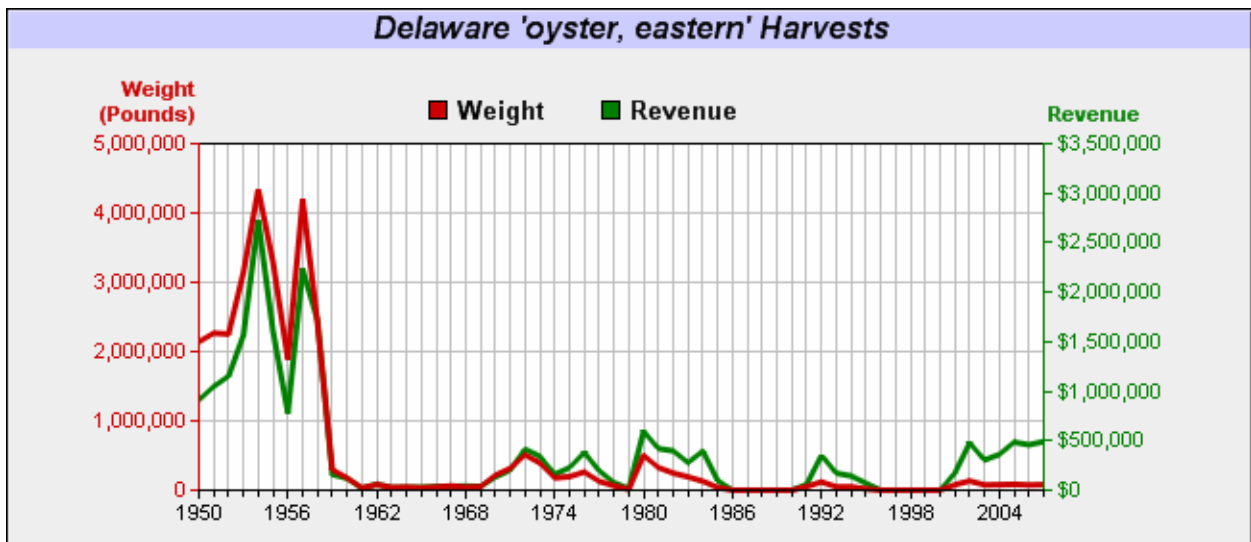
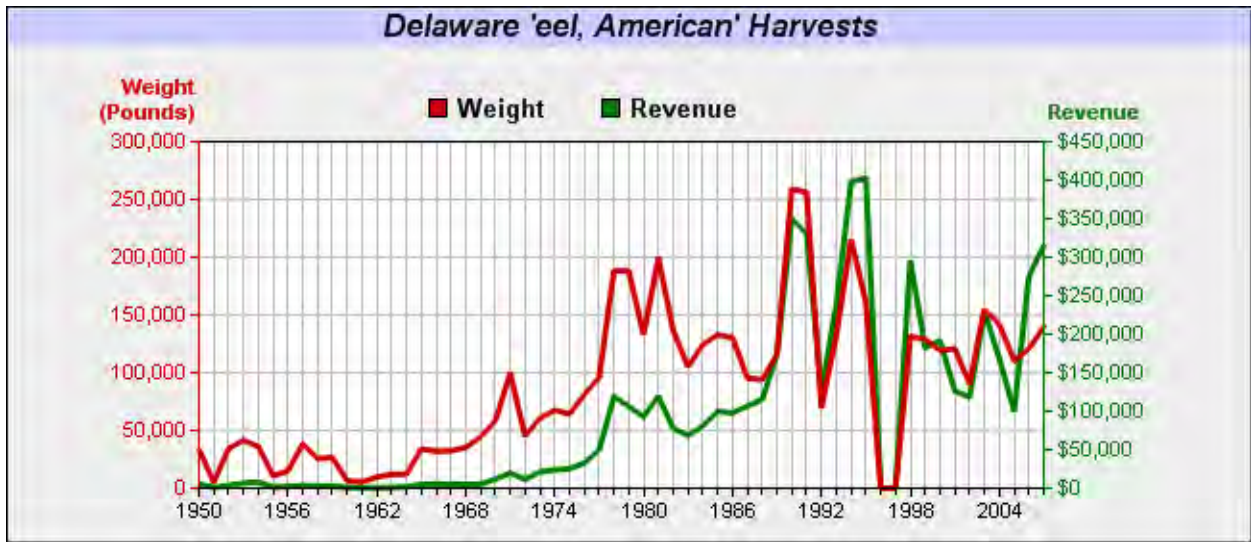
**Table 31.** Fish landings and value in the Delaware Estuary in \$2010

Delaware Estuary Species <sup>1</sup>	Value (\$2000) <sup>2</sup>	Value (\$2010) <sup>3</sup>
Crab, Blue	\$10,800,297	\$14,472,398
Flounder, Summer	\$3,999,988	\$5,359,984
Menhaden, Atlantic	\$3,200,359	\$4,288,481
Oyster, Eastern	\$2,721,300	\$3,646,542
Bass, Striped	\$1,717,372	\$2,301,278
Eel, American	\$625,511	\$838,185
Herring, Atlantic	\$563,083	\$754,531
Bluefish	\$508,128	\$680,892
Whelk, Chan'd/Knob	\$511,172	\$684,970
Weakfish	\$261,228	\$350,046
Shad, American	\$119,423	\$160,027
Perch, White	\$84,500	\$113,230
Shellfish	\$76,119	\$101,999
Perch, Yellow	\$71,847	\$96,275
Snails (Conchs)	\$59,016	\$79,081
Crab, Horseshoe	\$48,978	\$65,631
Carp, Common	\$27,670	\$37,078
Drum, Black	\$22,311	\$29,897
Catfish, Channel	\$3,929	\$5,265
Herring, Blueback	\$609	\$816
<b>Total</b>	<b>\$25,422,840</b>	<b>\$34,066,606</b>

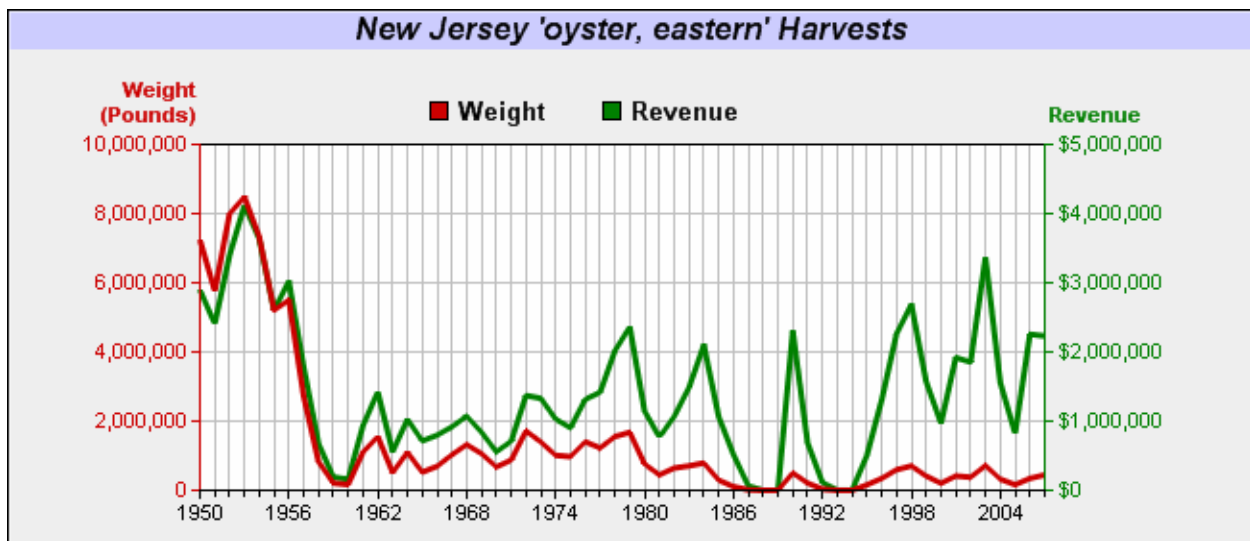
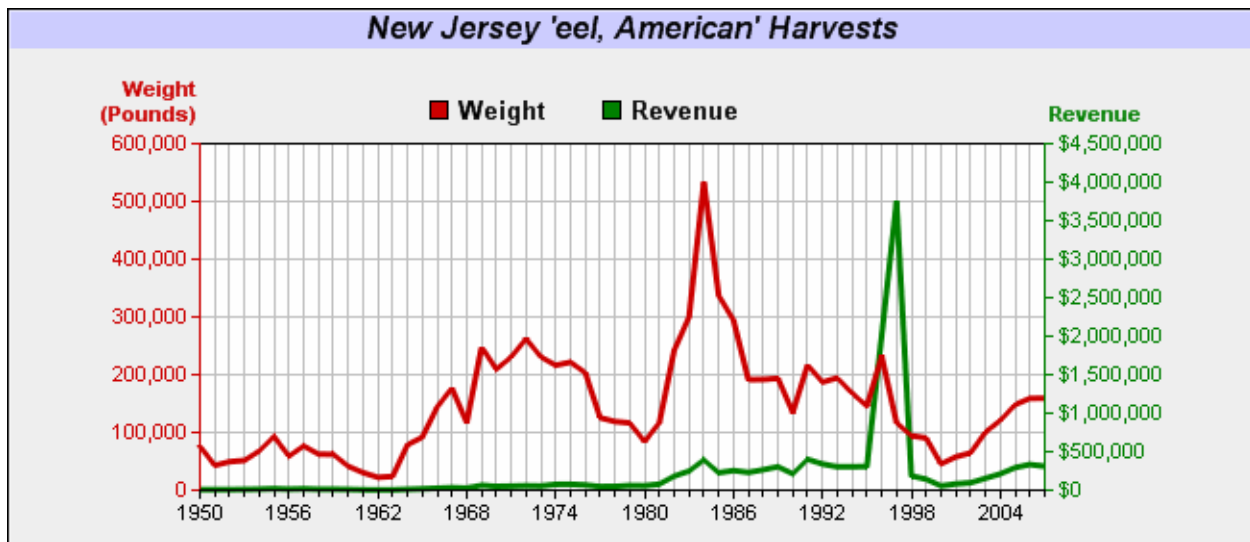
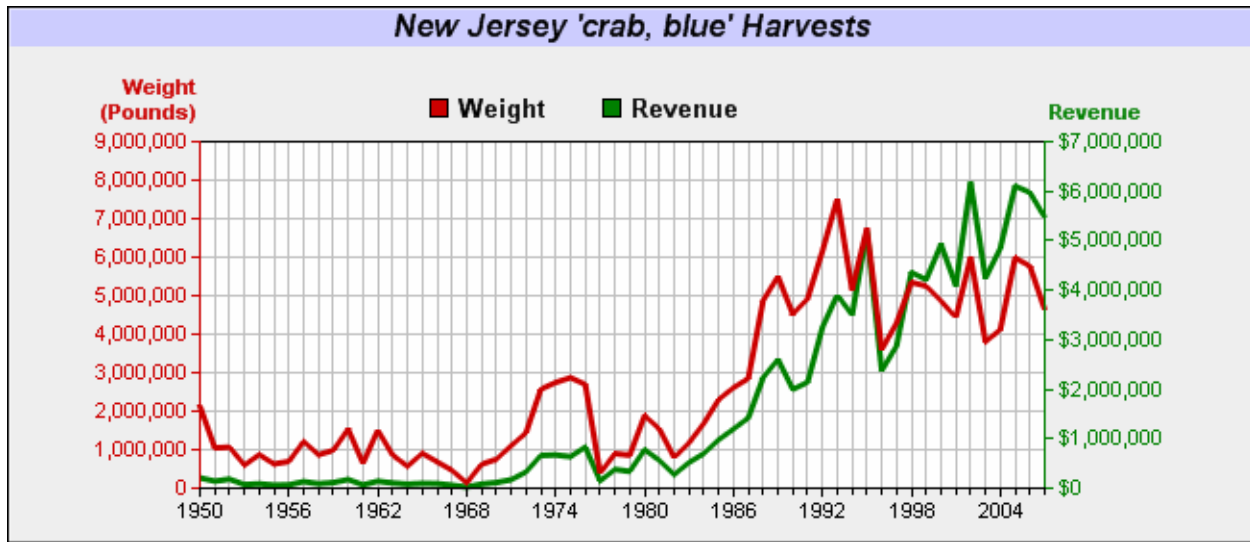


**Figure 8.** Fish landings in the Delaware Estuary (NMFS and NOEP 2007)

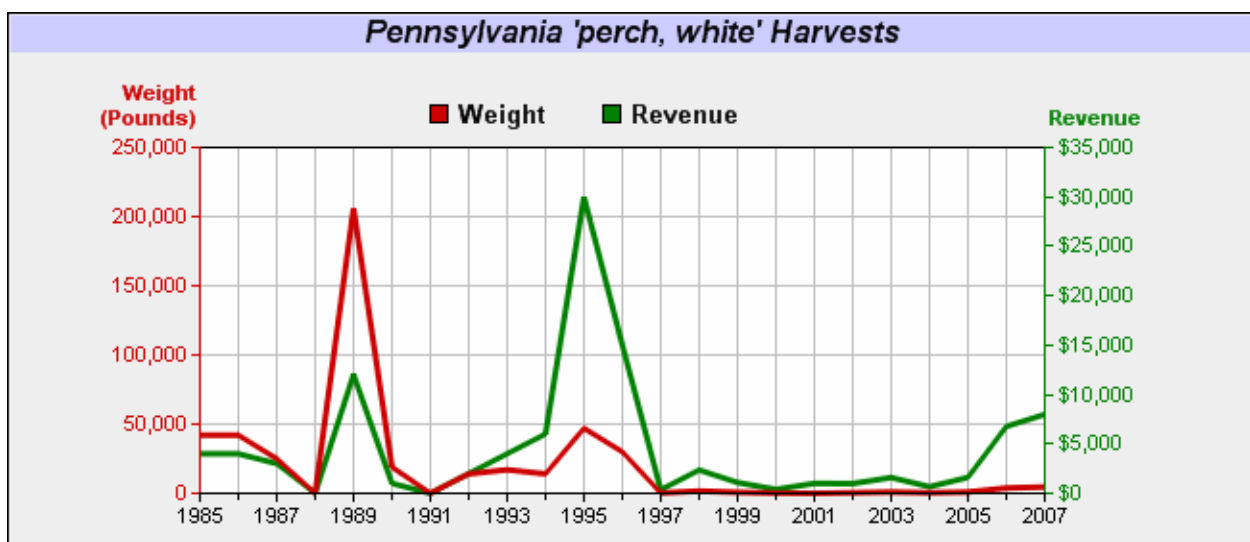
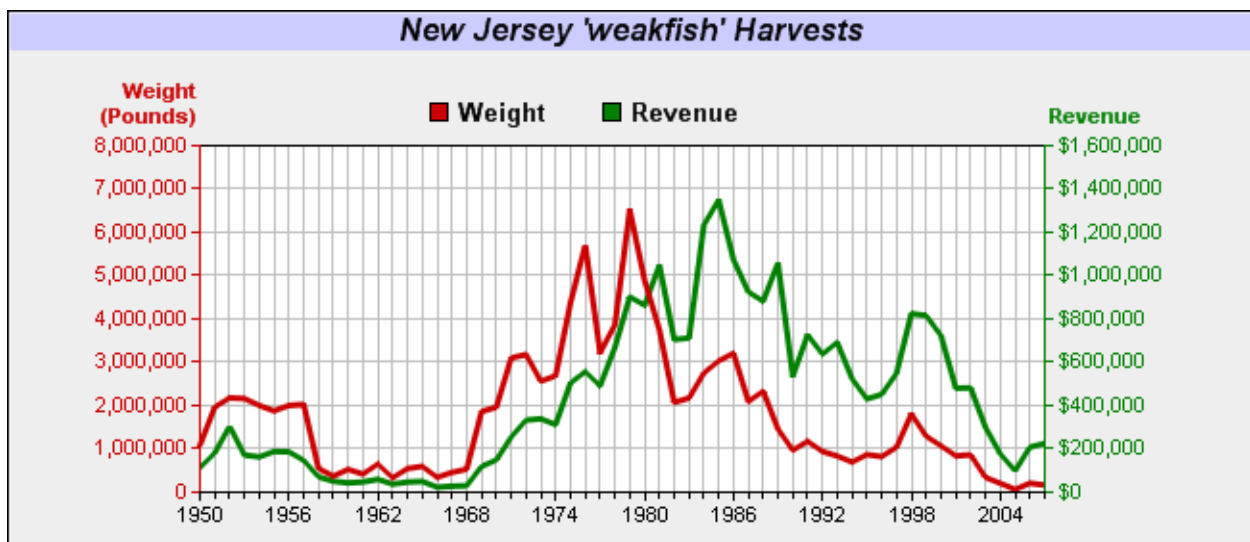
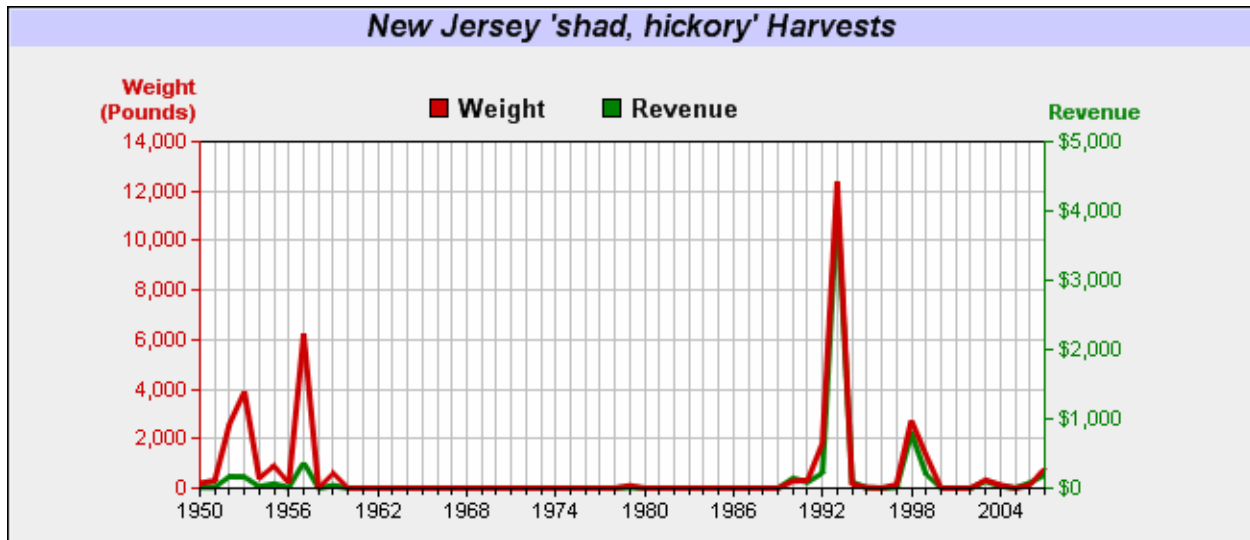




**Figure 8.** Fish landings in the Delaware Estuary, con't. (NMFS and NOEP 2007)



**Figure 8.** Fish landings in the Delaware Estuary, con't. (NMFS and NOEP 2007)



**Figure 8.** Fish landings in the Delaware Estuary, con't. (NMFS and NOEP 2007)

## Fishing, Hunting, and Bird/Wild-life Watching

In Delaware, New Jersey, New York, and Pennsylvania, the U. S. Fish and Wildlife Service (2008) estimated the annual economic value of fishing, hunting, birding and wild-life/bird watching recreation was \$9.2 billion in \$2006. Trip-related expenditures include food and lodging, transportation, and hunting, fishing, and wildlife watching equipment. Most fishing, hunting, and birding/wildlife recreation occurs on farm, forest, wetlands, and open water ecosystems such as the Prime Hook and Bombay Hook National Wildlife Refuges in Delaware, the Cape May National Wildlife Refuge and Pine Barrens National Reserve in New Jersey, the Catskill Mountain Preserve in New York, the Delaware Water Gap National Recreation Area in Pennsylvania, and on the Delaware River and Bay and tributaries as well.

The Delaware Basin includes 50% of Delaware's land area, 40% of New Jersey's land area, 5% of New York State's land area, 14% of Pennsylvania's land area. Prorating based on the ratio of the area of the state within the basin to total state area, estimated economic value of fishing, hunting, and wild-life associated recreation in the Delaware Basin is \$1,477 million/yr in \$2006 or \$134 million/yr in Delaware, \$574 million/yr in New Jersey, \$160 million/yr in New York, and \$608 million/yr in Pennsylvania (Table 32).

**Table 32.** Value of fishing, hunting, and wildlife recreation in the Delaware River Basin

Recreation Activity	DE by state <sup>1</sup> (\$M)	NJ by state <sup>1</sup> (\$M)	NY by state <sup>1</sup> (\$M)	PA by state <sup>1</sup> (\$M)	DE in basin <sup>2</sup> (\$M)	NJ in basin <sup>2</sup> (\$M)	NY in basin <sup>2</sup> (\$M)	PA in basin <sup>2</sup> (\$M)	Del. Basin (\$M)
<b>Fishing</b>	97	752	926	1,291	48	301	46	181	576
Trip Related	49	471	585	299	24	188	29	42	284
Equipment/other	48	281	341	993	24	112	17	139	293
<b>Hunting</b>	41	146	716	1,609	21	58	36	225	340
Trip-related	14	73	202	274	7	29	10	38	84
Equipment/other	28	73	514	1,335	14	29	26	187	256
<b>Wildlife/Bird-watching</b>	131	537	1,568	1,443	65	215	78	202	561
Trip Related	13	146	696	325	7	59	35	46	145
Equipment/other	118	391	872	1,118	59	156	44	156	415
<b>Total</b>	<b>269</b>	<b>1,436</b>	<b>3,209</b>	<b>4,343</b>	<b>134</b>	<b>574</b>	<b>160</b>	<b>608</b>	<b>1,477</b>

1. (USFWS 2008). Prorated by ratio of basin to state land area, Del. (50%), NJ (40%), NY (5%), and Pa. (14%).

### Shad Fishing

The Pennsylvania Fish and Boat Commission (2011) published a fact sheet on the economic value of fishing and boating in Pennsylvania. A 1986 study of shad fishing on the Delaware River showed:

- Anglers spent an average of \$25.40 per trip on gasoline, food, lodging, and tackle. Multiplied by 63,000 trips in 1986, anglers spent \$1.6 million during a nine week season. Adjusting by 3% annually, the economic contribution by shad anglers would be about \$3.2 million in \$2010.
- The average shad angler was willing to pay \$50 per day of shad fishing or \$102 per day when adjusted to \$2010 at 3% annually. Multiplied by 63,000 angler days, the annual economic value based on willingness to pay for the Delaware River shad fishery was \$3.2 million in 1986 or \$6.5 million adjusted to \$2010.

## Wild Trout Fishing

Releases from New York City reservoirs and excellent water quality in the forested Catskill watersheds contribute to a thriving cold water fishery in the upper Delaware Basin. Along the Beaverkill and East Branch, West Branch, and upper main stem of the Delaware River in New York, wild trout fishing contributes almost \$18 million in annual business revenue, over \$29 million in economic activity, and almost 350 jobs with \$3.6 million in wages (Maharaj, McGurrin, and Carpenter, 1998).

## Agriculture

In Delaware Basin counties, the USDA (2009) estimates the annual market value of agricultural products sold is \$4.79 billion on 2,857,870 acres (4,465 sq mi) for crops (corn, wheat, oats, barley, soybeans, potatoes, and vegetables) and livestock and poultry (Table 33). On 1,926,524 acres (3,010 sq mi) of farmland within the Delaware Basin, the prorated annual market value of agricultural products sold is \$3.37 billion or \$1,750 per acre. The Delaware Basin covers 12,769 sq mi or just 13% of the combined land areas of Delaware (1,953 sq mi), New Jersey (7,417 sq mi), New York (47,214 sq mi), and Pennsylvania (44,816 sq mi) yet accounts for \$3.37 billion or 27% of total annual farm products sold in the four states (Table 34).

**Table 33.** Farm products sold in the Delaware River Basin

State	State area (sq mi)	Area in Del. Basin (sq mi)	Ratio area basin/area state (%)	Farm products sold in state (\$ million)	Farm products Del. Basin (\$ million)	Products in basin/state (%)
Delaware	1,953	965	49%	1,083	636	59%
New Jersey	7,417	2,961	40%	987	603	61%
New York	47,214	2,555	5%	4,418	105	2%
Pennsylvania	44,816	6,280	14%	5,808	2,027	35%
<b>Total</b>	<b>101,400</b>	<b>12,761</b>	<b>13%</b>	<b>12,296</b>	<b>3,371</b>	<b>27%</b>

**Table 34.** Value of cropland and agriculture in the Delaware River Basin

County	Farmland by county <sup>1</sup> (ac)	Products sold by county <sup>1</sup> (\$ million)	Products sold by county (\$/ac)	Farmland in Del. Basin (ac)	Products sold in Del. Basin (\$ million)
New Castle	51,913	45.7	880		
Kent	146,536	188.4	1,286		
Sussex	234,324	848.9	3,623		
<b>Delaware</b>	<b>432,773</b>	<b>1,083.0</b>	<b>2,502</b>	<b>254,143</b>	<b>636</b>
Burlington	85,790	86.3	1,006		
Camden	8,760	18.6	2,123		
Cape May	7,976	14.6	1,830		
Cumberland	69,489	156.9	2,258		
Gloucester	46,662	93.9	2,012		
Hunterdon	100,027	69.7	697		
Mercer	21,736	18.6	856		
Monmouth	44,130	105.4	2,388		
Ocean	9,833	11.5	1,170		
Salem	96,530	80.0	829		
Sussex	65,242	21.2	325		
Warren	74,975	75.5	1,007		
<b>New Jersey</b>	<b>631,150</b>	<b>752.2</b>	<b>1,192</b>	<b>505,507</b>	<b>602</b>
Broome	86,613	29.9	345		
Delaware	165,572	55.1	333		
Greene	44,328	16.4	370		
Orange	80,990	73.7	910		
Sullivan	50,443	42.1	835		
Ulster	75,205	65.6	872		
<b>New York</b>	<b>503,151</b>	<b>282.8</b>	<b>562</b>	<b>187,561</b>	<b>105</b>
Berks	170,760	367.8	2,154		
Bucks	58,012	70.6	1,217		
Carbon	20,035	8.9	444		
Chester	117,145	553.3	4,723		
Delaware	1,646	9.4	5,711		
Lackawanna	39,756	16.2	407		
Lancaster	326,648	1,072.1	3,282		
Lebanon	89,566	257.1	2,871		
Lehigh	72,737	72.1	991		
Luzerne	66,577	18.1	272		
Monroe	29,165	7.8	267		
Montgomery	28,563	30.0	1,050		
Northampton	68,252	31.8	466		
Philadelphia	150	0.5	3,333		
Pike	27,569	2.5	91		
Schuylkill	81,276	124.7	1,534		
Wayne	92,939	29.4	316		
<b>Pennsylvania</b>	<b>1,290,796</b>	<b>2,672.3</b>	<b>2,070</b>	<b>979,313</b>	<b>2,027</b>
<b>Delaware Basin</b>	<b>2,857,870</b>	<b>4,790.3</b>	<b>1,676</b>	<b>1,926,524</b>	<b>3,371</b>

1. Census of Agriculture 2007 (USDA 2009)

## Forests

The U. S. Forest Service and Delaware Center for Horticulture (Nowak et al. 2008) estimated 7,137 acres of forests in New Castle County have a carbon storage benefit of \$5.9 million (\$827/ac) and air pollution removal of \$1.9 million (\$266/ac/yr). Applying these multipliers, Tables 35 and 36 indicate 4,343,190 (6,786 sq mi) of forests in the Delaware Basin have economic benefits from carbon storage (\$3,591 million), air pollution removal (\$1,155 million), building energy savings (\$243 million), and carbon sequestration (\$126 million).

**Table 35.** Economic benefits of forests in the Delaware River Basin

Forest Benefits	New Castle County. <sup>1</sup> (\$/ac)	Delaware Basin <sup>2</sup> (\$ mil.)
Carbon storage	827	3,592
Carbon Sequestration	29	126
Air Pollution Removal	266	1,155
Building Energy Savings	56	243
Avoided Carbon Emissions	3	13

1. Nowak et al. 2008.

2. Computed for Delaware Basin forests (4,343,190 ac).

**Table 36.** Economic benefits of forests in the Delaware River Basin by state

Forest Benefits	Del. (\$ mil.)	NJ (\$ mil.)	NY (\$ mil.)	Pa. (\$ mil.)	Del. Basin (\$ mil.)
Carbon Storage	78.8	564.8	1,147.5	1,800.8	3,592
Carbon Sequest.	2.8	19.8	40.2	63.1	126
Air Pollution Contr.	25.4	181.7	369.1	579.2	1,155
Energy Savings	5.4	38.2	77.7	121.9	243
Avoid Carbon Emiss.	0.3	2.0	4.2	6.5	13

## Open Space

### Public Parks

The Trust for Public Land (2009) found the 444-acre City of Wilmington park and recreation system provides annual economic value and savings to the public from health benefits from exercise in the parks (\$9,734/ac), community cohesion benefit from people socializing in the parks (\$2,383/ac), water pollution benefit from parks in treating stormwater (\$921/ac), air pollution mitigation value from tree and shrub absorption (\$88/ac).

Using value transfer from the data gathered for the City of Wilmington study, Table 37 indicates public parks (169 sq mi) within the Delaware Basin provide the following annual economic value:

- Health benefits from exercise in the parks (\$1,283 million).
- Community cohesion benefit from people socializing in the parks (\$314 million).
- Water pollution benefit from parks in treating stormwater (\$121million).
- Air pollution mitigation value from tree and shrub absorption (\$12 million).

**Table 37.** Value of public parks in the Delaware River Basin

State/county	Parks in Del. Basin (ac)	Health Benefits (\$9,734/ac)	Community Cohesion (\$2,383/ac)	Stormwater Benefit (\$921/ac)	Air Pollution (\$88/ac)
Kent	4,587	44,649,858	10,930,821	4,224,627	403,656
New Castle	12,440	121,090,960	29,644,520	11,457,240	1,094,720
Sussex	1,389	13,520,526	3,309,987	1,279,269	122,232
<b>Delaware<sup>1</sup></b>	<b>18,416<sup>1</sup></b>	<b>179,261,344</b>	<b>43,885,328</b>	<b>16,961,136</b>	<b>1,620,608</b>
Burlington	7,970	77,579,980	18,992,510	7,340,370	701,360
Camden	2,985	29,055,990	7,113,255	2,749,185	262,680
Cape May	2,911	28,335,674	6,936,913	2,681,031	256,168
Cumberland	2,640	25,697,760	6,291,120	2,431,440	232,320
Gloucester	4,868	47,385,112	11,600,444	4,483,428	428,384
Hunterdon	3,170	30,856,780	7,554,110	2,919,570	278,960
Mercer	8,283	80,626,722	19,738,389	7,628,643	728,904
Monmouth	105	1,022,070	250,215	96,705	9,240
Ocean	199	1,937,066	474,217	183,279	17,512
Salem	2,144	20,869,696	5,109,152	1,974,624	188,672
Sussex	2,961	28,822,374	7,056,063	2,727,081	260,568
Warren	5,563	54,150,242	13,256,629	5,123,523	489,544
<b>New Jersey<sup>2</sup></b>	<b>31,800<sup>2</sup></b>	<b>426,339,466</b>	<b>104,373,017</b>	<b>40,338,879</b>	<b>3,854,312</b>
Broome	389	3,786,526	926,987	358,269	34,232
Delaware	546	5,314,764	1,301,118	502,866	48,048
Orange	413	4,020,142	984,179	380,373	36,344
Sullivan	1,570	15,282,380	3,741,310	1,445,970	138,160
Ulster	50	486,700	119,150	46,050	4,400
<b>New York<sup>3</sup></b>		<b>28,890,512</b>	<b>7,072,744</b>	<b>2,733,528</b>	<b>261,184</b>
Berks	3,979	38,731,586	9,481,957	3,664,659	350,152
Bucks	11,402	110,987,068	27,170,966	10,501,242	1,003,376
Carbon	2,820	27,449,880	6,720,060	2,597,220	248,160
Chester	12,020	117,002,680	28,643,660	11,070,420	1,057,760
Delaware	6,274	61,071,116	14,950,942	5,778,354	552,112
Lehigh	2,500	24,335,000	5,957,500	2,302,500	220,000
Luzerne	195	1,898,130	464,685	179,595	17,160
Monroe	875	8,517,250	2,085,125	805,875	77,000
Montgomery	14,138	137,619,292	33,690,854	13,021,098	1,244,144
Northampton	1,393	13,559,462	3,319,519	1,282,953	122,584
Philadelphia	9,689	94,312,726	23,088,887	8,923,569	852,632
Pike	125	1,216,750	297,875	115,125	11,000
Schuylkill	829	8,069,486	1,975,507	763,509	72,952
Wayne	350	3,406,900	834,050	322,350	30,800
<b>Pennsylvania<sup>4</sup></b>	<b>58,331<sup>3</sup></b>	<b>648,177,326</b>	<b>158,681,587</b>	<b>61,328,469</b>	<b>5,859,832</b>
<b>Total</b>	<b>108,547</b>	<b>1,282,668,648</b>	<b>314,012,676</b>	<b>121,362,012</b>	<b>11,595,936</b>

1. State, county, and municipal park land in Delaware from county and local comprehensive plans.
2. County and municipal park land from New Jersey State Comprehensive Outdoor Recreation Plan (SCORP).
3. County/municipal parks in New York from county and local comprehensive plans.
4. County/municipal parks in Pennsylvania from DVRPC 2007 & Berks/Schuylkill counties comprehensive plans.

#### Delaware Water Gap National Recreation Area

The Delaware Water Gap National Recreation Area (DWGNRA) preserves almost 109 square miles of forest and floodplain along 40 miles of the upper Delaware River and 29 miles of the Appalachian Trail. Stynes and Sun (2002) estimated the DWGNRA had 4,867,272 recreation visits in 2001 including 487,727 local day trips, 3,650,455 non-local day trips, 486,727 motel visits, and



243,364 camping overnights. Total visitor spending in the DWGNRA in 2001 was \$100 million including \$12.4 million for local day trips, \$46.5 million for non-local day trips, \$30.9 million for motels, and \$10.3 million for camping overnights. In 2001, the DWGNRA generated \$106 million in sales, and 7,563 direct/indirect jobs with \$100 million in wages.

### **Marcellus Shale Natural Gas**

The U.S. Geological Survey concluded that the Marcellus Shale Formation is a voluminous economic resource that lies under 4,700 square miles or 36% of the Delaware River Basin. Drilling for natural gas through the hydraulic fracturing process requires large quantities of water and has the potential to consume sizable tracts of land in the forested headwaters of the Delaware Basin (Figure 9). Hydraulic fracturing requires pumping water under high pressure to open fractures in the shale to allow natural gas to flow to the well. The hydrofracturing water must be recovered and treated before disposal to surface and ground waters. In forests, natural gas well drilling can require clearing of pads that range from 3 to 5 acres in area.

The DRBC is considering revisions to Article 7 of the Water Quality Regulations to protect the water resources of the Delaware Basin during construction and operation of natural gas projects with the following considerations:

- Gas drilling projects in the Marcellus Shale may reduce the flow in streams and aquifers.
- On-site drilling operations may potentially release pollutants into ground or surface water.
- The recovered hydrofracturing water must be treated and disposed of properly.

The Marcellus Shale Formation covers 54,000 square miles and lies up to a mile and a half below parts of Kentucky, New Jersey, New York, Ohio, Pennsylvania, and West Virginia (Figure 10). The Marcellus Shale lies under 4,700 square miles or 36% of the Delaware River Basin in New York, Pennsylvania, and a small tip of New Jersey (Figure 11). About 8.7% of the Marcellus Shale Formation lies within the Delaware River Basin (4,700 sq mi/54,000 sq mi).

The U.S. Geological Survey (Coleman et al. 2011) estimated the entire 54,000 square-mile Marcellus Shale Formation potentially contains a mean volume of 84 trillion cubic feet of recoverable natural gas with a range of 43 tcf (95 percentile) to 144 tcf (5 percentile). If the Delaware River Basin covers 4,700 sq mi or 8.7% of the Marcellus Shale, then by proportion approximately 7.3 trillion cubic feet of natural gas is potentially recoverable within the basin boundary ( $0.087 \times 54,000$ ). These estimates can vary as the thickness of Marcellus Shale in the Delaware Basin generally increases to the north toward the New York/Pennsylvania border and may range from 50 feet thick near Stroudsburg to more than 250 feet thick at Lackawaxen in Wayne County, Pennsylvania (Figure 12).

The U.S. Energy Information Administration (2011) reported the 2010 mean natural gas wellhead price was \$4.16/1000 cf. The price of natural gas for residential customers was \$11.21/1000 cf. At these unit prices, the estimated value of natural gas from the Marcellus Shale Formation within the Delaware River Basin is \$30.4 billion at the wellhead and \$81.8 billion when sold to residential customers (Tables 38 and 39).

Environmental economists classify natural gas as a nonrenewable resource with finite stock value over a defined time frame (say 25 or 50 years). Assuming the natural gas can be recovered within 25

years, the annual value of the Marcellus Shale gas recoverable from within the Delaware Basin is \$1.2 billion/year at the wellhead and \$3.3 billion/year when sold to residential customers.

**Table 38.** Wellhead value of Marcellus shale natural gas within the Delaware River Basin

State/Basin	Area Marcellus Shale (sq mi)	Wellhead Natural Gas Price <sup>1</sup> (\$/1000 cf)	Volume Natural Gas <sup>2</sup> (tcf)	Wellhead Natural Gas Value (\$ billion)	Wellhead Natural Gas Value <sup>3</sup> (\$ billion/yr)
Pennsylvania	2,338	\$4.16	3.6	\$15.0	\$0.6
New York	2,362	\$4.16	3.7	\$15.4	\$0.6
<b>Delaware Basin</b>	<b>4,700</b>	<b>\$4.16</b>	<b>7.3</b>	<b>\$30.4</b>	<b>\$1.2</b>

1. EIA 2010. 2. USGS 2011. 3. Assumes 25 year natural gas recovery period.

**Table 39.** Residential value of Marcellus shale natural gas within the Delaware River Basin

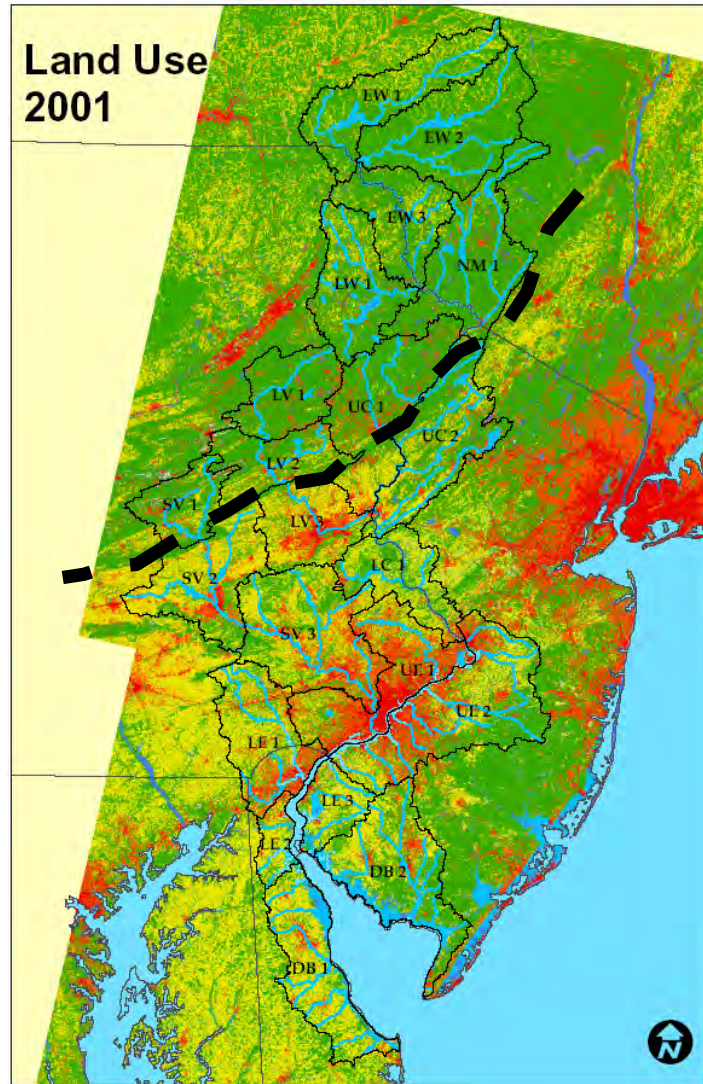
State/Basin	Area Marcellus Shale (sq mi)	Residential Natural Gas Price <sup>1</sup> (\$/1000 cf)	Volume Natural Gas <sup>2</sup> (tcf)	Residential Natural Gas Value (\$ billion)	Wellhead Natural Gas Value <sup>3</sup> (\$ billion/yr)
Pennsylvania	2,338	\$11.21	3.6	\$40.4	\$1.6
New York	2,362	\$11.21	3.7	\$41.5	\$1.7
<b>Delaware Basin</b>	<b>4,700</b>	<b>\$11.21</b>	<b>7.3</b>	<b>\$81.8</b>	<b>\$3.3</b>

1. EIA 2010. USGS 2011. 3. Assumes 25 year natural gas recovery period.

On a per volume basis, the value of untreated drinking water in streams and wells (at \$7.48/1000 cf or \$1.00/1000 gal) exceeds the value of natural gas at the wellhead (at \$4.16/1000 cf) in the Delaware Basin. The total value of untreated drinking water from streams/wells (1,803 mgd) in the Delaware Basin is \$0.7 billion/year, less than the estimated value of natural gas recoverable at the wellhead (\$1.2 billion/year). The value of treated drinking water in the basin (at \$35.70/1000 cf or \$4.78/1000 gal) is \$3.1 billion/year which is comparable to the total natural gas value sold to residential customers or \$3.3 billion/year (Table 40).

**Table 40.** Value of Marcellus shale gas compared to drinking water in the Delaware River Basin

Price/Value	Natural Gas	Drinking Water
Quantity	7.3 trillion cf	1,803 mgd
Unit Price Wellhead Gas or Untreated Drinking Water	\$4.16/1000 cf	\$7.48/1000 cf
Total Value Wellhead Gas or Untreated Drinking Water	\$1.2 billion/yr	\$0.7 billion/yr
Unit Price Residential Gas or Treated Drinking Water	\$11.21/1000 cf	\$35.70/1000 cf
Total Value Residential Gas or Treated Drinking Water	\$3.3 billion/yr	\$3.1 billion/yr



**Figure 9.** Land use including forested headwaters in the Delaware Basin (Marcellus Shale southerly boundary delineated as dashed line).

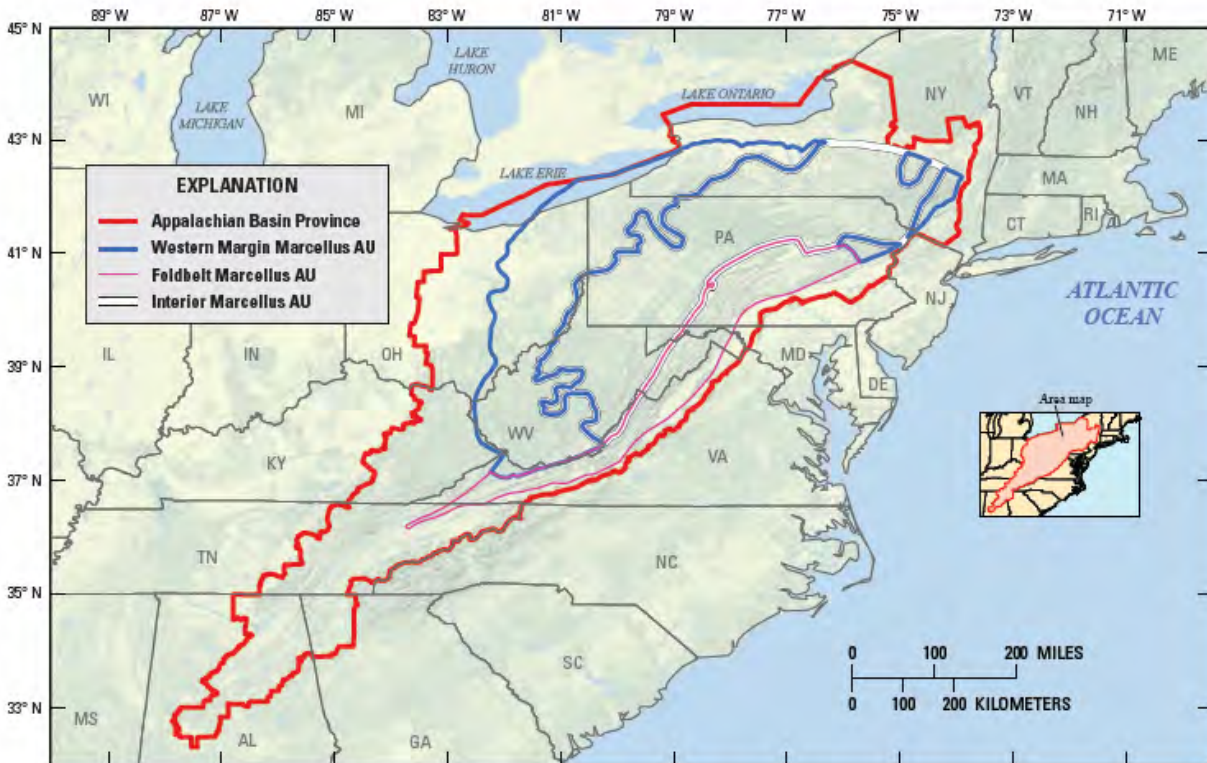


Figure 10. Marcellus Shale Formation in the Appalachian Basin Province (USGS 2011)

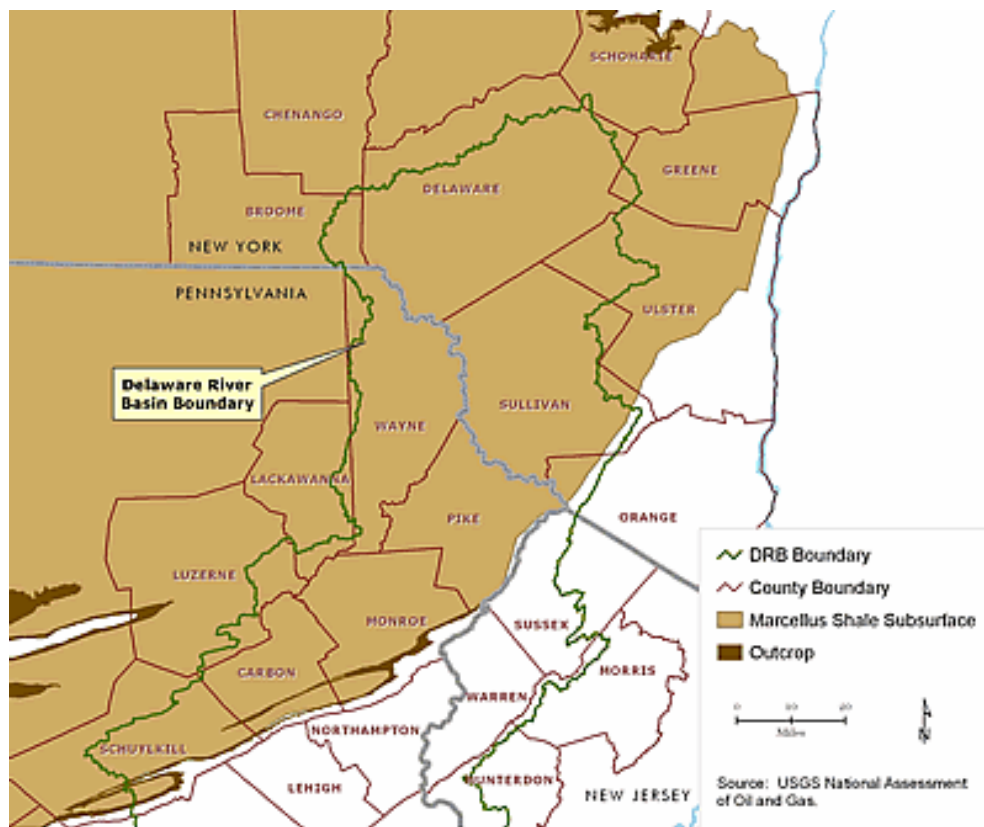
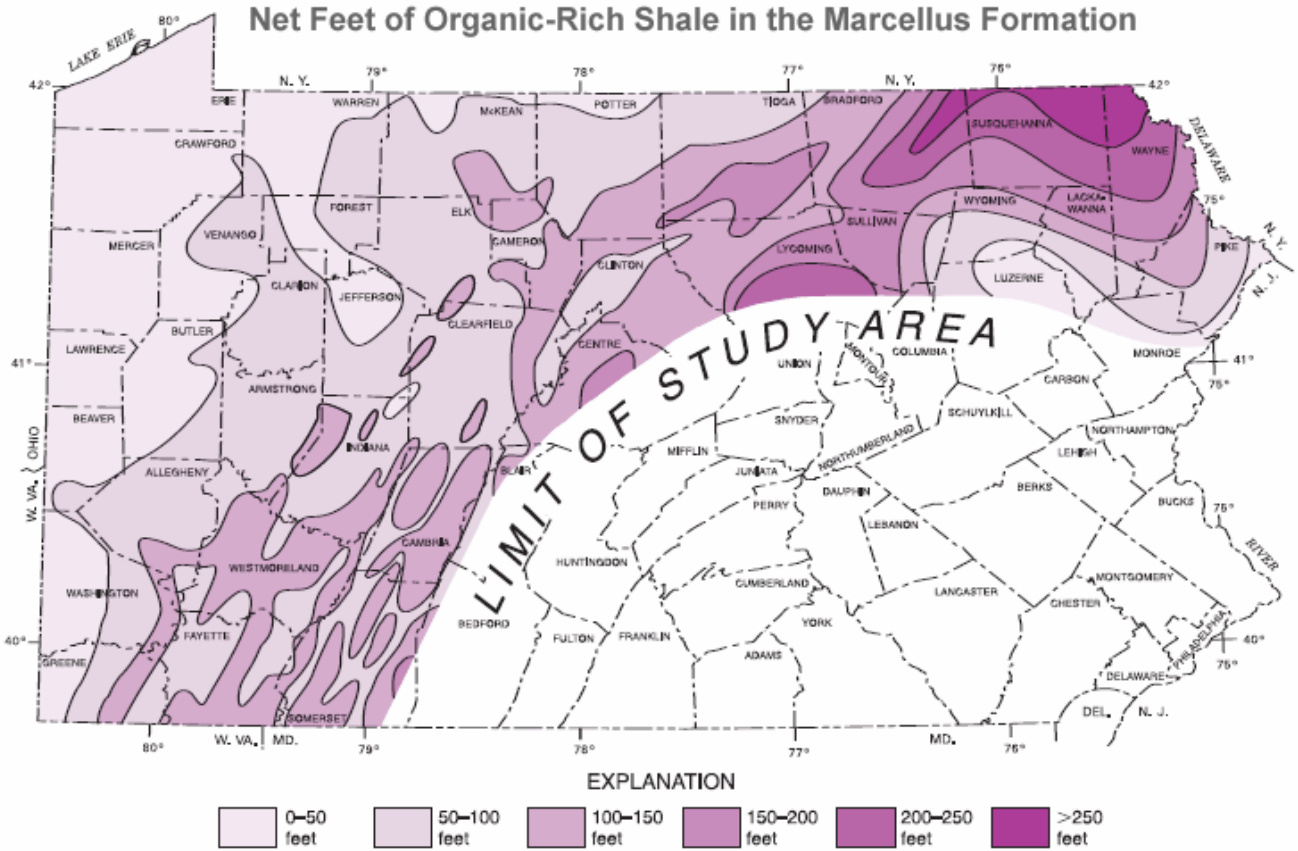


Figure 11. Marcellus Shale Formation within the Delaware River Basin (USGS)



**Figure 12.** Thickness of Marcellus shale in Pennsylvania (Pennsylvania Geological Survey)

## Maritime Transportation

### Navigation

The 130-mile long Delaware River and Bay ship channel from Cape Henlopen to the head of navigation at Trenton has significant instream navigation use value. The Delaware River port from Wilmington to Chester, Paulsboro, Camden, and Philadelphia is the 6<sup>th</sup> largest port in the U.S. based on imports. The volume of the 720 square mile Delaware Estuary at mean depth of 32 feet is 14.7 million ac-ft or 4.8 trillion gallons. A study of the economic value of freshwater in the U.S. estimated the median value of instream navigation uses is \$10/ac-ft in \$1996 (Frederick et al. 1996) or \$15/ac-ft in \$2010 based on 3% annually. Accordingly, the instream navigation value of the Delaware River and Bay (14.7 million ac-ft) from the ocean to head of tide at Trenton is \$220 million.

### C&D Canal

The 35-foot deep Chesapeake & Delaware Canal is a valuable commercial conduit that flows through the Delaware Basin in Delaware and carries 40% of all ship traffic to/from the Port of Baltimore. The C&D Canal trims 300 miles from the trip for ships that would otherwise sail up the Chesapeake Bay to Baltimore from the ocean. Normally 6 to 35 ships per day sail through the C&D Canal.

The Port of Baltimore is responsible for 16,700 direct jobs and \$3.7 billion in wages (Maryland Port Administration 2010). Of 360 ports in the U.S., Baltimore is No. 1 in forest product, gypsum, and sugar imports and No. 2 in automobile exports. In 2009, the Port of Baltimore was 11<sup>th</sup> among all U.S. port districts with \$10.8 billion in exports after Seattle (9<sup>th</sup>) and San Francisco (10<sup>th</sup>). Baltimore was 12<sup>th</sup> in the U.S. with \$19.4 billion in imports after Norfolk (10<sup>th</sup>) and Port Arthur, Texas (11<sup>th</sup>). If 40% of all Baltimore-bound ship traffic sails through the C&D Canal, then 40% of the economic activity generated by the port can be indirectly attributed to this avenue of commerce that cuts through Delaware River Basin in Delaware (Table 41).

**Table 41.** Economic activity generated by Port of Baltimore through the C&D Canal

Activity	Port of Baltimore <sup>1</sup>	C&D Canal <sup>2</sup>
Jobs	16,700	6,700
Wages	\$3.7 billion	\$1.5 billion
Imports	\$19.4 billion	\$7.8 billion
Exports	\$10.8 billion	\$4.3 billion

1. Maryland Port Authority 2010. 40% of Baltimore-bound shipping sails through C&D Canal.

#### Port Activity

For over 300 years since the time of William Penn, the Delaware River has been an economic engine that is now the largest freshwater port in the world. The Economy League of Greater Philadelphia (2008) concluded that Delaware River ports from Wilmington to Philadelphia to Trenton:

- Collectively is the largest freshwater port in the world with \$2.4 billion in total economic output.
- Generate \$81 million in tax revenues to Delaware, Pennsylvania, New Jersey (Table 42).
- Import 1/2 of the nation’s cocoa beans, 1/3 of the bananas, and 1/4 of all fruit and nuts.
- Rank 5<sup>th</sup> among ports in the USA in import cargo value and 20<sup>th</sup> in export value.
- In Chester, Philadelphia, Wilmington, Camden and Paulsboro handled 16% of container trade in the U.S. and 51% of container trade value nationwide.
- Biggest commodity is petroleum that accounts for 65% of the port’s imports while fruits and nuts account for 4%.

**Table 42.** Tax revenues from Delaware River ports, 2005  
(Economy League of Greater Philadelphia 2008)

Type	DE	NJ	PA	Total
Individual Income Tax	\$2,538,803	\$6,679,380	\$13,102,579	\$22,320,762
Sales and Use Tax		5,326,255	13,851,735	\$19,177,990
Corporate Income Tax	888,055	1,988,447	3,632,195	\$6,508,697
Selective Tax	1,075,499	2,674,104	7,807,469	\$11,557,072
Other State Tax, License, Fees	2,536,226	1,597,420	5,199,444	\$9,333,090
<b>Total State and Local Tax</b>	<b>7,038,582</b>	<b>18,266,605</b>	<b>55,974,357</b>	<b>\$81,279,544</b>

The Economy League reports that nearly 2,900 ships (8 per day) docked at Delaware River ports in 2006, up 10% from 1995. Most shipping traffic were tankers, containers, bulk, refrigerated (meat/fruits/vegetables) and auto transport vessels (Table 43).

**Table 43.** Delaware River port vessel calls, 1996-2000  
(Economy League of Greater Philadelphia 2008)

Year	General	Container	Roll on	Refrg	Bulk	Tanker	Chem	Auto	Passengr	Total
1995	304	368	84	333	405	812	138	110	16	2,570
2006	248	581	78	373	402	861	144	121	39	2,847
change	-56	213	-6	40	-3	49	6	11	23	277
% change	-18%	-58%	-7%	12%	-1%	6%	4%	10%	144%	11%

Top Delaware River port exports (Table 44) are motor vehicles (31%) and petroleum products (12%) and top imports are petroleum (65%) and iron and steel (7%).

**Table 44.** Top exports and imports at Delaware River ports (Economy League 2008)

Cargo	Exports	Imports
Motor Vehicles	31%	
Petroleum	12%	65%
Precious stones/Metals	7%	
Industrial Machinery	6%	2%
Plastics	6%	
Iron and Steel		7%
Fruits and Nuts		4%
Meat		3%

In 2005, Delaware River ports at Philadelphia, Chester, and Camden were the 6<sup>th</sup>, 35<sup>th</sup>, and 37<sup>th</sup> largest ports in the U.S. based on imports of goods and cargo (Table 45). The five ports along the Delaware River had combined imports of \$41 billion, the 5<sup>th</sup> largest port in the U.S. after Los Angeles, Newark (NJ), Houston, and Long Beach (CA) and ahead of Seattle, Norfolk (VA), and Baltimore. The five ports along the Delaware had combined exports of \$6.4 billion making it the 20<sup>th</sup> largest port in the USA after Oakland (CA) and Baltimore but ahead of Charleston (SC).

**Table 45.** Rank of Delaware River imports/exports in United States by value of goods, 2005

Imports Rank in U.S.	Port	Imports (\$)
6	Philadelphia	\$29,500,000,000
35	Chester	\$5,700,000,000
37	Wilmington	\$5,500,000,000
79	Paulsboro	\$250,000,000
103	Camden	67,000,000
<b>5</b>	<b>Delaware R.</b>	<b>\$41,017,000,000</b>
Exports Rank in U.S.	Port	Exports (\$)
22	Philadelphia	\$2,400,000,000
24	Wilmington	\$2,200,000,000
32	Chester	\$1,600,000,000
74	Camden, NJ	\$150,000,000
84	Paulsboro, NJ	\$89,000,000
<b>20</b>	<b>Delaware R.</b>	<b>\$6,439,000,000</b>

## 4. Ecosystem Services

### Other Studies

Data from the following studies were examined to estimate the value of ecosystem services in the Delaware River Basin in Delaware, New Jersey, New York, and Pennsylvania:

- Cecil County green infrastructure study by the Conservation Fund, Annapolis, Md (2007).
- New Jersey Department of Environmental Protection with the University of Vermont (2007)
- Ecosystem services value of forests by the Wilderness Society (2001)
- Ecosystem services value of Peconic Estuary watershed by University of Rhode Island (2002)
- U.S. National Wildlife Refuge System by Univ. of Maryland and Nature Conservancy (2008)
- Economic value of ecosystem services in Massachusetts by the Audubon Society (2003).

Ecosystem services include air filtration, water filtration, recycling nutrients, soil conservation, pollinating crops and plants, climate regulation, carbon sequestration, flood/stormwater control, and hydrologic cycle regulation. Ecological resources provide marketable goods and services such as timber, fish and wildlife recreation, hiking, and boating/kayaking. A Cecil County, Md. study by the Conservation Fund (Table 46) found the largest ecosystem services values result from stormwater/flood control, water supply, and clean water functions (Weber 2007).

**Table 46.** Ecosystem services values for Cecil County, Maryland  
(Weber 2007)

Ecosystem Service	Upland Forest (\$/ac/yr)	Riparian Forest Wetlands (\$/ac/yr)	Nonriparian Wetlands (\$/ac/yr)	Tidal Marsh (\$/ac/yr)
Carbon sequestration	31	65	65	65
Clean air	191	191	191	
Soil and peat formation	17	946	450	1,351
Stormwater/flood control	679	32,000	32,000	1,430
Water supply	8,630	8,630	8,630	
Clean water	1,100	1,925	1,100	11,000
Erosion/sediment control	151	3,418	151	12,700
Water temperature regulation		4,450		
Pest control	50	50	50	
Pollination	75	75	75	
Wood products	142			
Recreation, fish, wildlife habitat	486	534	534	544
Community services savings	439	439	439	439
Increase in property values	42	42		
<b>Total</b>	<b>12,033</b>	<b>52,765</b>	<b>43,685</b>	<b>28,146</b>

The New Jersey Department of Environmental Protection (2007) partnered with the University of Vermont and estimated the value of New Jersey’s natural capital was \$20 billion/year plus or minus



\$9 billion/year in \$2004 with a net present value of \$681 billion based on a discount rate of 3% calculated in perpetuity (over 100 years in the future). Natural capital is the sum of goods (commodities like water, crops, and timber that can be sold) and services (functions like flood control, water filtration, and wildlife/fisheries habitat) provided by watershed ecosystems such as wetlands, forests, farms, and open water. In addition to these direct benefits, ecosystems also provide indirect benefits such as ecotourism by hunters, fishermen, boaters, and hikers who spend money to visit natural sites and realize value from improved water quality and habitat. Table 47 summarizes total ecosystem goods and services in New Jersey. Farm products, fish, minerals, and water supply provide the most ecosystem goods. Nutrient cycling, soil disturbance regulation, water regulation, habitat, aesthetic/recreational, waste treatment, and water supply provide the greatest ecosystem services.

**Table 47.** Ecosystem goods and services provided by New Jersey natural capital (NJDEP 2007)

<b>Ecosystem</b>	<b>\$ million/yr</b>	<b>%</b>
<b>Natural Goods</b>	<b>\$5,864</b>	<b>100%</b>
Farm products	3,676	63%
Commercial/recreational fish	958	16%
Minerals	587	10%
Raw Water	381	7%
Saw timber	147	3%
Fuelwood	95	2%
Game/fur animals	21	1%
<b>Ecoservices</b>	<b>\$19,803</b>	<b>100%</b>
Nutrient cycling	5,074	26%
Disturbance regulation	3,383	17%
Water regulation	2,433	12%
Habitat	2,080	11%
Aesthetic/recreational	1,999	10%
Waste treatment	1,784	9%
Water supply	1,739	9%
Cultural//spiritual	778	4%
Gas/climate regulation	246	1%
Pollination	243	1%
Biological control	35	<1%
Soil formation	8	<1%

The Wilderness Society (Krieger 2001) concluded forest ecosystem services values from climate regulation, water supply, water quality, and recreation benefits totaled \$392/ac in \$1994 or \$631/ac in \$2010 at a 3% annual discount rate (Table 48).

**Table 48.** Forest ecosystem service values for U.S. temperate forests (Krieger 2001)

<b>Ecosystem Good or Service</b>	<b>1994 Value (\$/ac)</b>	<b>2010 Value<sup>1</sup> (\$/ac)</b>
Climate regulation	57.1	91.9
Disturbance regulation	0.8	1.3
Water regulation	0.8	1.3
Water supply	1.2	1.9
Erosion and sediment control	38.8	62.5
Soil formation	4.0	6.4
Nutrient cycling	146.1	235.2
Waste Treatment	35.2	56.7
Biological Control	0.8	1.3
Food Production	17.4	28.0
Raw Materials	55.8	89.8
Genetic Resources	6.5	10.5
Recreation	26.7	43.0
Cultural	0.8	1.3
<b>Total</b>	<b>392.1</b>	<b>631.3</b>

1. \$2010 computed at 3% annually.

A contingent value study by University of Rhode Island economists found natural resources values in the Peconic Estuary watershed in Suffolk County on Long Island New York ranged from \$6,560/ac for wetlands to \$9,979/ac for farmland in \$1995 (Johnston et al. 2002). The University of Maryland studied the National Wildlife Refuge System and determined ecosystem values of freshwater wetlands and forests were \$6,268/ac and \$845/ac, respectively (Ingraham and Foster 2008). The Audubon Society found the economic value of ecosystems in Massachusetts ranged from \$984/ac for forests to \$15,452/ac for saltwater wetlands (Breunig 2003).

According to the 2007 USDA Census of Agriculture (2009) the market value of agricultural crops, poultry, and livestock sold from 1,926,524 acres of farmland in the Delaware River Basin was \$3.37 billion or \$1,676/ac. The market value of agriculture from 254,143 acres of farmland in Delaware in the basin was \$636 million or \$2,502/ac. The market value of agriculture from 505,507 acres of farmland in New Jersey was \$602 million or \$1,192/ac. The market value of agriculture from 187,561 acres of farmland in New York in the basin was \$105 million or \$562/ac. The market value of agriculture from 979,313 acres of farmland in Pennsylvania counties in the basin was \$2.0 billion or \$2,070/ac.

Table 49 compares ecosystem services values (\$/acre) from other studies. Data from the NJDEP/University of Vermont study are used for value transfer since the Delaware Basin includes New Jersey ecosystems and two adjacent states in the watershed (Del. and Pa.) share a similar climate (humid continental) at 40 degrees north in latitude, similar physiographic provinces (Piedmont/Coastal Plain) and similar aquifers, soils, and ecosystems. Farmland natural goods values are estimated from market values from the 2007 USDA Census of Agriculture. Cecil County, Maryland occupies a small sliver of the Delaware Basin and utilized higher ecosystem values on a per acre basis for forests and wetlands than the other studies. The NJDEP ecosystem service estimates (\$/ac) are lower than Cecil County values for wetlands/forests and Mass Audubon values for

wetlands but higher than Wilderness Society values for forests and U. S. Wildlife Refuge values for freshwater wetlands and forests. Values from previous studies were adjusted to \$2010 based on 3% annually. Net present values were calculated based on an annual discount rate of 3% in perpetuity (over 100 years in the future).

**Table 49.** Comparison of ecosystem service value studies

Ecosystem	Cecil Co. Maryland 2006 (\$/ac/yr)	New Jersey DEP 2004 (\$/ac/yr)	Wilderness Society 2001 (\$/ac/yr)	Peconic Estuary 1995 (\$/ac/yr)	US Wildlife Refuge 2008 (\$/ac/yr)	Mass Audubon 2003 (\$/ac/yr)	USDA Census <sup>1</sup> 2007 (\$/ac/yr)
Freshwater wetland	43,685	11,802			6,268	15,452	
Marine		8,670					
Farmland		6,229		9,979		1,387	1,676
Forest land	12,033	1,714	641		845	984	
Saltwater wetland	28,146	6,269		\$6,560		12,580	
Undeveloped				\$2,080			
Urban		296					
Beach/dune		42,149					
Open freshwater		1,686			217	983	
Riparian buffer	52,765	3,500					
Shellfish areas				\$4,555			

1. Value of goods only as measured by agricultural crops, livestock, and poultry sold.

## Delaware Basin

The estimated value of natural goods and services provided by ecosystems in the Delaware River Basin (12,742 sq mi) is \$21 billion (\$2010) with a net present value (NPV) of \$683 billion (Table 50). The ecosystems services value of the Delaware portion of the Delaware Basin (965 sq mi) is \$2.5 billion (\$2010) with a NPV of \$81.4 billion (Figure 13). The ecosystems services value of the New Jersey portion of the Delaware Basin (2,960 sq mi) is \$6.6 billion (\$2010) with a NPV of \$213.4 billion. The ecosystems services value of the New York portion of the Delaware Basin (2,556 sq mi) is \$3.5 billion (\$2010) with a NPV of \$113.6 billion. The ecosystems services value of the Pennsylvania portion of the basin (6,290 sq mi) is \$8.6 billion (\$2010) with a NPV of \$279.6 billion. NPV is based on an annual discount rate of 3% over a perpetual life time (>100 years).

Natural goods are commodities that can be sold such as water supply, farm crops, fish, timber, and minerals). Natural services provide ecological benefits to society such as flood control by wetlands, water filtration by forests, and fishery habitat by beach and marine areas. Ecosystems within the Delaware Basin are comprised of forests (53%), farmland (24%), freshwater wetlands (5%), saltwater wetlands (2%), and open water/marine (1%). Over 15% of the Delaware Basin is urban (Figure 14).

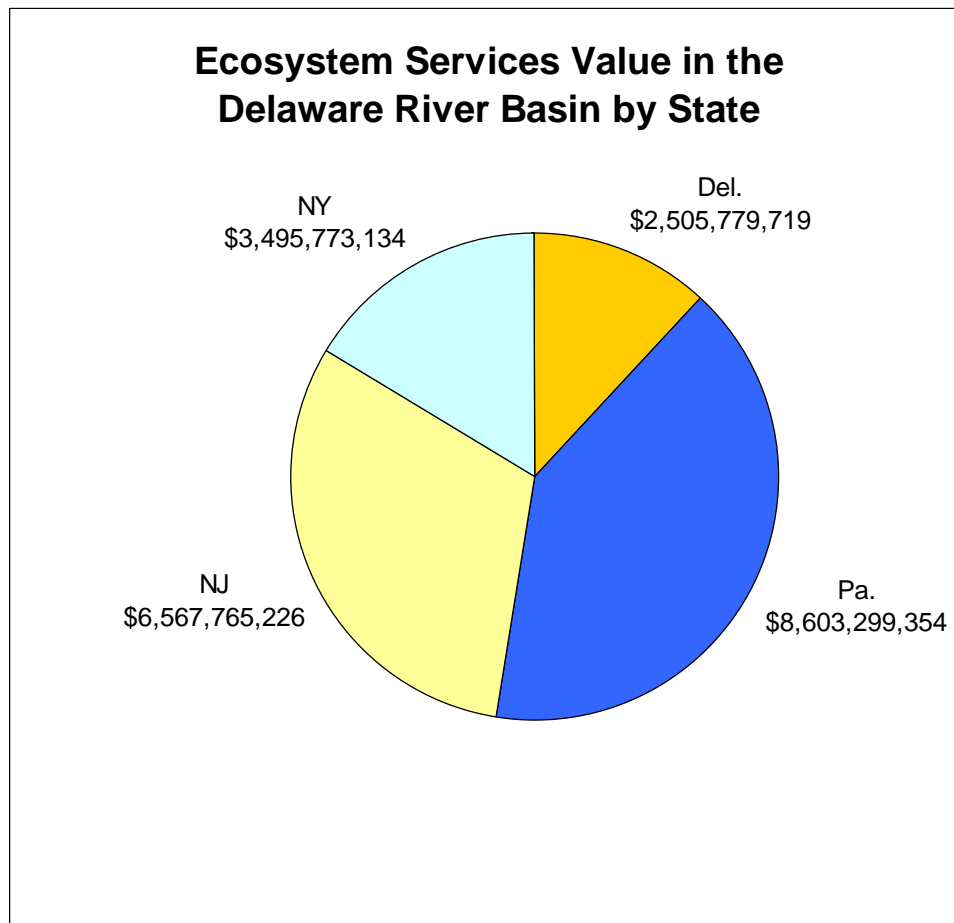
Farms, freshwater wetlands, forests, and saltwater wetlands provide the highest total ecosystems goods and services values (Table 51 and Figures 15 and 16). Ecosystems that provided the highest natural good values are farmland (\$3.2 billion or \$1,676/ac/ yr), followed by forest (\$1.2 billion or \$275/ac), and freshwater wetlands (\$114 million or \$270/ac). The highest natural ecosystem services values are provided by forests (\$7.4 billion or \$1,703/ac) followed by freshwater wetlands

(\$5.6 billion or \$13,351/ac), farmland (\$1.6 billion or \$827/ac), and saltwater wetlands (\$1.0 billion or \$7,076/ac).

The DB2 Delaware Bay (\$2,497,635,761), UE2 New Jersey Coastal Plain (\$2,093,235,974), DB1 Delaware Bay (\$1,922,732,778), NM1 Neversink R. (\$1,212,219,295), EW2 West Branch Del. R. (\$1,137,547,038), UC1 Pocono Mt. (\$1,106,108,992), UC2 NJ Highlands (\$1,072,263,808), SV3 Schuylkill above Philadelphia (\$1,098,758,690), and LW1 Lackawaxen R. (\$1,006,865,455) watersheds each provide over \$1 billion in annual ecosystem services value (Table 52 and Figure 17).

Watersheds with the highest value of annual ecosystem services per acre include the DB2 Delaware Bay (\$4,991/ac), DB1 Delaware Bay (\$4,797/ac), LE3 Salem River (\$4,288/ac), LE2 C&D Canal (\$3,941/ac), UE2 New Jersey Coastal Plain (\$3,205/ac), LW1 Lackawaxen R. (\$2,631/ac), NM1 Neversink R. (\$2,321/ac), SV2 Schuylkill above Valley Forge (\$2,276/ac), and LV1 Lehigh River above Lehighon (\$2,263/ac) as these systems have high amounts (over 75%) of forests, wetlands, and farm habitat (Figure 18).

The above estimates do not include the ecosystem services value of open water (720 sq mi) in the tidal Delaware River and Bay between the shores of Delaware, Pennsylvania, and New Jersey. The ecosystem services value of open water habitat in the river and bay is \$61 billion or \$1,946/ac.



**Figure 13.** Ecosystem service value in the Delaware Basin by state

**Table 50.** Ecosystem services values in the Delaware River Basin by state

Ecosystem	Area (ac)	\$/ac/yr 2010	PV 2010 \$	NPV \$
<b>Delaware Basin</b>				
Freshwater wetlands	422,838	13,621	5,759,329,048	187,178,194,067
Marine	16,588	10,006	165,982,947	5,394,445,767
Farmland	1,926,524	2,503	4,823,030,404	156,748,488,136
Forest land	4,343,190	1,978	8,591,367,360	279,219,439,184
Saltwater wetland	145,765	7,235	1,054,617,851	34,275,080,170
Urban	1,206,504	342	412,157,579	13,395,121,322
Beach/dune	900	48,644	43,758,633	1,422,155,566
Open water	92,615	1,946	180,210,703	5,856,847,857
<b>Total</b>	<b>8,154,924</b>		<b>\$21,030,454,525</b>	<b>\$683,489,772,069</b>
<b>Delaware</b>				
Freshwater wetlands	58,390	13,621	795,317,362	25,847,814,257
Marine	16,274	10,006	162,840,906	5,292,329,460
Farmland	254,143	3,329	846,164,877	27,500,358,509
Forest land	95,346	1,978	188,605,634	6,129,683,090
Saltwater wetland	61,617	7,235	445,802,585	14,488,584,028
Urban	123,048	342	42,034,778	1,366,130,274
Beach/dune	256	48,644	12,429,832	403,969,529
Open water	6,467	1,946	12,583,745	408,971,719
<b>Total</b>	<b>615,541</b>		<b>\$2,505,779,719</b>	<b>\$81,437,840,867</b>
<b>New Jersey</b>				
Freshwater wetlands	246,857	13,621	3,362,352,134	109,276,444,364
Marine	314	10,006	3,142,040	102,116,307
Farmland	505,507	2,019	1,020,866,015	33,178,145,495
Forest land	682,931	1,978	1,350,922,709	43,904,988,032
Saltwater wetland	83,563	7,235	604,583,594	19,648,966,813
Urban	321,090	342	109,688,612	3,564,879,893
Beach/dune	499	48,644	24,253,858	788,250,378
Open water	47,259	1,946	91,956,264	2,988,578,571
<b>Total</b>	<b>1,888,020</b>		<b>6,567,765,226</b>	<b>213,452,369,853</b>
<b>New York</b>				
Freshwater wetlands	34,792	13,621	473,886,107	15,401,298,475
Marine	0	10,006	0	0
Farmland	187,561	1,389	260,613,634	8,469,943,113
Forest land	1,387,514	1,978	2,744,673,732	89,201,896,298
Saltwater wetland	0	7,235	0	0
Urban	20,806	342	7,107,761	231,002,225
Beach/dune	0	48,644	0	0
Open water	4,878	1,946	9,491,900	308,486,749
<b>Totalac</b>	<b>1,635,551</b>		<b>3,495,773,134</b>	<b>113,612,626,859</b>
<b>Pennsylvania</b>				
Freshwater wetlands	82,799	13,621	1,127,773,445	36,652,636,971
Marine	0	10,006	0	0
Farmland	979,313	2,897	2,837,548,786	92,220,335,530
Forest land	2,177,399	1,978	4,307,165,285	139,982,871,763
Saltwater wetland	585	7,235	4,231,672	137,529,329
Urban	741,560	342	253,326,429	8,233,108,930
Beach/dune	145	48,644	7,074,943	229,935,659
Open freshwater	34,011	1,946	66,178,794	2,150,810,818
<b>Total</b>	<b>4,015,812</b>		<b>8,603,299,354</b>	<b>279,607,229,001</b>

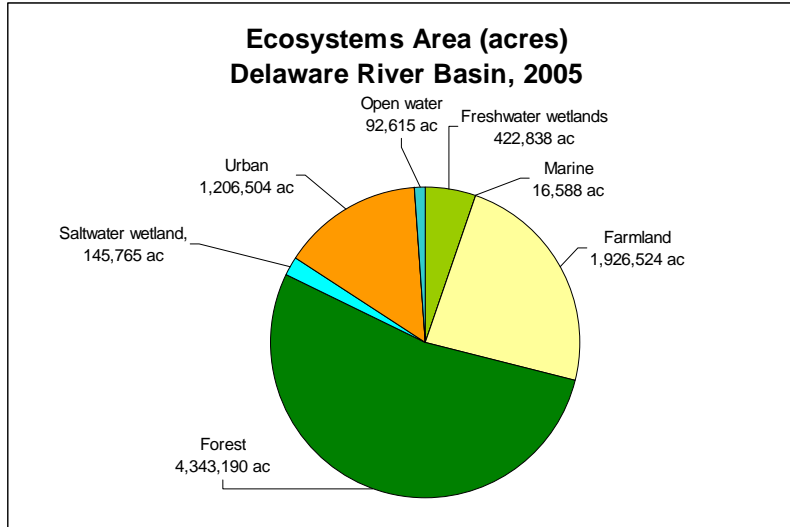


Figure 14. Ecosystem service areas within the Delaware River Basin

Table 51. Value of ecosystem goods and services in the Delaware River Basin

Natural Goods						
Ecosystem	Area (ac)	\$/ac/yr 2004	\$/yr 2004	\$/ac/yr 2010	\$/yr 2010	NPV \$
Freshwater wetlands	422,838	234	98,943,997	270	114,191,069	3,711,209,745
Marine	16,588	1,125	18,661,829	1,298	21,537,580	699,971,336
Farmland	1,926,524	1,676	3,228,854,342	1,676	3,228,854,342	104,937,766,110
Forest land	4,343,190	238	1,033,679,112	275	1,192,966,996	38,771,427,378
Saltwater wetland	145,765	139	20,261,377	160	23,383,615	759,967,482
Urban	1,206,504	13	15,684,557	15	18,101,515	588,299,247
Beach/dune	900	0	0	0	0	0
Open water	92,615	921	85,298,217	1,063	98,442,502	3,199,381,302
<b>Total</b>	<b>8,154,924</b>		<b>4,501,383,431</b>		<b>4,697,477,618</b>	<b>152,668,022,601</b>
Natural Services						
Ecosystem	Area (ac)	\$/ac/yr 2004	\$/yr 2004	\$/ac/yr 2010	\$/yr 2010	NPV \$
Freshwater wetlands	422,838	11,568	4,891,385,289	13,351	5,645,137,979	183,466,984,322
Marine	16,588	7,544	125,142,079	8,707	144,426,223	4,693,852,233
Farmland	1,926,524	717	1,381,317,758	827	1,594,176,062	51,810,722,026
Forest land	4,343,190	1,476	6,410,547,773	1,703	7,398,400,363	240,448,011,806
Saltwater wetland	145,765	6,131	893,687,073	7,076	1,031,402,464	33,520,580,080
Urban	1,206,504	283	341,440,730	327	394,056,064	12,806,822,075
Beach/dune	900	42,149	37,915,873	48,644	43,758,633	1,422,155,566
Open water	92,615	765	70,850,311	883	81,768,202	2,657,466,554
<b>Total</b>	<b>8,154,924</b>		<b>14,152,286,885</b>		<b>16,333,125,990</b>	<b>530,826,594,663</b>
Goods & Services						
Ecosystem	Area (ac)	\$/ac/yr 2004	\$/yr 2004	\$/ac/yr 2010	\$/yr 2010	NPV \$
Freshwater wetlands	422,838	11,802	4,990,329,286	13,621	5,759,329,048	187,178,194,067
Marine	16,588	8,670	143,820,496	10,006	165,982,947	5,394,445,767
Farmland	1,926,524	2,503	4,823,030,404	2,503	4,823,030,404	156,748,488,136
Forest land	4,343,190	1,714	7,444,226,885	1,978	8,591,367,360	279,219,439,184
Saltwater wetland	145,765	6,269	913,802,685	7,235	1,054,617,851	34,275,080,170
Urban	1,206,504	296	357,125,287	342	412,157,579	13,395,121,322
Beach/dune	900	42,149	37,915,873	48,644	43,758,633	1,422,155,566
Open water	92,615	1,686	156,148,527	1,946	180,210,703	5,856,847,857
<b>Total</b>	<b>8,154,924</b>		<b>18,866,399,443</b>		<b>21,030,454,525</b>	<b>683,489,772,069</b>

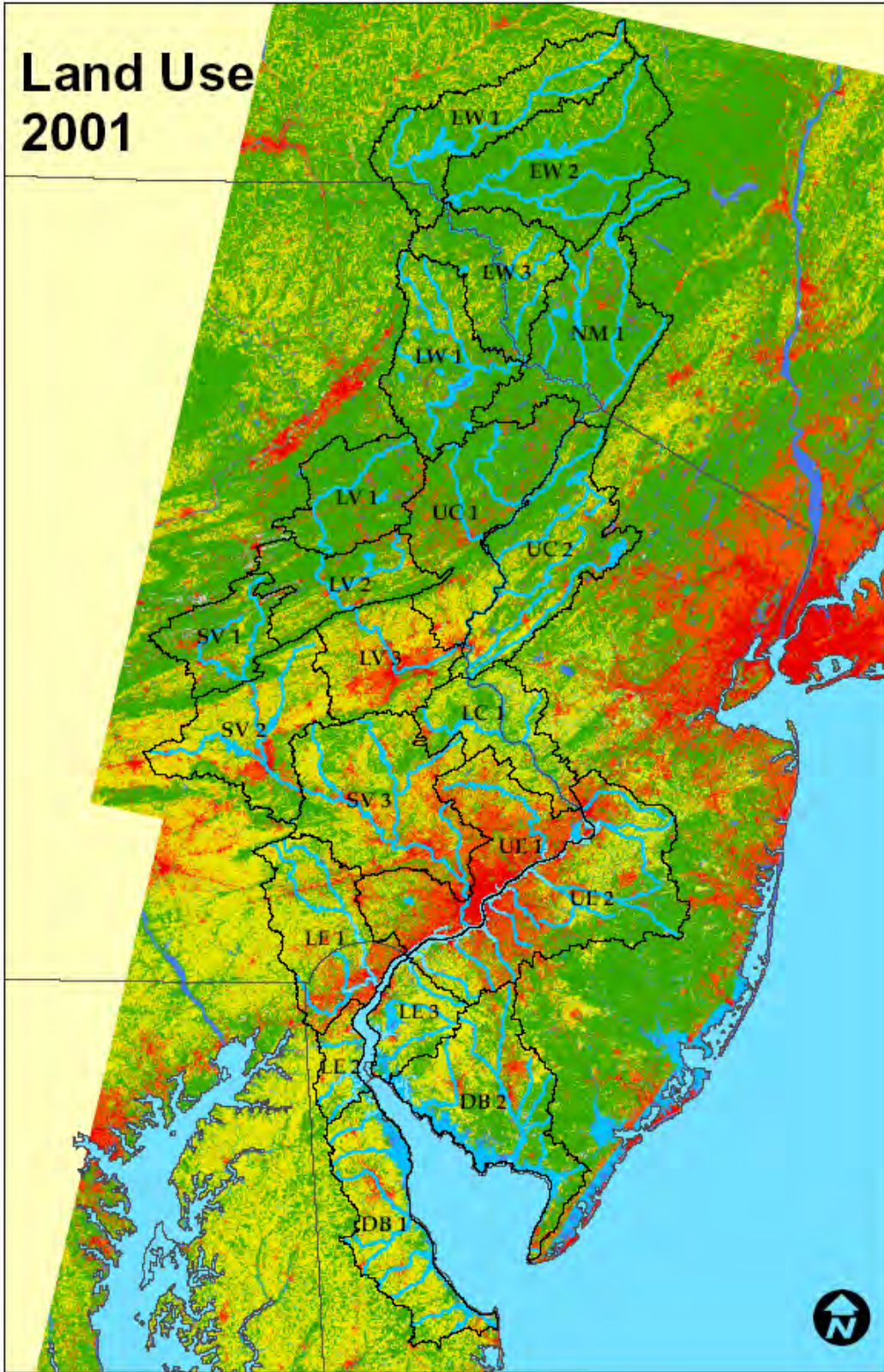


Figure 15. Land cover in the Delaware River Basin (NOAA CSC 2001)

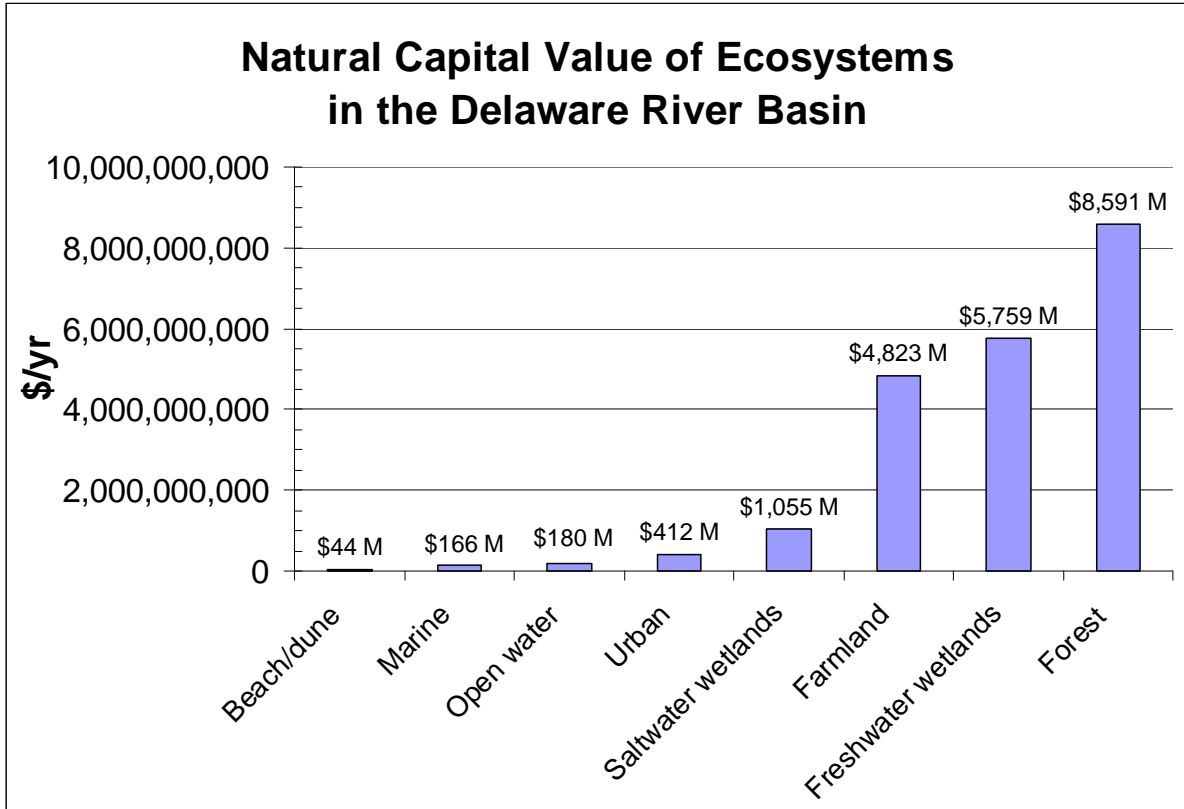


Figure 16. Ecosystem service value (\$2010) of habitat within the Delaware River Basin

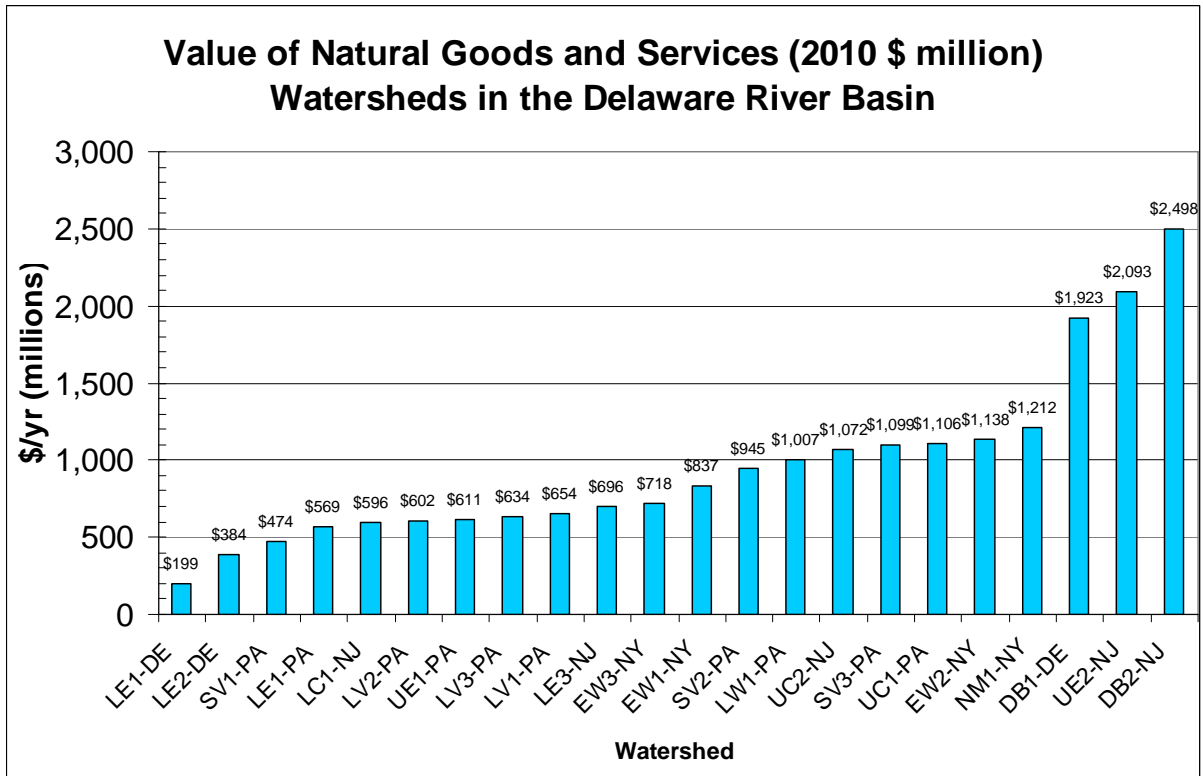


Figure 17. Ecosystem services values of watersheds within the Delaware River Basin



**Table 52.** Ecosystem services value of watersheds in the Delaware River Basin

Watershed	Area (sq mi)	2010 \$/yr	2010 \$/ac/yr
LE1 Brandywine/Christina	187	199,035,649	1,664
LE2 C&D Canal	152	384,011,292	3,941
DB1 Delaware Bay	626	1,922,732,778	4,797
<b>Delaware</b>	<b>962</b>	<b>2,505,779,719</b>	<b>4,071</b>
UC2 NJ Highlands	745	1,072,263,808	2,248
LC1 Del. R. above Trenton	159	208,902,978	2,053
UE2 New Jersey Coastal Plain	1,021	2,093,235,974	3,205
LE3 Salem River	254	695,858,091	4,288
DB2 Delaware Bay	782	2,497,635,761	4,991
<b>New Jersey</b>	<b>2,950</b>	<b>6,567,765,226</b>	<b>3,479</b>
EW1 East Branch Del. R.	666	836,579,484	1,963
EW2 West Branch Del. R.	841	1,137,547,038	2,114
EW3 Del. R. above Pt. Jarvis	314	430,101,000	2,142
NM1 Neversink R.	734	1,076,794,000	2,321
<b>New York</b>	<b>2,556</b>	<b>3,495,773,134</b>	<b>2,137</b>
EW3 Del. R. above Pt. Jarvis	210	287,647,100	2,142
NM1 Neversink R.	82	135,425,000	2,321
LW1 Lackawaxen R.	598	1,006,865,455	2,631
UC1 Pocono Mt.	779	1,106,108,992	2,219
LV1 Lehigh River above Lehighton	451	653,896,676	2,263
LV2 Lehigh River above Jim Thorpe	430	601,508,831	2,183
LV3 Lehigh River above Bethlehem	480	633,649,592	2,064
LC1 Del. R. above Trenton	295	387,587,286	2,053
SV1 Schuylkill above Reading	348	474,099,567	2,126
SV2 Schuylkill above Valley Forge	649	945,100,081	2,276
SV3 Schuylkill above Philadelphia	874	1,098,758,690	1,965
UE1 Penna Fall Line	693	611,041,618	1,377
LE1 Brandywine/Christina	401	568,524,810	2,216
<b>Pennsylvania</b>	<b>6,275</b>	<b>8,603,299,354</b>	<b>2,142</b>
<b>Delaware Basin</b>	<b>12,742</b>	<b>21,030,454,525</b>	<b>2,579</b>

Estimates of ecosystem services in the Delaware River Basin using the NJDEP/University of Vermont values coupled with market values from the USGS Census of Agriculture (\$21.0 billion or \$683.5 billion NPV) are conservative and in the lower end of the range. If lower per acre estimates of ecosystem services value from other studies were used instead of the NJDEP values, the total value of natural resources in the Delaware Basin would be \$9.6 billion or NPV = \$311 billion (Table 53). If higher per acre estimates of ecosystem services value from other studies were used, the total value of natural resources in the Delaware Basin would be \$94.7 billion or NPV = \$3.1 trillion (Table 54).

<u>Estimate</u>	<u>PV \$B</u>	<u>NPV \$B</u>
Low	9.6	311
NJDEP/USDA	21.0	683
High	94.7	3,100

**Table 53.** Low range estimate of ecosystem services in the Delaware River Basin

Ecosystem	Area (ac)	\$/ac/yr	PV \$	NPV \$
Freshwater wetlands	422,838	6,268 <sup>5</sup>	2,650,346,040	86,136,246,300
Marine	16,588	8,670 <sup>2</sup>	143,820,496	4,674,166,116
Farmland	1,926,524	1,387 <sup>6</sup>	2,672,088,886	86,842,888,779
Forest land	4,343,190	641 <sup>3</sup>	2,783,984,500	90,479,496,255
Saltwater wetland	145,765	6,269 <sup>2</sup>	913,802,685	29,698,587,269
Barren land	18,630	0	0	0
Urban	1,206,504	296 <sup>2</sup>	357,125,287	11,606,571,818
Beach/dune	900	42,149 <sup>2</sup>	37,915,873	1,232,265,862
Open water	92,615	217 <sup>5</sup>	20,097,408	653,165,771
<b>Total</b>	<b>acres</b>	<b>8,173,554</b>	<b>9,579,181,174</b>	<b>311,323,388,171</b>
	<b>sq mi</b>	<b>12,771</b>		

**Table 54.** High range estimate of ecosystem services in the Delaware River Basin

Ecosystem	Area (ac)	\$/ac/yr	PV \$	NPV \$
Freshwater wetlands	422,838	43,685 <sup>1</sup>	18,471,660,300	600,328,959,736
Marine	16,588	8,670 <sup>2</sup>	143,820,496	4,674,166,116
Farmland	1,926,524	9,979 <sup>4</sup>	19,224,783,698	624,805,470,173
Forest land	4,343,190	12,033 <sup>1</sup>	52,261,599,829	1,698,501,994,444
Saltwater wetland	145,765	28,146 <sup>1</sup>	4,102,710,221	133,338,082,193
Barren land	18,630	0	0	0
Urban	1,206,504	296 <sup>2</sup>	357,125,287	11,606,571,818
Beach/dune	900	42,149 <sup>2</sup>	37,915,873	1,232,265,862
Open water	92,615	1,686 <sup>2</sup>	156,148,527	5,074,827,144
<b>Total</b>	<b>acres</b>	<b>8,173,554</b>	<b>94,755,764,230</b>	<b>3,079,562,337,486</b>
	<b>sq mi</b>	<b>12,771</b>		

1. Cecil Co., Md. 2006.
2. NJDEP 2007.
3. Wilderness Society 2001.
4. Peconic Estuary 1995.
5. U. S. Nat'l. Wildlife Refuge 2008.
6. Mass Audubon Society 2003.
7. USDA Agric. Census 2007.

## 5. Jobs and Wages

The Delaware River Basin is a jobs engine that supports 600,000 direct and indirect jobs with \$10 billion in annual wages in the coastal, farm, ecotourism, water/wastewater, recreation, and port industries (Table 55).

**Table 55.** Direct and indirect jobs and wages related to the Delaware River Basin

Sector	Jobs	Wages (\$ million)	Data Source
Direct Basin Related	240,621	4,900	U.S. Bureau of Labor Statistics, 2009
Indirect Basin Related	288,745	4,000	U.S. Census Bureau, 2009
Coastal	44,658	947	National Coastal Economics Program, 2009
Farm	45,865	1,880	USDA Census of Agriculture, 2007
Fishing/Hunting/Birding	44,941	1,476	U.S. Fish and Wildlife Service, 2008
Water Supply Utilities	8,750	485	UDWRA and DRBC, 2010
Wastewater Utilities	1,298	61	UDWRA and DRBC, 2010
Watershed Organizations	201	10	UDWRA and DRBC, 2010
Ski Area Jobs	1,753	\$88	Penna. Ski Areas Association
Paddling-based Recreation	4,226		Outdoor Industry Association (2006
River Recreation	448	\$9	U. S. Forest Service/Nat'l. Park Service, 1990
Canoe/Kayak/Rafting	225		Canoe Liveries and UDWRA, 2010
Wild Trout Fishing	350	\$4	Maharaj, McGurrin, and Carpenter, 1998
Del. Water Gap Nat'l. Rec. Area	7,563	101	Stynes and Sun, 2002
Port Jobs	12,121	772	Economy League of Greater Phila., 2008
<b>Delaware Basin Total</b>	<b>&gt; 600,000</b>	<b>&gt;\$10 billion</b>	

Jobs and salaries in the Delaware Basin were obtained from U. S. Bureau of Labor Statistics (2009) and U. S. Census Bureau (2009) data bases for the following scenarios (Tables 56-58):

1. Total number of jobs in each county within the Delaware Basin with jobs determined by NAICS industry code (formerly SIC code) and then grouped by census tract.
2. Direct Delaware Basin-related jobs such as water and sewer construction, living resources, maritime, tourism/recreation, ports, environmental services, and water/wastewater management determined for each NAICS code by state and county within the basin boundary.
3. Indirect jobs/wages provided by purchases of goods and services by direct jobs earners within the Delaware Basin in the interlinked regional economy. Indirect jobs were estimated by a multiplier of 2.2 applied to direct jobs and 1.8 to direct wages (Latham and Stapleford 1990), i.e., 100 direct jobs fund 120 indirect jobs and direct wages of \$1,000 provide \$800 indirect wages.

Within the Delaware Basin are 3,480,483 jobs earning \$172.6 billion in annual wages including:

- Delaware (316,014 jobs, \$16.5 billion wages)
- New Jersey (823,294 jobs, \$38.1 billion wages)
- New York (69,858 jobs, \$2.5 billion wages)
- Pennsylvania (2,271,317 jobs, \$115.5 billion wages)

Jobs directly associated with the Delaware River Basin (such as water/sewer construction, water utilities, fishing, recreation, tourism, and ports) employ 240,621 with \$4.9 billion in wages including:

- Delaware (15,737 jobs, \$340 million wages)
- New Jersey (62,349 jobs, \$1.3 billion wages)
- New York (32,171 jobs, \$550 million wages)
- Pennsylvania (130,364 jobs, \$2.8 billion wages)

Jobs indirectly related to the waters of the Delaware Basin (based on multipliers of 2.2 for jobs and 1.8 for salaries) employ 288,745 people with \$4.0 billion in wages including:

- Delaware (18,884 jobs, \$270 million wages)
- New Jersey (74,819 jobs, \$1.0 billion in wages)
- New York (38,605 jobs, \$400 million in wages)
- Pennsylvania (156,437 jobs, \$2.2 billion in wages)

### **National Coastal Economy Report**

The National Ocean Economic Program (2009) published a report that summarized the coastal economy in the United States that includes 6 industrial sectors:

- Marine Transportation
- Tourism and Recreation
- Living Marine Resources
- Marine Construction
- Ship and Boat Building
- Mineral Extraction.

According to the National Ocean Economic program (2009), the coastal counties within the Delaware Basin boundary contribute 44,658 coastal jobs with \$947 million in annual wages with contributions of \$1.8 billion toward the GDP. Table 59 summarizes employment, wages, and employment within the Delaware Basin obtained by multiplying the 2009 NOEP report county-wide values by the ratios of coastal county area within the basin by total coastal county area within the state which are 80% for Delaware, 5% for New Jersey and 86% for Pennsylvania. Using these ratios, 80%, 5%, and 86% of the employment and wages for coastal counties in Delaware, New Jersey, and Pennsylvania from the NOEP report are within the Delaware Basin boundary.

**Table 56.** Direct basin-related jobs within the Delaware River Basin by state, 2009

Sector	Industry	1997 NAICS Code	DE Jobs	DE Wages x\$1,000	NJ Jobs	NJ Wages \$1,000	NY Jobs	NY Wages \$1,000	PA Jobs	PA Wages x\$1,000	
<b>Construction</b>	Marine Related	237120			81	4,532			923	58,999	
	Water and Sewer	23711	529	21,838	2,485	109,527	551	36,387	3,138	211,691	
	Construction	237990	126	5,678	318	19,547			306	16,427	
<b>Living Resources</b>	Fish Hatcheries	112511									
	Aquaculture	112512									
	Fishing/Forestry	11411			50	2,028	21	424	67	2,485	
	Finfish Fishing	114111			111	5,591					
	Shellfish Fishing	114112			28	995					
	Seafood Markets	445220	39	1,447	81	1,550			283	6,348	
	Seafood Process.	31171			97	6,734					
	Comm. Fisheries		0	0	0	0			0	0	
	<b>Minerals</b>	Sand & Gravel	212321			166	8,109				
		212322	0	0	81	3,865					
	Oil & Gas	541360	16	752					39	3,802	
<b>Ship/Boat Building</b>	Boat Bldg. Repair	336612									
	Ship Bldg. Repair	336611									
	Shipbuilding		0	0	0	0			0	0	
<b>Tourism/Recreation</b>	Recreation	487990			52	1,184					
		611620	64	513	305	5,301			675	12,270	
		532292			50	774					
	Amusement	713990	250	4,102	2,426	35,967	11,537	162,246	2,008	31,251	
	Misc. Recreation				0	0	1,100	16,574	0	0	
	Boat Dealers	441222	198	7,489	157	5,945					
		Restaurants	722110	3,714	173,787	26,512	415,604	17,029	264,832	59,217	974,264
			722211	6,797	4,102	14,697	190,314			31,766	422,438
			722212	265	3,876	312	4,717			1,138	18,281
			722213	942	13,509	2,388	32,495			7,628	119,695
		Hotels & Lodging	721110	650	11,673	2,323	52,310			6,965	243,253
			721191			92	1,583				
		Marinas	713930			202	6,410				
		RV Park/Camps	721211	105	3,611	339	11,894			39	494
	Scenic Tours	487210	18	393	37	748					
	Sporting Good	339920	0	0	245	5,287	702	9,972	245	3,780	
	Zoos, Aquaria	712130							55	1,959	
		712190			58	3,411			466	28,459	
<b>Transportation</b>	Deep Sea Freight	483111									
	Marine Transport.	483112	954	32,378	1,823	71,222			904	43,155	
	Search/Navigation	334511	39	2,856					716	61,370	
	Warehousing	493110	313	13,739	2,396	95,952			8,477	336,427	
			493120			361	14,120			337	14,571
		Ports		0	0	0	0			0	0
		Dredging/Disposal		0	0	0	0			0	0
<b>Education/Research</b>	Environ.organizations	813312	83	2,976	61	2268	103	1,221	682	23,574	
	Environ. consulting	54162	205	10,745	1,193	61,107	133	7,700	1,441	895	
<b>Water/Wastewater</b>	Water/sewage systms	2213	267	20,004	679	8,169	23	1,101	203	774	
	Waste management	562	146	6,028	1,928	92,495	882	41,649	2,372	113,437	
	Septic tank services	562991	17	644	215	10,381	90	4,173	274	10,145	
<b>Total</b>			<b>15,737</b>	<b>342,140</b>	<b>62,349</b>	<b>1,292,136</b>	<b>32,171</b>	<b>546,279</b>	<b>130,364</b>	<b>2,760,244</b>	

**Table 57.** Jobs and wages directly and indirectly related to the Delaware River Basin, 2009

State/County	(1) Total Jobs	(2) Basin Jobs	(3) Direct Jobs	(4) Indirect Jobs	(1) Total Wages \$ billion	(2) Basin Wages \$ billion	(3) Direct Wages \$ billion	(4) Indirect Wages \$ billion
<b>Delaware</b>	<b>390,900</b>	<b>316,014</b>	<b>15,737</b>	<b>18,884</b>	<b>19.5</b>	<b>16.5</b>	<b>0.34</b>	<b>0.27</b>
Kent	60,100	50,412			2.4	2.0		
New Castle	264,600	252,534			14.7	14.1		
Sussex	66,200	13,068			2.4	0.5		
<b>New Jersey</b>	<b>1,362,200</b>	<b>823,294</b>	<b>62,349</b>	<b>74,819</b>	<b>61.6</b>	<b>38.1</b>	<b>1.3</b>	<b>1.0</b>
Burlington	194,500	187,758			9.1	8.8		
Camden	196,800	169,909			8.7	7.5		
Cape May	47,500	14,545			1.4	0.4		
Cumberland	62,000	61,868			2.5	2.5		
Gloucester	99,100	89,183			3.9	3.6		
Hunterdon	47,300	23,650			2.8	1.4		
Mercer	222,900	178,320			12.4	9.9		
Monmouth	246,600	9,864			11.4	0.5		
Ocean	149,900	7,495			5.5	0.3		
Salem	21,900	21,900			1.0	1.0		
Sussex	38,200	23,302			1.4	0.9		
Warren	35,500	35,500			1.5	1.5		
<b>New York</b>	<b>341,300</b>	<b>69,858</b>	<b>32,171</b>	<b>38,605</b>	<b>12.8</b>	<b>2.5</b>	<b>0.55</b>	<b>0.4</b>
Broome	94,100	11,292			3.4	0.4		
Delaware	16,000	14,240			0.6	0.5		
Greene	14,300	572			0.5	19.9		
Orange	130,700	10,456			5.2	0.4		
Sullivan	26,300	25,511			0.9	0.9		
Ulster	59,900	7,787			2.2	0.3		
<b>Pennsylvania</b>	<b>2,596,260</b>	<b>2,271,317</b>	<b>130,364</b>	<b>156,437</b>	<b>126.5</b>	<b>115.5</b>	<b>2.8</b>	<b>2.2</b>
Berks	159,106	150,665			6.2	5.9		
Bucks	244,453	244,453			10.6	10.6		
Carbon	16,730	16,730			0.5	0.5		
Chester	231,368	212,996			13.6	12.5		
Delaware	201,208	201,208			10.1	10.1		
Lackawanna	96,604	4,830			3.2	0.2		
Lebanon	45,826	2,750			1.5	0.1		
Lehigh	166,932	166,932			7.4	7.4		
Luzerne	134,574	8,074			4.6	0.3		
Monroe	56,025	56,025			2.1	2.1		
Montgomery	453,962	453,771			27.7	27.7		
Northampton	96,536	96,536			3.8	3.8		
Philadelphia	619,396	619,396			33.3	33.3		
Pike	9,874	9,874			0.3	0.3		
Schuylkill	49,116	27,077			1.6	0.9		
Wayne	14,550	14,114			0.5	0.4		
<b>Delaware Basin</b>	<b>4,690,660</b>	<b>3,480,483</b>	<b>240,621</b>	<b>288,745</b>	<b>220.3</b>	<b>172.6</b>	<b>4.9</b>	<b>4.0</b>

**Table 58.** Direct basin-related and indirect jobs within the Delaware River Basin, 2009

Sector	Industry	1997 NAICS Codes	Direct Jobs	Direct Wages (x\$1,000)	Indirect Jobs <sup>1</sup>	Indirect Wages <sup>2</sup> (x\$1,000)
<b>Construction</b>	Marine Related	237120	1,004	63,531	1,205	50,825
	Water and Sewer	23711	6,703	379,443	8,044	303,554
	Construction	237990	750	41,652	900	33,322
<b>Living Resources</b>	Fish Hatcheries	112511	0	0	0	0
	Aquaculture	112512	0	0	0	0
	Fishing/Forestry	11411	138	4,937	166	3,950
	Finfish Fishing	114111	111	5,591	133	4,473
	Shellfish Fishing	114112	28	995	34	796
	Seafood Markets	445220	403	9,345	484	7,476
	Seafood Process.	31171	97	6,734	116	5,387
	Comm. Fisheries		0	0	0	0
	<b>Minerals</b>	Sand & Gravel	212321	166	8,109	199
		212322	81	3,865	97	3,092
	Oil & Gas	541360	55	4,554	66	3,643
<b>Ship/Boat Building</b>	Boat Bldg. Repair	336612	0	0	0	0
	Shipbuilding		0	0	0	0
<b>Tourism/Recreation</b>	Recreation	487990	52	1,184	62	947
		611620	1,044	18,084	1,253	14,467
		532292	50	774	60	619
	Amusement	713990	16,221	233,566	19,465	186,853
	Misc. Recreation		1,100	16,574	1,320	13,259
	Boat Dealers	441222	355	13,434	426	10,747
	Restaurants	722110	106,472	1,828,487	127,766	1,462,790
		722211	53,260	616,854	63,912	493,483
		722212	1,715	26,874	2,058	21,499
		722213	10,958	165,699	13,150	132,559
	Hotels & Lodging	721110	9,938	307,236	11,926	245,789
		721191	92	1,583	110	1,266
	Marinas	713930	202	6,410	242	5,128
	RV Park/Camps	721211	483	15,999	580	12,799
	Scenic Tours	487210	55	1,141	66	913
	Sporting Good	339920	1,192	19,039	1,430	15,231
Zoos, Aquaria	712130	55	1,959	66	1,567	
	712190	524	31,870	629	25,496	
<b>Transportation</b>	Deep Sea Freight	483111	0	0	0	0
	Marine Transport.	483112	3,681	146,755	4,417	117,404
	Search/Navigation	334511	755	64,226	906	51,381
	Warehousing	493110	11,186	446,118	13,423	356,894
		493120	698	28,691	838	22,953
	Ports		0	0	0	0
	Dredging/Disposal		0	0	0	0
<b>Education/Research</b>	Environ.organizations	813312	929	30,039	1,115	24,032
	Environ. consulting	54162	2,972	80,447	3,566	64,357
<b>Water/Wastewater</b>	Water/sewage systms	2213	1,172	30,048	1,406	24,038
	Waste management	562	5,328	253,609	6,394	202,887
	Septic tank services	562991	596	25,343	715	20,275
<b>Total</b>			<b>240,621</b>	<b>4,940,799</b>	<b>288,745</b>	<b>3,952,639</b>

1. Direct jobs are directly related to the Delaware Basin. 2. Indirect jobs/salaries are derived from purchases of goods and services calculated by multipliers of 2.2 for jobs and 1.8 for wages.

**Table 59.** Coastal employment, wages, and GDP within the Delaware River Basin  
(National Ocean Economic Program 2009)

Sector	Employment	Wages (\$ million)	GDP (\$ million)
<b>Delaware</b>	<b>12,139</b>	<b>\$214</b>	<b>\$392</b>
Marine Construction			
Living Resources	354	\$8	\$15
Offshore Minerals			
Tourism & Recreation	10,398	\$151	\$299
Marine Transportation	1,744	\$53	\$72
Ship and Boat Building			
<b>New Jersey</b>	<b>4,423</b>	<b>\$140</b>	<b>\$235</b>
Marine Construction			\$9
Living Resources			\$7
Offshore Minerals			\$1
Tourism & Recreation	2,939		\$110
Marine Transportation			\$104
Ship and Boat Building			\$4
<b>Pennsylvania</b>	<b>28,096</b>	<b>\$593</b>	<b>\$1,204</b>
Marine Construction			\$4
Living Resources			\$172
Offshore Minerals			\$13
Tourism & Recreation	<b>20,093</b>		\$538
Marine Transportation			\$383
Ship and Boat Building			\$68
<b>Delaware Basin</b>	<b>44,658</b>	<b>\$947</b>	<b>\$1,831</b>
Marine Construction			\$12
Living Resources	354	\$8	\$195
Offshore Minerals			\$14
Tourism & Recreation	33,430	\$151	\$947
Marine Transportation	1,744	\$53	\$560
Ship and Boat Building			\$72

### Farm Jobs

In 2007 there were 30,455 farms in Delaware Basin counties or 21,840 farms within the basin boundary ( $30,455 \times 0.67 = 21,840$ ). The USDA estimates each farm employs 2.1 full time equivalent jobs. Farming provides 45,865 jobs with \$1.9 billion in wages in the Delaware Basin (Table 60).



**Table 60.** Farm jobs in the Delaware River Basin

County	Farmland by County <sup>1</sup> (ac)	Farmland in Del. Basin (ac)	Ratio Farmland County/Basin	Farms in County <sup>1</sup>	No. of Farms in Basin	Farm jobs in Basin (2.1 jobs/farm)
New Castle	51,913			825		
Kent	146,536			347		
Sussex	234,324			1,374		
<b>Delaware</b>	<b>432,773</b>	<b>254,143</b>	<b>59%</b>	<b>2,546</b>	<b>1,495</b>	<b>3,140</b>
Burlington	85,790			922		
Camden	8,760			225		
Cape May	7,976			201		
Cumberland	69,489			615		
Gloucester	46,662			669		
Hunterdon	100,027			1,623		
Mercer	21,736			311		
Monmouth	44,130			932		
Ocean	9,833			255		
Salem	96,530			759		
Sussex	65,242			1,060		
Warren	74,975			933		
<b>New Jersey</b>	<b>631,150</b>	<b>505,507</b>	<b>80%</b>	<b>8,505</b>	<b>6,812</b>	<b>14,305</b>
Broome	86,613			580		
Delaware	165,572			747		
Greene	44,328			286		
Orange	80,990			642		
Sullivan	50,443			323		
Ulster	75,205			501		
<b>New York</b>	<b>503,151</b>	<b>187,561</b>	<b>37%</b>	<b>3,079</b>	<b>1,148</b>	<b>2,410</b>
Berks	170,760			1,980		
Bucks	58,012			934		
Carbon	20,035			207		
Chester	117,145			1,733		
Delaware	1,646			79		
Lackawanna	39,756			417		
Lancaster	326,648			5,462		
Lebanon	89,566			1,193		
Lehigh	72,737			516		
Luzerne	66,577			610		
Monroe	29,165			349		
Montgomery	28,563			719		
Northampton	68,252			486		
Philadelphia	150			17		
Pike	27,569			54		
Schuylkill	81,276			966		
Wayne	92,939			603		
<b>Pennsylvania</b>	<b>1,290,796</b>	<b>979,313</b>	<b>76%</b>	<b>16,325</b>	<b>12,386</b>	<b>26,010</b>
<b>Total</b>	<b>2,857,870</b>	<b>1,926,524</b>	<b>67%</b>	<b>30,455</b>	<b>21,840</b>	<b>45,865</b>

Census of Agriculture 2007 (USDA 2009)

**Fishing/Hunting/Bird and Wildlife Recreation Jobs**

The 2007 NJDEP study estimates the average annual salary per ecotourism job is \$32,843 using figures from the U.S. Fish and Wildlife Service (2001) report on fishing, hunting, and wildlife associated recreation. If fishing, hunting, and bird/wildlife associated recreation in the Delaware

River Basin accounts for \$1.5 billion in annual economic activity (\$2006), then ecotourism provides for 44,941 jobs (Table 61).

**Table 61.** Jobs from fishing, hunting, and wildlife recreation in the Delaware River Basin

Recreation Activity <sup>1</sup>	DE in Basin <sup>2</sup> (2006 \$M)	NJ in Basin <sup>2</sup> (2006 \$M)	NY in Basin <sup>2</sup> (2006 \$M)	PA in Basin <sup>2</sup> (2006 \$M)	Delaware Basin (2006 \$M)
Fishing	48	301	46	181	576
Hunting	21	58	36	225	340
Wildlife/Bird-watching	65	215	78	202	560
<b>Total</b>	<b>134</b>	<b>574</b>	<b>160</b>	<b>608</b>	<b>1,476</b>
	<b>DE Jobs @ \$32,843</b>	<b>NJ Jobs @ \$32,843</b>	<b>NY Jobs @ \$32,843</b>	<b>PA Jobs @ \$32,843</b>	<b>Del. Basin Jobs @ \$32,843</b>
Fishing	1,461	9,165	1,401	5,511	17,538
Hunting	639	1,766	1,096	6,851	10,352
Wildlife/Bird-watching	1,979	6,546	2,375	6,150	17,051
<b>Total</b>	<b>4,080</b>	<b>17,477</b>	<b>4,872</b>	<b>18,512</b>	<b>44,941</b>

1. (USFWS 2008). 2. Prorated by ratio of basin area within state to state land area: Delaware (50%), New Jersey (40%), New York (5%) and Pennsylvania (14%).

### Water Utility Jobs

Over 300 public and private water utilities (including the City of New York with 5,600 employees and the City of Philadelphia with over 800 water system employees) withdraw up to 1,800 mgd of drinking water from surface water and groundwater supplies in the Delaware River Basin.

According to the American Water Works Association, the average salary of a water system employee is \$55,407. Therefore, water utilities in the Delaware River Basin employ at least 8,750 jobs with annual wages of \$485 million (Table 62).

### Wastewater Utility Jobs

Over 60 wastewater utilities discharge almost 1.2 billion gallons per day of treated wastewater to the Delaware River Basin. These wastewater utilities employ 1,298 employees who earn \$61 million in annual wages (Table 63).

**Table 62.** Public water supply jobs in the Delaware River Basin (DRBC and UDWRA 2010)

<b>Water Purveyor</b>	<b>Jobs</b>	<b>Salaries</b>
<b>Delaware</b>	<b>141</b>	<b>7,812,387</b>
United Water Delaware	55	3,047,385
City of Wilmington	31	1,717,617
City of Dover	14	775,698
City of Newark	7	387,849
City of Milford	6	332,442
Lewes Board of Public Works	5	277,035
Tidewater Utilities	5	277,035
Dover Air Force Base	1	55,407
New Castle Mun. Services Comm.	1	55,407
Town of Smyrna	1	55,407
Harrington	1	55,407
Camden-Wyoming Water Authority	1	55,407
Town of Milton	1	55,407
Other	12	664,884
<b>New Jersey</b>	<b>823</b>	<b>45,599,961</b>
Delaware and Raritan Canal	123	6,815,061
NJ American Water Co.	118	6,538,026
City of Trenton	78	4,321,746
City of Camden	33	1,828,431
City of Vineland	25	1,385,175
Aqua New Jersey	31	1,717,617
Merchantville-Pennsauken Water	18	997,326
Washington Twp. MUA	14	775,698
Willingboro Twp. MUA	14	775,698
Mount Holly Water	13	720,291
City of Bridgeton	11	609,477
City of Wildwood	11	609,477
Evesham Twp. MUA	8	443,256
Millville City Water Dept.	8	443,256
Evesham MUA	7	387,849
Hackettstown MUS	7	387,849
Millville Water Dept	8	443,256
Moorestown	8	443,256
Bordentown	7	387,849
Burlington Twp.	6	332,442
Mt. Laurel	6	332,442
Glassboro	6	332,442
Collingswood	6	332,442
Mapleshade	6	332,442
West Deptford	5	277,035
Woodbury	5	277,035
Burlington City	5	277,035
Pennsgrove	5	277,035
Deptford Twp.	5	277,035
Nesquehoning Boro Auth.	5	277,035
Medford Twp.	5	277,035
NJ American Mansfield/Oxford	5	277,035
Florence Twp.	5	277,035
Salem City	5	277,035
Other	201	11,136,807

<b>New York</b>	<b>5,600</b>	<b>310,279,200</b>
New York City	5,600	310,279,200
<b>Pennsylvania</b>	<b>2,186</b>	<b>121,119,702</b>
City of Philadelphia	863	47,816,241
Aqua Pennsylvania, Inc.	307	17,009,949
Forest Park/Point Pleasant Diversion	50	2,770,350
Bethlehem	46	2,548,722
Allentown	45	2,493,315
North Wales Water Authority	45	2,493,315
Bucks Co. Water and Sewer Auth.	45	2,493,315
Reading Area Water Authority	43	2,382,501
Bucks Co. Water and Sewer Auth.	41	2,271,687
Penna. American Water Co.	30	1,662,210
North Penn Water	26	1,440,582
Easton	24	1,329,768
Pennsylvania-American Water Co.	22	1,218,954
Schuylkill Co. Municipal. Authority	15	831,105
Pottstown Water Authority	14	775,698
Schuylkill Co. MUA	13	720,291
Muhlenberg Twp.	12	664,884
Lehigh County	12	664,884
PA American Nazareth	12	664,884
Hazleton	12	664,884
PA American Coatesville	12	664,884
Allentown City	12	664,884
Phoenixville Mun. Waterworks	12	664,884
Northampton Boro.	10	554,070
East Stroudsburg	10	554,070
PA American Yardley	10	554,070
Phoenixville	10	554,070
Morrisville	10	554,070
PA American Home District	10	554,070
PA American Penn District	10	554,070
Falls Twp.	10	554,070
Northampton Bucks Co. Auth.	10	554,070
Warminster Twp. MUA	10	554,070
Horsham Water and Sewer Auth.	10	554,070
Newtown Artesian Water	10	554,070
Milford	7	387,849
Tamaqua MWA	7	387,849
Leighton MWA	7	387,849
Ambler Boro	7	387,849
Brodhead Creek Reg. Auth.	7	387,849
South Whitehall Twp. Auth.	7	387,849
Emmaus Munic. Water	7	387,849
Warrington Twp.	7	387,849
Wyomissing Boro	7	387,849
Schuylkill Haven Boro.	7	387,849
PA American Water Glen Alsace	7	387,849
Palmerton Mun. Auth.	7	387,849
Quakertown Mun. Water	6	332,442
Other	263	14,572,041
<b>Delaware Basin</b>	<b>8,750</b>	<b>484,811,250</b>

**Table 63.** Jobs and salaries at wastewater utilities in the Delaware River Basin

NPDES ID	Facility	Location	State	Jobs	Salaries
DE0020338	Kent Co. Levy Court WWTR	Frederica	DE	15	705,000
DE0021512	Lewes City POTW	Lewes	DE	3	141,000
DE0020320	Wilmington Wastewater Plant	Wilmington	DE	90	4,230,000
<b>Delaware</b>				<b>108</b>	<b>5,076,000</b>
NJ0027481	Beverly City Sewer Auth. STP	Beverly	NJ	3	141,000
NJ0024678	Bordentown Sewerage Auth.	Bordentown	NJ	5	235,000
NJ0024651	Cumberland Co. Utility Auth.	Bridgeton	NJ	7	329,000
NJ0024660	Burlington City STP	Burlington	NJ	5	235,000
NJ0021709	Burlington Twp. DPW	Burlington	NJ	4	188,000
NJ0026182	Camden County MUA	Camden	NJ	80	3,760,000
NJ0021601	Carneys Point Twp. Sewer Auth	Carneys Point	NJ	3	141,000
NJ0024007	Cinnaminson Sewerage Auth.	Cinnaminson	NJ	4	188,000
NJ0023701	Florence Twp. Sewer Auth.	Florence	NJ	5	235,000
NJ0026301	Hamilton Twp. DPW WWTP	Hamilton.	NJ	16	752,000
NJ0020915	Lambertville City Sewer Auth.	Lambertville	NJ	4	188,000
NJ0024759	Ewing Lawrence Sewer Auth.	Lawrenceville	NJ	16	752,000
NJ0069167	Maple Shade Util. Authority	Maple Shade	NJ	5	235,000
NJ0026832	Medford Twp. Sewer Auth. STP	Medford	NJ	2	94,000
NJ0029467	Millville City Sewer Auth.	Millville	NJ	7	329,000
NJ0024996	Moorestown Twp. Utilities Auth	Moorestown	NJ	6	282,000
NJ0024015	Mount Holly Twp. MUA	Mount Holly	NJ	8	376,000
NJ0020184	Newton Town DPW	Newton	NJ	4	188,000
NJ0024821	Pemberton Twp. MUA STP	Pemberton	NJ	5	235,000
NJ0024023	Penns Grove Sewerage Auth.	Penns Grove	NJ	3	141,000
NJ0021598	Pennsville Twp. Sewer Auth.	Pennsville	NJ	4	188,000
NJ0024716	Phillipsburg Town STP	Phillipsburg	NJ	5	235,000
NJ0022519	Riverside Twp. DPW	Riverside	NJ	3	141,000
NJ0024856	Salem WWTP Facility	Salem	NJ	3	141,000
NJ0024686	Gloucester Co. Util. Auth. STP	Thorofare	NJ	24	1,128,000
NJ0020923	Trenton City DPW Sewer Auth.	Trenton	NJ	20	940,000
NJ0023361	Willingboro Twp. MUA	Willingboro	NJ	6	282,000
<b>New York</b>				<b>257</b>	<b>12,079,000</b>
NY0020265	Delhi WWTP	Delhi	NY	4	188,000
NY0030074	Liberty WWTF	Liberty	NY	4	188,000
NY0022454	Monticello STP	Monticello	NY	6	282,000
NY0029271	Sidney WWTP	Sidney	NY	6	282,000
<b>New Jersey</b>				<b>20</b>	<b>940,000</b>
PA0026867	Abington Twp. STP	Abington	PA	6	282,000
PA0026000	Allentown City WWTP	Allentown	PA	45	2,115,000
PA0026042	Bethlehem City STP	Bethlehem	PA	95	4,465,000
PA0021181	Bristol Borough Water/Sewer	Bristol	PA	3	141,000
PA0027103	Delaware Co. Reg. Water Auth.	Chester	PA	44	2,068,000
PA0026859	Coatesville WWTP	Coatesville	PA	6	282,000
PA0026794	Conshohocken Borough Auth.	Conshohocken	PA	4	188,000
PA0026531	Downingtown Regional WPCC	Downingtown	PA	7	329,000
PA0026549	Borough of Doylestown WWTP	Doylestown	PA	29	1,363,000
PA0027235	Easton Area Joint Auth. WWTP	Easton, PA	PA	14	658,000
PA0029441	Upper Dublin Twp. MS4 UA	Ft. Washington	PA	3	141,000
PA0051985	Horsham Twp. STP	Horsham	PA	3	141,000
PA0024058	Kennett Square Borough WWTP	Kennett Sq.	PA	3	141,000

PA0026298	Whitemarsh STP	Lafayette Hill	PA	4	188,000
PA0026182	Lansdale Borough STP	Lansdale	PA	5	235,000
PA0039004	Upper Gwynedd Towam. STP	Lansdale	PA	7	329,000
PA0026468	Morrisville Mun. Auth. Water	Morrisville	PA	10	470,000
PA0027421	Norristown Borough WWTP	Norristown	PA	10	470,000
PA0020532	Upper Montgomery Joint Sewer	Pennsburg	PA	4	188,000
PA0026689	Northeast WPCP	Philadelphia	PA	210	9,870,000
PA0026662	Philadelphia Southeast POTW	Philadelphia	PA	112	5,264,000
PA0026671	SW Water Pollution Control	Philadelphia	PA	200	9,400,000
PA0020460	Quakertown WWTP	Quakertown	PA	10	470,000
PA0026549	Reading WWTP	Reading	PA	29	1,363,000
PA0020168	East Stroudsburg Filtration Plant	Stroudsburg	PA	10	470,000
PA0029289	Stroudsburg STP	Stroudsburg	PA	10	470,000
PA0027031	Goose Creek STP	West Chester	PA	4	188,000
PA0026018	West Chester Taylor Run STP	West Chester	PA	4	188,000
PA0028584	West Goshen STP	West Chester	PA	8	376,000
PA0023256	Upper Gwynedd Twp. WWTP	West Point	PA	7	329,000
PA0025976	Upper Moreland Hatboro Sewer	Willow Grove	PA	7	329,000
<b>Pennsylvania</b>				<b>913</b>	<b>42,911,000</b>
<b>Del. Basin</b>				<b>1,298</b>	<b>61,006,000</b>

### Watershed Jobs

Over 100 nonprofit watershed and environmental organizations employ at least 200 staff who earn at least 9.5 million in wages on programs to restore the watersheds in the Delaware Basin (Table 64).

**Table 64.** Watershed organization jobs and salaries in the Delaware River Basin

Watershed Organization	Town	State	Jobs	Salaries
Christina Conservancy, Inc.	Wilmington	DE	1	48,000
Coalition for Natural Stream Valleys	Newark	DE		0
Delaware Audubon Society	Wilmington	DE	1	48,000
Delaware Nature Society	Hockessin	DE	20	960,000
Fairfield Watershed Association	Newark	DE		0
Friends of Bombay Hook	Smyrna	DE	1	48,000
Friends of White Clay Creek State Park	Newark	DE	1	48,000
Naamans Creek Watershed Association	Arden	DE		0
Nature Conservancy of Delaware	Wilmington	DE	2	96,000
Partnership for the Delaware Estuary, Inc.	Wilmington	DE	10	480,000
Save Wetlands and Bays	Millsboro	DE		0
St. Jones River Greenway Commission	Magnolia	DE		0
St. Jones River Watershed Association	Dover	DE	1	48,000
Waterfront Watch of Wilmington	Wilmington	DE	1	48,000
White Clay Creek Watershed Mgmt. Committee	Newark	DE	1	48,000
<b>Delaware</b>			<b>39</b>	<b>1,872,000</b>
Cape May County Watershed Area 16	Cape May Ct. Hse.	NJ	1	48,000
Citizens United to Protect the Maurice River	Millville	NJ	1	48,000
Cooper River Watershed Association	Haddonfield	NJ		0
Crafts Creek Spring Hill Brook Watershed	Bordentown	NJ		0
Crosswicks Creek Watershed Association	Yardville	NJ	1	48,000
Crosswicks-Doctors Creeks Watershed Association	New Egypt	NJ	1	48,000
Delaware River Greenway Partnership	Burlington	NJ	1	48,000
Fairview Lake & Watershed Conservation Foundation	West Caldwell	NJ		0
Friends Hamilton-Trenton-Bordentown Marsh	Robbinsville	NJ		0

Hunterdon Land Trust Alliance	Flemington	NJ	2	96,000
Mantua/Woodbury Creeks Watershed Association	Glassboro	NJ	1	48,000
Musconetcong Watershed Association	Asbury	NJ	1	48,000
New Jersey Coalition of Lake Associations	Sparta	NJ	1	48,000
Newton Creek Watershed Association	Collingswood	NJ	1	48,000
Oldmans Creek Watershed Association.	Mullica Hill	NJ	1	48,000
Paulinskill-Pequest Watershed Association	Blairstown	NJ	1	48,000
Phillipsburg Riverview Organization	Phillipsburg	NJ	3	144,000
Pinelands Preservation Alliance	Southampton	NJ	1	48,000
Pinelands Watershed Alliance	Tuckerton	NJ	1	48,000
Pohatcong Creek Watershed Association	Phillipsburg	NJ	1	48,000
Pompeston Creek Watershed Association	Cinnaminson	NJ	1	48,000
Raccoon Creek Watershed Association, Inc.	Mullica Hill	NJ	1	48,000
Rancocas Conservancy	Vincentown	NJ	2	96,000
Salem County Watershed Task Force	Woodstown	NJ		0
South Jersey Land and Water Trust	Glassboro	NJ	2	96,000
Upper Maurice River Watershed Association	Franklinville	NJ	1	48,000
<b>New Jersey</b>			<b>26</b>	<b>1,248,000</b>
Neversink River Program/The Nature Conservancy	Cuddebackville	NY	3	144,000
<b>New York</b>			<b>3</b>	
Aquashicola/Pohopoco Watershed Conservancy	Kresgeville	PA	1	48,000
Berks County Conservancy	Reading	PA	5	240,000
Bertsch-Hokendauqua-Catasauqua Watershed Assoc.	Bethlehem	PA	1	48,000
Brandywine Valley Association	West Chester	PA	8	384,000
Brodhead Forest & Stream Association	Stroudsburg	PA	1	48,000
Brodhead Watershed Association	Henryville	PA	1	48,000
Bushkill Stream Conservancy	Tatamy	PA	1	48,000
Chester Creek Watershed Association	Glen Mills	PA	1	48,000
Chester-Ridley-Crum Watersheds Association	Media	PA	5	240,000
Cooks Creek Watershed Association	Springtown	PA	1	48,000
Crum Creek Watershed Partnership	Swarthmoore	PA	1	48,000
Darby Cobbs Watershed Partnership	Philadelphia	PA	1	48,000
Darby Creek Valley Association	Drexel Hill	PA	1	48,000
Delaware River Shad Fishermen's Association	Bethlehem	PA	1	48,000
Delaware Riverkeeper Network	Bristol	PA	13	624,000
French and Pickering Creeks Conservation Trust	Valley Forge	PA	7	336,000
Friends of Cherry Valley	Stroudsburg	PA	1	48,000
Friends of Cobbs Creek Park	Philadelphia	PA	1	48,000
Friends of Crum Creek	Philadelphia	PA	1	48,000
Friends of Lake Afton	Yardley	PA	1	48,000
Friends of Mingo Creek	Royersford	PA	1	48,000
Friends of Poquessing Watershed, Inc.	Philadelphia	PA	1	48,000
Friends of Tacony Creek Park	Philadelphia	PA	1	48,000
Friends of the Del. Water Gap Nat'l. Recreation Area	Bushkill	PA	1	48,000
Friends of the Manayunk Canal	Philadelphia	PA	1	48,000
Friends of the Pennypack Park	Philadelphia	PA	1	48,000
Friends of the Wissahickon	Philadelphia	PA	1	48,000
Fry's Run Watershed Association	Easton	PA		0
Greater Pottstown Watershed Alliance	Pottstown	PA		0
Green Valleys Association	Pottstown	PA	3	144,000
Hay Creek Watershed Association	Geigertown	PA	1	48,000
Lackawaxen River Conservancy	Rowland PA	PA	1	48,000
Lake Wallenpaupack Watershed Association	Paupack	PA	2	96,000
Little Schuylkill Conservation Club	Delano	PA		0
Lower Merion Conservancy	Gladwyne	PA	6	288,000

Maiden Creek Watershed Association	Kempton	PA		0
Martins-Jacoby Watershed Association	Martins Creek	PA	1	48,000
Mid-Atlantic Council of Watershed Associations	West Chester	PA		0
Middle Anthracite Watershed Association	Sybertsville	PA	1	48,000
Mill Creek Council, Inc.	Philadelphia	PA	1	48,000
Monocacy Creek Watershed Association, Inc.	Bethlehem	PA	1	48,000
Neshaminy Creek Watershed Association	Rushland	PA	1	48,000
North Branch Watershed Association	Doylestown	PA	1	48,000
North Pocono CARE	Thornhurst	PA	2	96,000
Palisades Region Watershed Partnership	Pipersville	PA		0
Paunacussing Watershed Association	Carversville	PA		0
Pennsylvania Organization Watersheds and Rivers	Harrisburg	PA	3	144,000
Pennypack Ecological Restoration Trust	Huntington Valley	PA	8	384,000
Pennypack Watershed Partnership	Philadelphia	PA	1	48,000
Perkiomen Watershed Conservancy	Schwenksville	PA	4	192,000
Poquessing Watershed Partnership	Philadelphia	PA		0
Red Clay Valley Association	West Chester	PA	4	192,000
Saucon Creek Watershed Association	Bethlehem	PA	1	48,000
Schuylkill Action Network	Philadelphia	PA	2	96,000
Schuylkill Canal Association	Oaks	PA	1	48,000
Schuylkill Headwaters Association	Pottsville	PA	2	96,000
Schuylkill River Greenway Association	Pottstown	PA	1	48,000
Southampton Watershed Association	Southampton	PA	1	48,000
Springton Lake/Crum Creek Conservancy	Newtown Square	PA	1	48,000
Stony Creek Watershed Committee	Norristown	PA	1	48,000
Swarthmore College's Watershed Projects	Swarthmore	PA	2	96,000
Tinicum Conservancy	Erwinna	PA	4	192,000
Tinicum Creek Watershed Association	Upper Black Eddy	PA	2	96,000
Tobyhanna/Tunkhannock Creek Watershed Association	Pocono Lake	PA	1	48,000
Tohickon Creek Watershed Association	Pipersville	PA	1	48,000
Tookany/Tacony - Frankford Watershed Partnership	Philadelphia	PA	1	48,000
Upper Perkiomen Watershed Coalition	Palm	PA	1	48,000
Water Resources Association Delaware River Basin	Exton	PA	1	48,000
White Clay Watershed Association	Landenberg	PA	1	48,000
Wildlands Conservancy	Emmaus	PA	5	240,000
Wissahickon Restoration Volunteers	Philadelphia	PA	1	48,000
Wissahickon Valley Watershed Association	Ambler	PA	1	48,000
Wissahickon Watershed Partnership	Philadelphia	PA	1	48,000
<b>Pennsylvania</b>			<b>133</b>	<b>6,384,000</b>
<b>Delaware Basin</b>			<b>201</b>	<b>9,504,000</b>

## Ski Area Jobs

In the Pocono Mountains of Pennsylvania, 9 ski resorts employ 1,753 direct jobs in the Delaware Basin from aggregate annual revenues of \$87,655,063 from 1,908,228 skier visits based on an average mid-week lift ticket rate of \$45/day.

## Paddling-based Recreation

In the Mid-Atlantic census division (NY, NJ, PA), the Outdoor Industry Association (2006) estimates that paddling-based recreation is practiced by 11% of the population and is responsible for 3,356,000 participants and 22,844 jobs. Given the Delaware Basin is the home of 18.5% of the three



state's total population of 40,800,000 people, then the prorated paddling-based recreation in the basin is responsible for 620,860 participants and 4,226 jobs.

### River Recreation

Cordel et al. (1990) from the U. S. Forest Service and U.S. National Park Service estimated river recreation along the Upper Delaware River and Delaware Water Gap was responsible for 448 jobs with wages of \$8.8 million in \$1986.

### Canoe/Kayak/Rafting

The 37 canoe and kayak liveries along the Delaware, Lehigh, and Schuylkill, and Brandywine Rivers employ 225 people to lease watercraft to approximately 225,000 visitors with earnings of \$9 million per year assuming a daily rental fee of \$40 per person.

### Wild Trout Fishing

Along the Beaverkill, East Branch, West Branch and upper main stem of the Delaware River in New York, wild trout fishing provides for 350 jobs with \$3.6 million in wages.

### Delaware Water Gap National Recreation Area

Stynes and Sun (2002) estimated the Delaware Water Gap Nat'l. Recreation Area recorded 4,867,272 visits in 2001 that generated \$106 million in sales, 7,563 direct/indirect jobs, and \$100 million wages.

### Port Jobs

The Economy League of Greater Philadelphia (2008) reported that Delaware River ports:

- Employ 4,056 workers earning \$326 million in wages (Table 65).
- Indirectly support an additional two jobs each in port activity and employee spending for a total of 12,121 port jobs with \$772 million wages and \$2.4 billion annual economic output.
- Most of the 4,056 direct port jobs are in cargo handling and warehousing with petroleum port jobs adding up to less than 10% of employment.
- Provide good jobs, the average salary of a port employee (with benefits) is over \$80,000.

**Table 65.** Jobs at Delaware River ports  
(Economy League of Greater Philadelphia 2008)

Employment Type	Jobs
<b>Direct</b>	<b>4056</b>
Cargo Handling	1,911
Warehousing	987
Federal Government	553
Construction	318
State/Local Government	152
Security	99
Wholesale	36
<b>Indirect (Industry)</b>	<b>4,655</b>
<b>Induced (Worker Spending)</b>	<b>3,410</b>
<b>Total</b>	<b>12,121</b>

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## Appendix A

### Economic Value (Potential) of Marcellus Shale Natural Gas in the Delaware River Basin

The U.S. Geological Survey (Coleman et al. 2011) estimated the entire 54,000 square-mile Marcellus Shale Formation from Kentucky and Ohio to Pennsylvania and New York potentially contains a mean volume of 84 trillion cubic feet of natural gas with a range of 43 tcf (95th percentile) to 144 tcf (5th percentile). If the Delaware River Basin covers 4,700 square miles or 8.7% of the Marcellus Shale, then by proportion a mean volume of 7.3 tcf of natural gas is potentially recoverable within the basin boundary (0.087 x 84 tcf) with a range of 3.7 tcf (95<sup>th</sup> percentile) to 12.5 tcf (5th percentile). These estimates may vary as the thickness of Marcellus Shale in the Delaware Basin increases to the northeast toward the New York/Pennsylvania border ranging from 50 feet thick near Stroudsburg to more than 250 feet thick under Lackawaxen in Wayne County, Pennsylvania.

In 2010, the U.S. Energy Information Administration reported the mean natural gas wellhead price was \$4.16/1000 cf, down from a peak of \$7.97/1000 cf in 2008. The residential customer price of natural gas was \$11.21/1000 cf, down two dollars from the 2008 peak. Table A1 lists fluctuating annual wellhead and residential consumer prices of natural gas in the U.S. from 2006 through 2010.

**Table A1.** Wellhead and residential prices of natural gas in the United States, 2006-2010 (EIA)

Year	Wellhead Price (\$/1000 cf)	Residential Price (\$/1000 cf)
2006	6.39	13.73
2007	6.25	13.08
2008	7.97	13.89
2009	3.67	12.14
2010	4.16	11.21

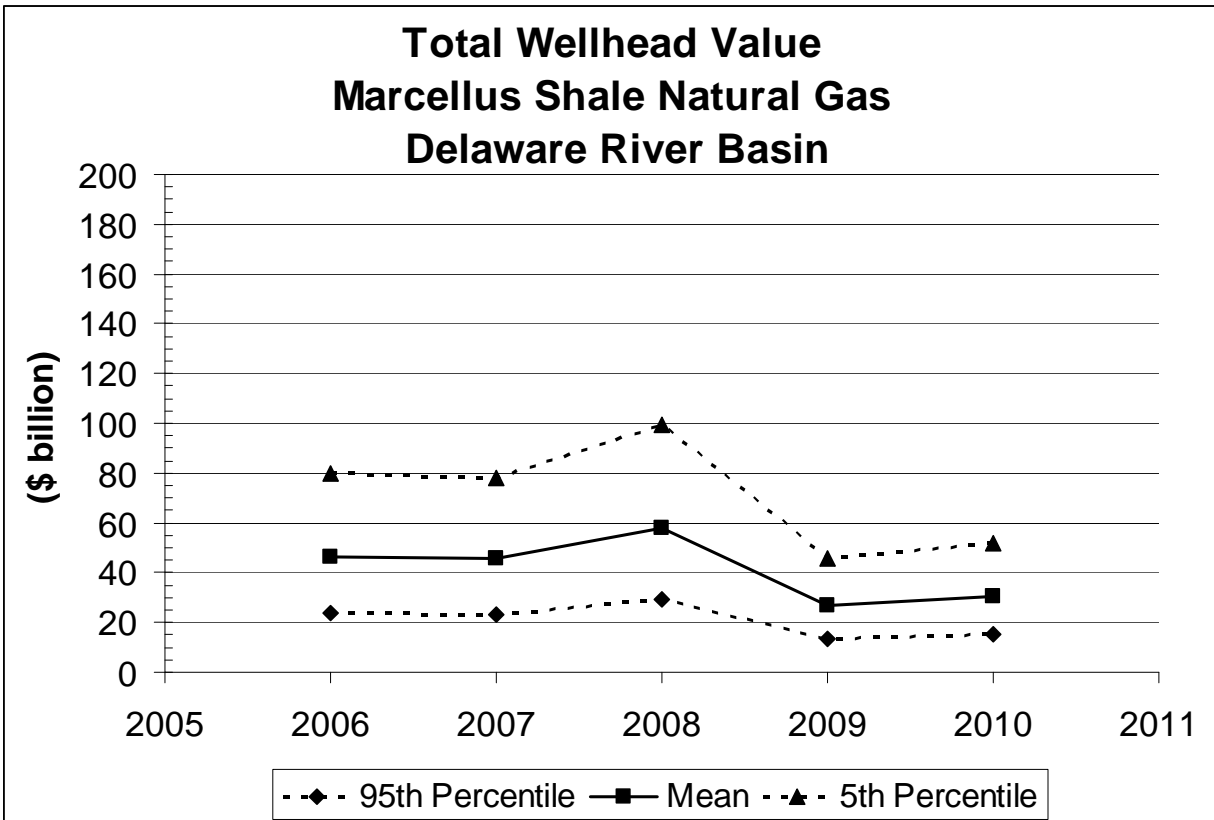
At the 2010 wellhead unit price (Table A2), the mean value of potentially recoverable natural gas from the Marcellus Shale Formation within the Delaware River Basin is projected to be \$30.4 billion with a range of \$15.4 billion (95<sup>th</sup> percentile) to \$52.0 billion (5th percentile). Assuming the natural gas can be recovered within 25 years, the mean annual wellhead value of Marcellus Shale gas within the Delaware Basin is potentially \$1.2 billion/year with a range of \$0.6 billion/year (95<sup>th</sup> percentile) to \$2.0 billion/year (5th percentile). Figures A1 and A2 project total and annual wellhead value of natural gas recoverable from the Delaware Basin based on variable prices from 2006 to 2010.

At the 2010 residential consumer unit price (Table A3), the mean value of natural gas from the Marcellus Shale Formation within the Delaware River Basin is \$81.8 billion with a range of \$41.5 billion (95<sup>th</sup> percentile) to \$140.1 billion (5th percentile). Assuming the natural gas can be recovered within 25 years, the mean annual residential consumer value of Marcellus Shale gas within the Delaware Basin is \$3.3 billion/year with a range of \$1.7 billion/year (95<sup>th</sup> percentile) to \$5.6 billion/year (5th percentile). Figures A3 and A4 project total and annual residential consumer value of natural gas recoverable from the Delaware Basin based on prices from 2006 to 2010.

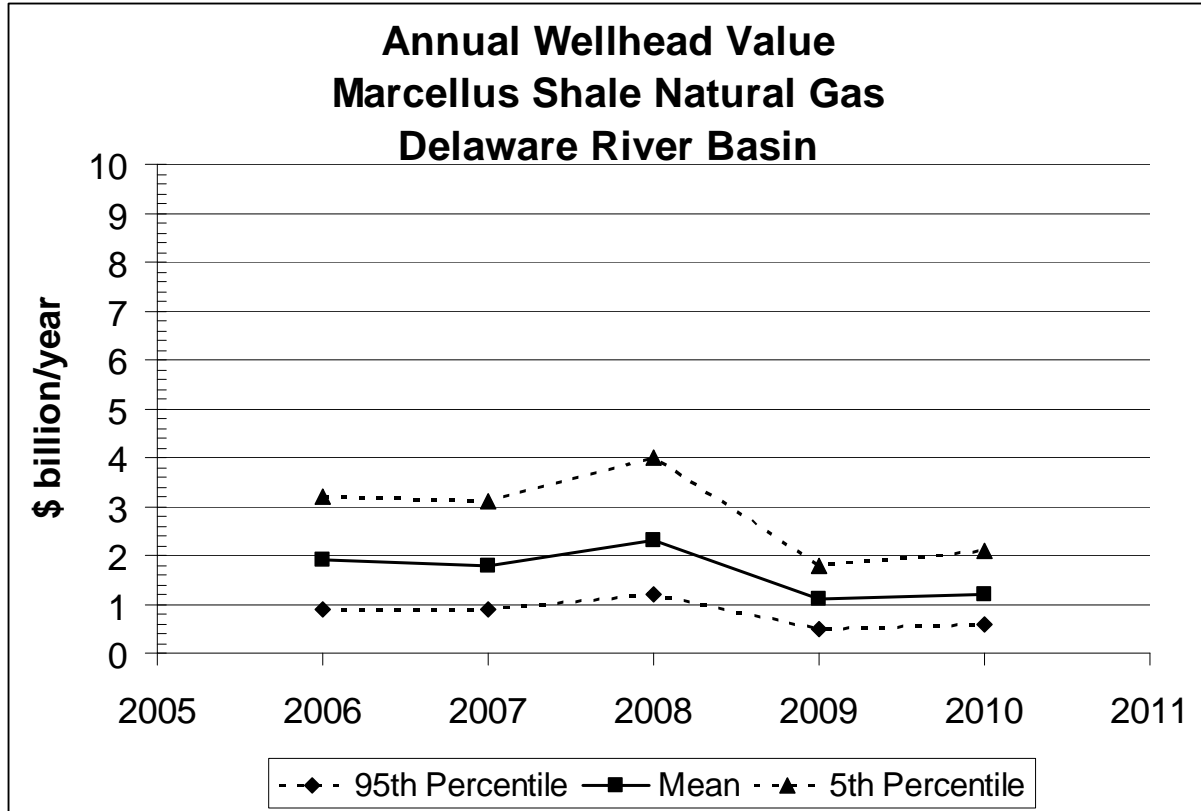
**Table A2.** Wellhead value of Marcellus Shale natural gas within the Delaware River Basin

State/Basin	Area Marcellus Shale (sq mi)	Wellhead Natural Gas Price <sup>1</sup> (\$/1000 cf)	Volume Natural Gas <sup>2</sup> (tcf)	Wellhead Natural Gas Value (\$ billion )	Wellhead Natural Gas Value <sup>3</sup> (\$ billion/yr)
<b>Mean</b>					
Pennsylvania	2,338	\$4.16	3.6	\$15.0	\$0.6
New York	2,362	\$4.16	3.7	\$15.4	\$0.6
Delaware Basin	4,700	\$4.16	7.3	\$30.4	\$1.2
<b>95th Percentile</b>					
Pennsylvania	2,338	\$4.16	1.8	\$7.5	\$0.3
New York	2,362	\$4.16	1.9	\$7.9	\$0.3
Delaware Basin	4,700	\$4.16	3.7	\$15.4	\$0.6
<b>5th Percentile</b>					
Pennsylvania	2,338	\$4.16	6.2	\$25.8	\$1.0
New York	2,362	\$4.16	6.3	\$26.2	\$1.0
Delaware Basin	4,700	\$4.16	12.5	\$52.0	\$2.0

1. EIA 2010. 2. USGS 2011. 3. Assumes 25 year natural gas recovery period.



**Figure A1.** Total wellhead value of Marcellus shale natural gas in the Delaware River Basin. Assumes mean volume of 7.3 tcf of natural gas potentially recoverable within basin boundary with a range of 3.7 tcf (95<sup>th</sup> percentile) to 12.5 tcf (5<sup>th</sup> percentile) as per Coleman et al. 2011 from the USGS. From EIA (2011), natural gas prices at wellhead (\$/1000 cf): 2006 (\$6.39), 2007 (\$6.25), 2008 (\$7.97), 2009 (\$3.67), and 2010 (\$4.16).

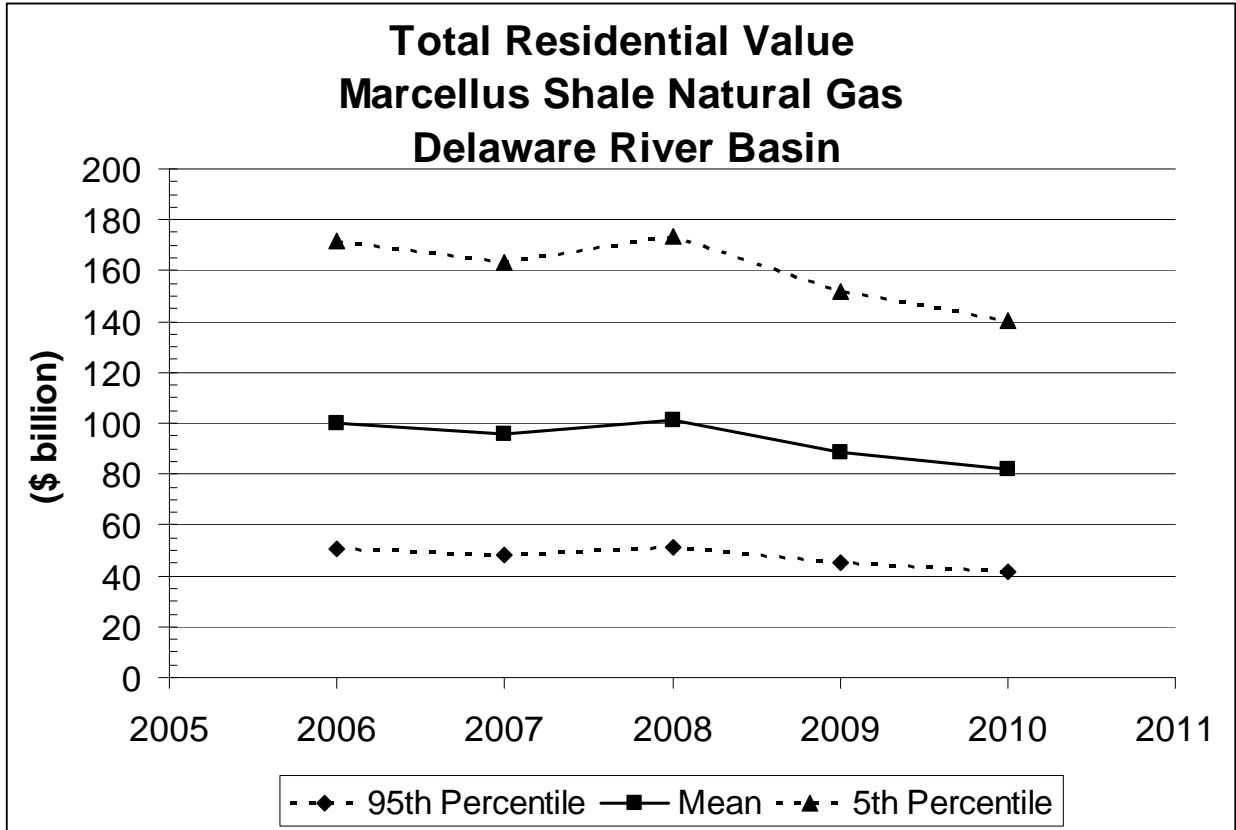


**Figure A2.** Total wellhead value of Marcellus shale natural gas in the Delaware River Basin. Assumes mean volume of 7.3 tcf of natural gas potentially recoverable within basin boundary with a range of 3.7 tcf (95<sup>th</sup> percentile) to 12.5 tcf (5th percentile) as per Coleman et al. 2011 from the USGS. From EIA (2011), natural gas prices at wellhead (\$/1000 cf): 2006 (\$6.39), 2007 (\$6.25), 2008 (\$7.97), 2009 (\$3.67), and 2010 (\$4.16). Assumes 25 year natural gas recovery period.

**Table A3.** Residential value of Marcellus Shale natural gas within the Delaware River Basin

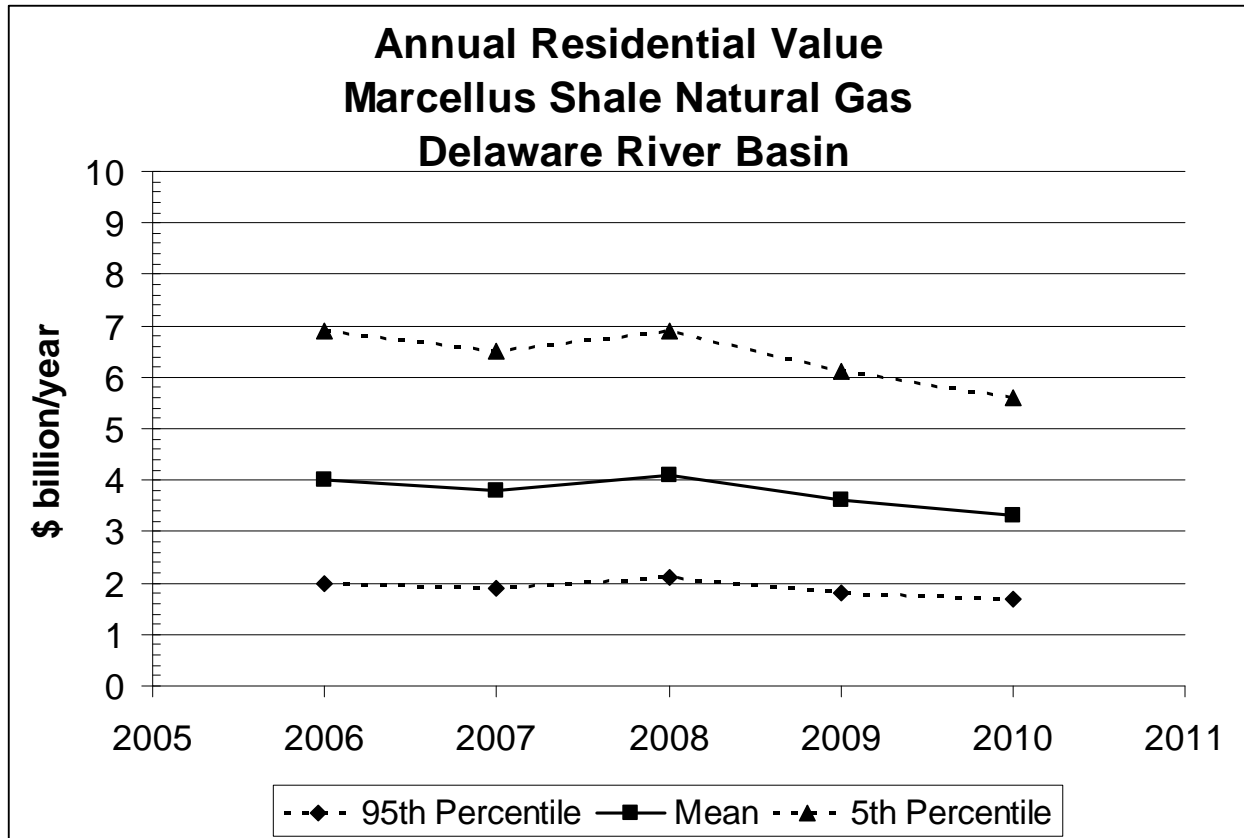
State/Basin	Area Marcellus Shale (sq mi)	Residential Natural Gas Price <sup>1</sup> (\$/1000 cf)	Volume Natural Gas <sup>2</sup> (tcf)	Residential Natural Gas Value (\$ billion )	Residential Natural Gas Value <sup>3</sup> (\$ billion/yr)
<b>Mean</b>					
Pennsylvania	2,338	\$11.21	3.6	\$40.4	\$1.6
New York	2,362	\$11.21	3.7	\$41.5	\$1.7
Delaware Basin	4,700	\$11.21	7.3	\$81.8	\$3.3
<b>95th Percentile</b>					
Pennsylvania	2,338	\$11.21	1.8	\$20.2	\$0.8
New York	2,362	\$11.21	1.9	\$21.3	\$0.9
Delaware Basin	4,700	\$11.21	3.7	\$41.5	\$1.7
<b>5th Percentile</b>					
Pennsylvania	2,338	\$11.21	6.2	\$69.5	\$2.8
New York	2,362	\$11.21	6.3	\$70.6	\$2.8
Delaware Basin	4,700	\$11.21	12.5	\$140.1	\$5.6

1. EIA 2010. 2. USGS 2011. 3. Assumes 25 year natural gas recovery period.



**Figure A3.** Total residential value of Marcellus shale natural gas in the Delaware River Basin. Assumes mean volume of 7.3 tcf of natural gas potentially recoverable within basin boundary with a range of 3.7 tcf (95<sup>th</sup> percentile) to 12.5 tcf (5<sup>th</sup> percentile) from Coleman et al. 2011 (USGS). From EIA (2011), natural gas sold to residential consumers (\$/1000 cf): 2006 (\$13.73), 2007 (\$13.08), 2008 (\$13.89), 2009 (\$12.14), and 2010 (\$11.21).





**Figure A4.** Annual residential value of Marcellus shale natural gas in the Delaware River Basin. Assumes mean volume of 7.3 tcf of natural gas potentially recoverable within basin boundary with a range of 3.7 tcf (95<sup>th</sup> percentile) to 12.5 tcf (5<sup>th</sup> percentile) from Coleman et al. 2011 (USGS). From EIA (2011), natural gas sold to residential consumers (\$/1000 cf): 2006 (\$13.73), 2007 (\$13.08), 2008 (\$13.89), 2009 (\$12.14), and 2010 (\$11.21). Assumes 25 year natural gas recovery period.

**Appendix B**  
Employment Codes by Industry, 2009  
(U. S. Bureau of Labor Statistics)

Industry		NAICS Code
Agriculture, Forestry, Fishing and Hunting		11
	Crop Production	111
	Animal Production	112
	Aquaculture	1125
	Forestry and Logging	113
	Fishing, Hunting and Trapping	114
	Fishing	1141
	Support Activities for Agriculture and Forestry	115
Mining, Quarrying, and Oil and Gas Extraction		21
	Oil and Gas Extraction	211
	Mining (except Oil and Gas)	212
	Nonmetallic Mineral Mining and Quarrying	2123
	Support Activities for Mining	213
Utilities		22
	Utilities	221
	Electric Power Generation, Transmission and Distribution	2211
	Natural Gas Distribution	2212
	Water, Sewage and Other Systems	2213
Construction		23
	Construction of Buildings	236
	Residential Building Construction	2361
	Nonresidential Building Construction	2362
	Heavy and Civil Engineering Construction	237
	Land Subdivision	2372
	Highway, Street, and Bridge Construction	2373
	Other Heavy and Civil Engineering Construction	2379
	Specialty Trade Contractors	238
Manufacturing		31
	Food Manufacturing	311
	Seafood Product Preparation and Packaging	3117
	Beverage and Tobacco Product Manufacturing	312
	Textile Mills	313
	Textile Product Mills	314
	Apparel Manufacturing	315
	Apparel Knitting Mills	3151
	Leather and Allied Product Manufacturing	316
	Wood Product Manufacturing	321
	Paper Manufacturing	322
	Petroleum and Coal Products Manufacturing	324
	Chemical Manufacturing	325
	Basic Chemical Manufacturing	3251
	Resin, Synthetic Rubber, and Artificial Synthetic Fibers and Filaments Manufacturing	3252
	Pesticide, Fertilizer, and Other Agricultural Chemical Manufacturing	3253
	Pharmaceutical and Medicine Manufacturing	3254
	Paint, Coating, and Adhesive Manufacturing	3255
	Soap, Cleaning Compound, and Toilet Preparation Manufacturing	3256
	Other Chemical Product and Preparation Manufacturing	3259
	Plastics and Rubber Products Manufacturing	326

	Nonmetallic Mineral Product Manufacturing	327
	Cement and Concrete Product Manufacturing	3273
	Lime and Gypsum Product Manufacturing	3274
	Other Nonmetallic Mineral Product Manufacturing	3279
	Primary Metal Manufacturing	331
	Fabricated Metal Product Manufacturing	332
	Machinery Manufacturing	333
	Computer and Electronic Product Manufacturing	334
	Computer and Peripheral Equipment Manufacturing	3341
	Communications Equipment Manufacturing	3342
	Audio and Video Equipment Manufacturing	3343
	Semiconductor and Other Electronic Component Manufacturing	3344
	Navigational, Measuring, Electromedical, and Control Instruments Manufacturing	3345
	Manufacturing and Reproducing Magnetic and Optical Media	3346
	Electrical Equipment, Appliance, and Component Manufacturing	335
	Transportation Equipment Manufacturing	336
	Motor Vehicle Manufacturing	3361
	Motor Vehicle Body and Trailer Manufacturing	3362
	Motor Vehicle Parts Manufacturing	3363
	Aerospace Product and Parts Manufacturing	3364
	Railroad Rolling Stock Manufacturing	3365
	Ship and Boat Building	3366
	Other Transportation Equipment Manufacturing	3369
	Furniture and Related Product Manufacturing	337
	Miscellaneous Manufacturing	339
Wholesale Trade		42
	Merchant Wholesalers, Durable Goods	423
	Merchant Wholesalers, Nondurable Goods	
	Wholesale Electronic Markets and Agents and Brokers	425
Retail Trade		44
	Motor Vehicle and Parts Dealers	441
	Furniture and Home Furnishings Stores	442
	Electronics and Appliance Stores	443
	Electronics and Appliance Stores	4431
	Building Material and Garden Equipment and Supplies Dealers	444
	Food and Beverage Stores	445
	Health and Personal Care Stores	446
	Gasoline Stations	447
	Clothing and Clothing Accessories Stores	448
	Sporting Goods, Hobby, Book, and Music Stores	451
	General Merchandise Stores	452
	Miscellaneous Store Retailers	453
	Nonstore Retailers	454
Transportation and Warehousing		48
	Air Transportation	481
	Scheduled Air Transportation	4811
	Nonscheduled Air Transportation	4812
	Rail Transportation	482
	Rail Transportation	4821
	Water Transportation	483
	Deep Sea, Coastal, and Great Lakes Water Transportation	4831
	Inland Water Transportation	4832
		4883
	Truck Transportation	484
	General Freight Trucking	4841

	Specialized Freight Trucking	4842
	Transit and Ground Passenger Transportation	485
	Urban Transit Systems	4851
	Interurban and Rural Bus Transportation	4852
	Taxi and Limousine Service	4853
	School and Employee Bus Transportation	4854
	Charter Bus Industry	4855
	Other Transit and Ground Passenger Transportation	4859
	Pipeline Transportation	486
	Pipeline Transportation of Crude Oil	4861
Information		51
	Publishing Industries (except Internet)	511
	Motion Picture and Sound Recording Industries	512
	Broadcasting (except Internet)	515
	Telecommunications	517
	Data Processing, Hosting, and Related Services	518
	Other Information Services	519
Finance and Insurance		52
	Monetary Authorities-Central Bank	521
	Credit Intermediation and Related Activities	522
	Securities, Commodity Contracts, and Other Financial Investments and Related Activities	523
	Insurance Carriers and Related Activities	524
	Funds, Trusts, and Other Financial Vehicles	525
Real Estate and Rental and Leasing		53
	Real Estate	531
	Rental and Leasing Services	532
	Lessors of Nonfinancial Intangible Assets (except Copyrighted Works)	533
Professional, Scientific, and Technical Services		54
	Professional, Scientific, and Technical Services	541
	Management, Scientific, and Technical Consulting Services	5416
	Scientific Research and Development Services	5417
Management of Companies and Enterprises		55
	Management of Companies and Enterprises	551
Administrative and Support and Waste Management and Remediation Services		56
	Administrative and Support Services	561
	Travel Arrangement and Reservation Services	5615
	Waste Management and Remediation Services	562
Educational Services		61
	Educational Services	611
	Colleges, Universities, and Professional Schools	6113
	Technical and Trade Schools	6115
	Educational Support Services	6117
Health Care and Social Assistance		62
	Ambulatory Health Care Services	621
	Hospitals	622
	Nursing and Residential Care Facilities	623
	Social Assistance	624
Arts, Entertainment, and Recreation		71
	Performing Arts, Spectator Sports, and Related Industries	711
	Museums, Historical Sites, and Similar Institutions	712
	Amusement, Gambling, and Recreation Industries	713
	Other Amusement and Recreation Industries	7139
Accommodation and Food Services		72
	Accommodation	721
	Traveler Accommodation	7211

	RV (Recreational Vehicle) Parks and Recreational Camps	7212
	Rooming and Boarding Houses	7213
	Food Services and Drinking Places	722
	Other Services (except Public Administration)	81
	Repair and Maintenance	811
	Personal and Laundry Services	812
	Religious, Grantmaking, Civic, Professional, and Similar Organizations	813
	Social Advocacy Organizations	8133
	Business, Professional, Labor, Political, and Similar Organizations	8139
	Private Households	814
	Public Administration	92
	Executive, Legislative, and Other General Government Support	921
	Justice, Public Order, and Safety Activities	922
	Administration of Human Resource Programs	923
	Administration of Environmental Quality Programs	924
	Administration of Housing Programs, Urban Planning, Community Development	925
	Administration of Economic Programs	926
	Space Research and Technology	927
	National Security and International Affairs	928

## ANNALS OF THE NEW YORK ACADEMY OF SCIENCES

Issue: *The Year in Ecology and Conservation Biology***Risks to biodiversity from hydraulic fracturing for natural gas in the Marcellus and Utica shales**

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High-volume horizontal hydraulic fracturing (HVHFF) for mining natural gas from the Marcellus and Utica shales is widespread in Pennsylvania and potentially throughout approximately 280,000 km<sup>2</sup> of the Appalachian Basin. Physical and chemical impacts of HVHFF include pollution by toxic synthetic chemicals, salt, and radionuclides, landscape fragmentation by wellpads, pipelines, and roads, alteration of stream and wetland hydrology, and increased truck traffic. Despite concerns about human health, there has been little study of the impacts on habitats and biota. Taxa and guilds potentially sensitive to HVHFF impacts include freshwater organisms (e.g., brook trout, freshwater mussels), fragmentation-sensitive biota (e.g., forest-interior breeding birds, forest orchids), and species with restricted geographic ranges (e.g., Wehrle's salamander, tongue-tied minnow). Impacts are potentially serious due to the rapid development of HVHFF over a large region.

**Keywords:** Appalachian Basin; biodiversity; forest fragmentation; hydraulic fracturing; salinization; shale gas

**Introduction**

High-volume horizontal hydraulic fracturing (HVHFF) occurs at increasing density across potentially 280,000 km<sup>2</sup> of the eastern United States underlain at depth by the natural gas-bearing Marcellus and Utica shales. These industrial installations and their edge effects alter as much as 80% of local landscapes.<sup>1</sup> The predicted intensity, speed, and extent of industrialization of the landscape have engendered concern about human health but little discussion of the effects on biodiversity,<sup>2–4</sup> although HVHFF has been identified as a global conservation issue.<sup>5</sup> Although the biota of the eastern United States is relatively well studied, many of the rare organisms potentially susceptible to industrial impacts are not. For example, the woodland salamanders (*Plethodon*) are diverse and sensitive to landscape and soil conditions; many species have only been described in recent decades; and as a group they are declining.<sup>6–8</sup> Although a direct survey of many taxa may be infeasible, indicator taxa may not effectively represent overall diversity.<sup>9</sup> In general, various taxa use different micro- and macrohabitats and have different conservation needs; one taxon

may not predict the occurrence or sensitivity to impacts of another taxon.<sup>10</sup> This review focuses on the physical and chemical impacts of HVHFF on habitats, taxa, and guilds, and suggests which organisms have particular sensitivities that may put them at risk.

**The Marcellus–Utica region**

Conservatively, 9.5% of the conterminous United States is underlain by gas shales;<sup>11</sup> Canada, southern South America, Europe, South Africa, North Africa, China, India, and Australia also have exploitable formations.<sup>12</sup> The most extensive resources in the eastern United States are the Marcellus and Utica shales, underlying the Appalachian Basin from approximately the Mohawk and Hudson rivers in New York, through extensive areas of Pennsylvania and Ohio, most of West Virginia, and into small parts of Maryland, Virginia, and Ontario (Fig. 1).<sup>13</sup> Much of the region is forested, with dominant trees that include oaks (*Quercus* spp.), hickories (*Carya* spp.), sugar maple (*Acer saccharum*), American beech (*Fagus grandifolia*), and yellow birch (*Betula allegheniensis*).<sup>14</sup> Elevations range



**Figure 1.** Map of the Marcellus–Utica shale region. Reprinted with the permission of Cambridge University Press.<sup>8</sup>

from less than 100 m near the Hudson River to more than 1500 m in north-central Pennsylvania.

The Marcellus and Utica shales are organic-rich, marine shales deposited during the Middle Devonian and Middle Ordovician periods, respectively. The formations vary from exposed (in small areas) to overlain by 3 km or more of other bedrock strata, with the Utica underlying the Marcellus and extending farther west and southwest. Some of the organic matter is methane, the principal constituent of natural gas, tightly bound in microscopic pores.

## Hydraulic fracturing

Horizontal drilling and hydraulic fracturing were developed in recent decades to mine gas from deep strata. In a typical installation, one to several wells are drilled from a single wellpad. Each well descends vertically 1.5 km or more to the target shale stratum, and then continues horizontally as much as 1.5 km. Fracturing fluid (water, chemicals, and sand) is forced under high pressure into the shale to open and prop spaces that let gas flow into the well.<sup>13</sup>

After fracturing, the gas and a portion of the fracturing fluid ascend the well and are collected. The gas is cleaned, compressed, and piped via collector lines to transmission pipelines.

Each HVHFF installation constitutes a wellpad, an access road, storage areas for water, chemicals, sand, and wastewater, a compressor station, and a collector pipeline. Installations often require extensive cut-and-fill, and some are on steep slopes.<sup>15</sup> In Pennsylvania in 2008, half of the installations were in forests and used, on average, 3.56 ha, thereby affecting approximately 15 ha of forest per installation.<sup>1</sup> An estimated 60,000 new wells will be in place by 2030.<sup>16</sup> A well is fractured at intervals of several years during its projected 40- to 50-year life, and each wellpad may support several wells. Each fracturing episode, per well, uses  $4\text{--}12 \times 10^6$  L of water, which is usually trucked from a lake or river (the amount per episode may be as high as  $15\text{--}25 \times 10^6$  L).<sup>17</sup> The portion of water and chemicals that returns to the surface as wastewater has been estimated at 9–100%.<sup>18</sup> More than 600 synthetic chemicals are used in HVHFF, including methanol, naphthalene, xylene, acetic acid, ammonia, and #2 fuel oil,<sup>2</sup> but those used in any given well are unidentified. These chemicals constitute about 0.5% of the fracturing fluid; because of the large volume of fluids,  $1 \times 10^6$  L of chemicals may be injected with a portion returning to the surface.<sup>4,13</sup> The wastewater, either return water during the fracturing operation or produced water afterward,<sup>4</sup> also contains substances from the shale, especially sodium, chloride, bromide, arsenic, barium, other heavy metals, organic compounds, and radionuclides.<sup>13</sup> Wastewater is often stored in lined, open ponds near wellpads, apparently to concentrate it, then trucked to treatment plants (including municipal plants not designed to remove salinity or radionuclides, and discharging effluent that has sometimes led to high salinity or total dissolved solids in rivers).<sup>13,18</sup> Wastewater is also reused for fracturing, disposed of by deep injection, spread on roads for dust control, or concentrated by evaporation and buried.<sup>2,15,18</sup>

## Assessing biodiversity risk

### *Water and soil pollutants*

Many spills or leaks of raw chemicals, fracturing fluids, or wastewater have been documented, involving volatile and gaseous organic chemicals, diesel fuel, surfactants, metals, sodium chloride, acidic wa-

ter, and other substances.<sup>2,3,19–21</sup> In one instance, the median chloride content of wastewater was  $56,900 \text{ mg L}^{-1}$ .<sup>18</sup> At a West Virginia site, wastewater with approximately  $4,000\text{--}14,000 \text{ mg L}^{-1}$  chloride was sprayed on ground and vegetation, killing trees and other plants.<sup>15</sup> Four northeastern amphibian species have been shown to be adversely affected by approximately  $50\text{--}1,000 \text{ mg L}^{-1}$  chloride, depending on the species and life stage,<sup>22</sup> suggesting that small amounts of HVHFF wastewater could render breeding habitats unsuitable. Many lichens,<sup>23–25</sup> liverworts,<sup>26</sup> sphagnum mosses,<sup>27–29</sup> conifers,<sup>30,31</sup> aquatic plants,<sup>32,33</sup> and bog plants<sup>34</sup> are also sensitive to salt; numerous streams are already salinized from road deicing.<sup>35</sup> Furthermore, lichens<sup>36–40</sup> and stoneworts<sup>41–43</sup> can be harmed by heavy metals. Wastewater ponds contain highly toxic synthetic chemicals<sup>2</sup> and could potentially be ecological traps for water birds, muskrat, turtles, frogs, and aquatic insects. Mixtures of these chemicals will have effects that cannot be predicted by knowledge of individual chemicals.<sup>3</sup>

Sediment pollution of streams and other habitats may be caused by heavy equipment on rural roads mobilizing mineral particles in runoff or airborne dust,<sup>13</sup> or by inadequate erosion control at HVHFF sites.<sup>21</sup> In an HVHFF region of Arkansas, stream turbidity was correlated with well density.<sup>3</sup> Suspended sediment additions to higher order streams could potentially harm benthic invertebrates and fish; native brook trout and freshwater mussels are among the most vulnerable taxa. Dust from roads can harm nearby plants and pollute streams.<sup>35</sup>

### *Forest loss and fragmentation*

Loss of forest cover and change in the spatial pattern of cover are often confounded, but cause different responses.<sup>44</sup> Edge effects on forest biota range from 10 m for trees to as much as 500 m for certain birds.<sup>45</sup> Forest fragmentation, which affects dispersal, pollination, herbivory, and predation, is a major conservation concern in HVHFF landscapes;<sup>1,16,46</sup> 20% or more of the forest cover may be removed for the establishment of HVHFF installations, and more than 80% of the land may be affected if a 100-m edge effect is considered.<sup>1</sup> This loss and fragmentation of forest would result in the warming and drying of the remaining forest, with greater penetration by nonnative plants, songbird nest predators, and the brood-parasitic



brown-headed cowbird (*Molothrus ater*). Several forest amphibians occur at lower abundances in forest within 25–35 m of clearcut edges,<sup>47</sup> and juvenile forest amphibians have trouble dispersing across open habitats.<sup>48,49</sup> At five conventional gas well sites in West Virginia, three salamander species were more abundant closer to the forest edge, but less so in the drier southwestern aspect than in the moister northeastern aspect; edge effect was offset by rock and coarse woody debris (CWD) microhabitats.<sup>50</sup> Organisms sensitive to forest fragmentation include lichens and bryophytes,<sup>51</sup> orchids,<sup>52</sup> other herbs,<sup>53</sup> the West Virginia white butterfly (*Pieris virginiensis*),<sup>54</sup> amphibians,<sup>8,48,55</sup> and birds.<sup>56–59</sup> Orchids are among the taxa most sensitive to habitat change in that many orchid species occur in small, isolated populations and depend on narrow ranges of soil moisture, organic matter, light, and nutrients; they also have complex obligate relationships with mycorrhizal fungi and pollinators.<sup>60</sup> In addition, drying of air and soils near forest edges can degrade habitat for certain grape ferns (*Botrychium*).<sup>61</sup>

Pennsylvania forests serve as habitat reserves for many species.<sup>46</sup> Forest fragmentation and loss threaten populations of several breeding birds of conservation concern in Pennsylvania and West Virginia, including wood thrush (*Hylocichla mustelina*), cerulean warbler (*Setophaga cerulea*), and summer tanager (*Piranga rubra*).<sup>62–64</sup> Concern has been raised about potential HVHFF impacts on breeding populations of area-sensitive forest interior songbirds, such as black-throated blue warbler (*Setophaga caerulescens*) and a wide-ranging forest raptor, the northern goshawk (*Accipiter gentilis*).<sup>1</sup> In a 5-year study of breeding birds at 469 sampling points in forest patches ranging from 0.1 to 3,000 ha in Maryland, Pennsylvania, West Virginia, and Virginia, the percentages of forest cover within 2 km and the forest patch area were significant habitat variables for 40 and 38 species, respectively, of 75 species studied; 26 birds were considered area sensitive.<sup>56</sup>

It may take 75–100 years, or more, for cleared forests to regenerate and mature. Forest floor species such as salamanders<sup>65</sup> and herbaceous plants<sup>66</sup> have limited dispersal ability and may take as many additional years to recolonize regrown forests.<sup>67</sup> The guild of forest herbs, often diverse and abundant in mature Appalachian forests, contains many species vulnerable to environmental changes.<sup>66</sup> Logging or

clearing reduces herb diversity, and the herb stratum may take several decades to recover. Herbivory by white-tailed deer (*Odocoileus virginianus*) is harmful to many forest herbs; it is possible that clearing for wellpads, roads, and pipelines may create a landscape that will support more deer and may subject forest herb populations to more intense grazing. One study reported that forests that are less than 70 years old supported fewer rare lichens and bryophytes than older forests;<sup>51</sup> this observation may pertain to young forests that develop following abandonment of HVHFF installations.

### Roads and pipelines

Roads act as corridors for the spread of nonnative weeds.<sup>35,68,69</sup> Nonnative or weedy native plants will colonize disturbed soils at roads,<sup>35,70</sup> wellpads, compressor stations, and pipelines, and spread from there into forests and other habitats. This has occurred at energy development sites in western North America.<sup>71</sup> Among possible nonnative weeds that could colonize eastern HVHFF sites are common reed (nonnative haplotype of *Phragmites australis*), stiltgrass (*Microstegium vimineum*), Japanese knotweed (*Polygonum cuspidatum*), spotted knapweed (*Centaurea stoebe*), mugwort (*Artemisia vulgaris*), angelica tree (*Aralia elata*), autumn-olive (*Elaeagnus umbellata*), tree-of-heaven (*Ailanthus altissima*), and empress tree (*Paulownia tomentosa*). These plants thrive on habitats resulting from cut-and-fill, and are colonizing recent disturbances from surface mining, roads, and gas pipelines in the Catskill Mountains and Hudson Highlands of New York and other eastern regions.<sup>72</sup> Common reed disperses along roads, and from there, into adjoining undisturbed habitats,<sup>73,74</sup> where it may adversely affect plant and animal assemblages. The combination of disturbed roadside habitat and salinization from deicing salts is favorable for common reed. Vegetation of pipeline rights-of-way is managed by mowing or spraying herbicide; runoff or spray drift may affect rare native plants in adjoining habitats.

Many forest songbirds avoid roads, trails, pipelines, and human activities.<sup>75</sup> In western Canada, territories of the ovenbird (*Seiurus aurocapillus*) straddled 3-m-wide cleared seismic exploration lines, but did not straddle 8-m-wide lines, leading to local population declines.<sup>75</sup> In another example, red-backed salamander (*Plethodon cinereus*) was less abundant near gravel roads in mature forests

in Virginia; this influence of roads on red-backed salamander appeared to be due to dessication of soils.<sup>76</sup> Some access roads and pipelines cross wetlands and streams, potentially creating barriers to movement of water and organisms. It takes an estimated 6,800 truck trips to fracture a single well.<sup>77</sup> Many amphibians, reptiles, birds, and mammals are vulnerable to road mortality; in Ontario, numbers of dead frogs increased, and nearby breeding choruses decreased in intensity, in proportion to the amount of traffic on roads.<sup>78</sup>

### Hydrological alteration

Many organisms of streams, wetlands, and temporary ponds require certain patterns of water levels and flows through the year (the hydropattern).<sup>79</sup> Hydrological changes, including the withdrawal of surface waters, and increases in runoff caused by deforestation and impervious surfaces of wellpads and access roads, presumably affect the hydropatterns of streams,<sup>80</sup> floodplains, wetlands, intermittent pools (vernal pools), springs, seeps, shallow groundwater, and karst complexes. Withdrawals from lakes and rivers for fracturing wells might reduce minimum instream flows in the summer. Stream fishes, including brook trout (*Salvelinus fontinalis*), and aquatic invertebrates that must remain in water during summer, such as crayfishes and stoneflies, may be adversely affected by reduced summer flows.<sup>81</sup> Reduced flows may also decrease dissolved oxygen, increase deposition of fine sediment, and increase water temperatures, causing macroinvertebrate species richness to decrease and community composition to shift toward forms tolerant of these conditions.<sup>82</sup> Other species that could potentially be affected include freshwater mussels (Unionoidea), diverse in the Marcellus–Utica region, that are sensitive to hydrology, water quality, and siltation of rivers.<sup>83,84</sup> Hellbender (*Cryptobranchus alleganiensis*), a giant aquatic salamander, requires cool, well-oxygenated, swift streams and is also sensitive to siltation and pollution.<sup>85–87</sup>

In addition, withdrawal and disposal of water could potentially affect groundwater tables and flows, changing groundwater inputs to streams or wetlands. Impacts may be greater during droughts, or where there are competing uses of water, such as in agriculture.<sup>3,13</sup> At a threshold of 10–20% cover by impervious surfaces in a watershed, water quality and species diversity decrease in streams;<sup>80,88–90</sup>

in some HVHFF landscapes, wellpads and access roads cover more than 10%.<sup>1</sup> Because of the density of HVHFF infrastructure on the landscape, and other impacts from siltation and chemical pollution, there may be cumulative impacts to wetlands and streams. Reduction of forest cover in watersheds may also have long-lasting effects on stream biodiversity.<sup>91</sup>

### Noise

At HVHFF installations, diesel compressors run 24 h/day, and the noise can be heard from long distances.<sup>20</sup> Continuous loud noise from, for example, transportation networks, motorized recreation, and urban development can interfere with acoustic communication of frogs, birds, and mammals, and cause hearing loss, elevated stress hormone levels, and hypertension in various animals.<sup>92</sup> One study showed that gas compressor station noise in Alberta reduced ovenbird pairing success.<sup>93</sup> In pinyon-juniper woodland of New Mexico, breeding bird species richness was greater, species composition different, and overall nest density similar near gas wellpads without compressors compared to wellpads with compressors, but daily nest survival was higher near pads with compressors due to less predation by western scrub jays (*Aphelocoma californica*).<sup>94</sup> In a comparison of breeding birds near wellpads with and without compressors in the boreal forest, total density and densities of one-third of the individual species were lower at the compressor sites.<sup>95</sup> Bats avoid continuous loud noise and it may impair foraging efficiency.<sup>96–100</sup>

### Light

Installations are brightly lit at night,<sup>20</sup> especially wellpads during drilling and fracturing and compressor stations continuously. Artificial night lighting variably affects different taxa; for example, adult moths and aquatic insects may be attracted and killed, whereas various species of bats may be harmed or benefited.<sup>96,101,102</sup> Night lighting potentially disrupts populations of stream insects, in turn affecting food webs and ecosystem function.<sup>103</sup> Mortality, reproduction, and foraging of many other animals are affected negatively or positively.<sup>101</sup> Polarized light pollution from artificial surfaces, especially smoother, darker surfaces including pavement, vehicles, and waste oil, creates another visual disturbance.<sup>104</sup> Animals that orient to polarized light, including many invertebrate and vertebrate

taxa, may be killed or have their reproduction disrupted. This potential impact of HVHFF installations has not been studied.

### *Air quality*

Air emissions, including diesel exhaust from compressors and trucks, volatile organics from fracturing fluids, ground-level ozone resulting from their interaction, and road dust, affect air quality around HVHFF sites.<sup>105</sup> Diesel smoke contains mutagenic and carcinogenic polycyclic aromatic hydrocarbons (PAHs)<sup>106</sup> that could affect animal health. In a relevant study, nitrogen oxides from vehicles affected mosses within 50–100 m of roads in England;<sup>107</sup> trees were adversely affected within the same distances, but the haircap moss *Polytrichum commune* showed a decline in frequency with distance from heavily traveled roads.<sup>108</sup> It is possible that diesel exhaust at HVHFF sites could produce similar effects. Lichens are especially sensitive to sulfur dioxide and other air pollutants,<sup>36,39,109,110</sup> and are harmed by road dust, as are sphagnum mosses.<sup>111</sup>

### *Range-restricted species*

A species that has a large part of its geographic range in the Marcellus–Utica region may potentially be at risk of extinction from HVHFF impacts (especially in combination with other widespread environmental change). A recent study<sup>8</sup> analyzed 15 plants, butterflies, fish, amphibians, and mammals with geographic ranges overlapping the Marcellus–Utica region by 36–100% (Figs. 2 and 3). Although most of these species are considered sensitive to forest fragmentation, habitat alteration, or water quality degradation, lungless salamanders (Plethodontidae; eight species analyzed) seemed especially at risk. Many species of invertebrates, higher plants, and cryptogams whose ranges have not been mapped in detail may be quasi-endemic to the region.

Species with larger geographic ranges may nonetheless have important population components or seasonal habitats within the Marcellus–Utica region. The Virginia big-eared bat (*Corynorhinus townsendii virginianus*) occupies 15 limestone caves, 11 of which are in West Virginia.<sup>112</sup> Limestones are often highly porous to water pollution; therefore, cave species could potentially be at greater risk of being affected by HVHFF.

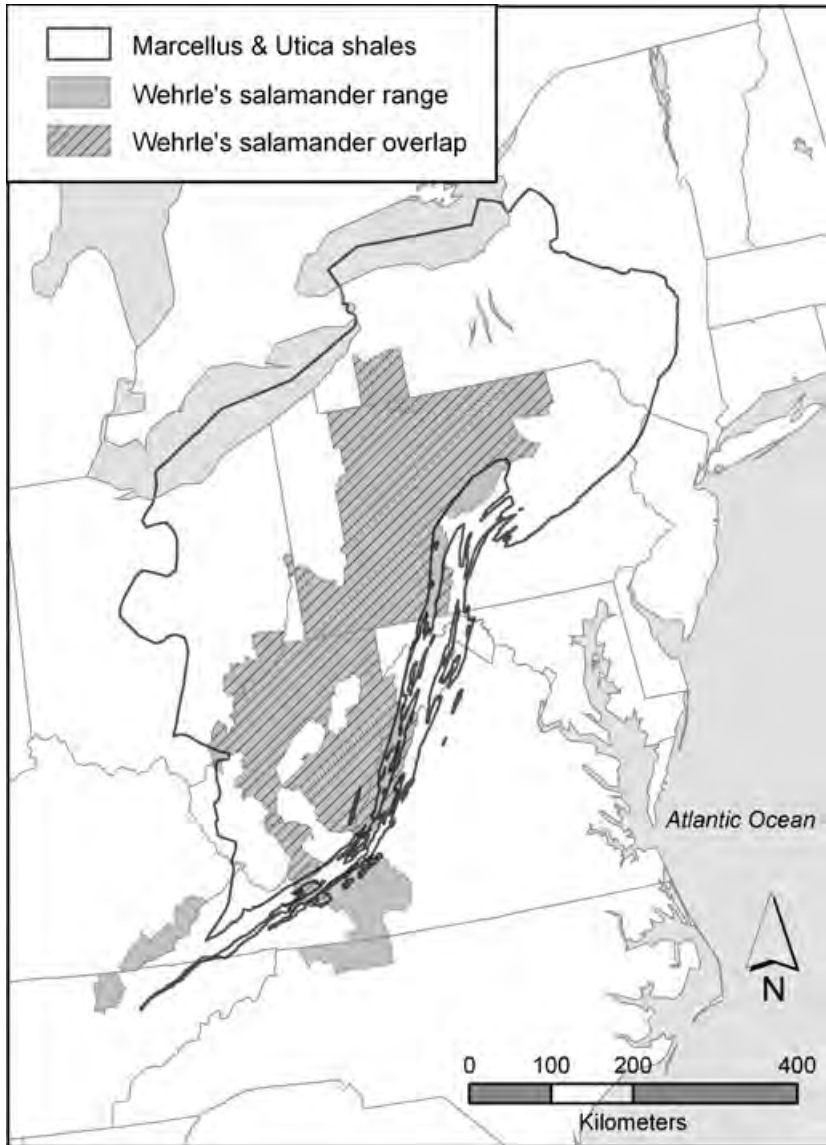
In each state, because of historic, political, social, and economic differences, and genetic differences within many species, environmental impacts

on, and management of, rare species differ. Therefore, a species that is restricted to the Marcellus–Utica region within one state could potentially be at higher risk. In Pennsylvania, all known populations of the green salamander (*Aneides aeneus*), and 73% of populations of the snow trillium (*Trillium nivale*), are in localities with a high probability of HVHFF.<sup>1</sup> In New York, bluebreast darter (*Etheostoma camurum*), spotted darter (*E. maculatum*), banded darter (*E. zonale*), and variegate darter (*E. variatum*) are apparently confined to the Marcellus region;<sup>113</sup> these stream fishes are likely to be sensitive to salt and sediment pollution.<sup>114,115</sup>

### *Species potentially benefiting from HVHFF*

Many native organisms use habitats created by construction or abandonment of industrial facilities, such as forest edges or bare soil. Some native bees and wasps dig nest burrows in bare soil, and reptiles often lay eggs in disturbed soils of road and railroad verges. Snakes, including timber rattlesnake (*Crotalus horridus*), are attracted by warm pavement in cooling weather. Several birds nest on bare or sparsely vegetated soil, including mallard (*Anas platyrhynchos*), common nighthawk (*Chordeiles minor*), killdeer (*Charadrius vociferus*), and spotted sandpiper (*Actitis macularia*), and many birds dust bathe on bare soils. White-tailed deer have been shown to be attracted to soils where HVHFF wastewater had been land-applied;<sup>15</sup> porcupine (*Erethizon dorsatum*)<sup>116</sup> and many butterflies<sup>117</sup> would also be attracted to salt. Metal-tolerant vascular plants and mosses could grow in these situations.<sup>118</sup> Postindustrial sites in England are important habitats for beetles, including rare species.<sup>119</sup>

Species of southern affinities would be attracted to wellpads and their peripheries due to solar warming. For example, water-filled wheel ruts and rain pools would serve as larval mosquito habitats; in Wyoming, there was a 75% increase in 5 years in potential mosquito larval habitats in ponds holding wastewater from coal bed gas drilling.<sup>120</sup> Access roads with numerous, long-lasting rain pools might support the globally rare feminine clam shrimp (*Cyzicus gynecia*).<sup>121</sup> It is possible that some grassland and shrubland species might colonize decommissioned facilities if they are extensive or adjoin other nonforested habitats. Most organisms able to colonize active or abandoned installations may be



**Figure 2.** Distribution of Wehrle's salamander (*Plethodon wehrlei*) in relation to the Marcellus–Utica shale region. Reprinted with the permission of Cambridge University Press.<sup>8</sup>

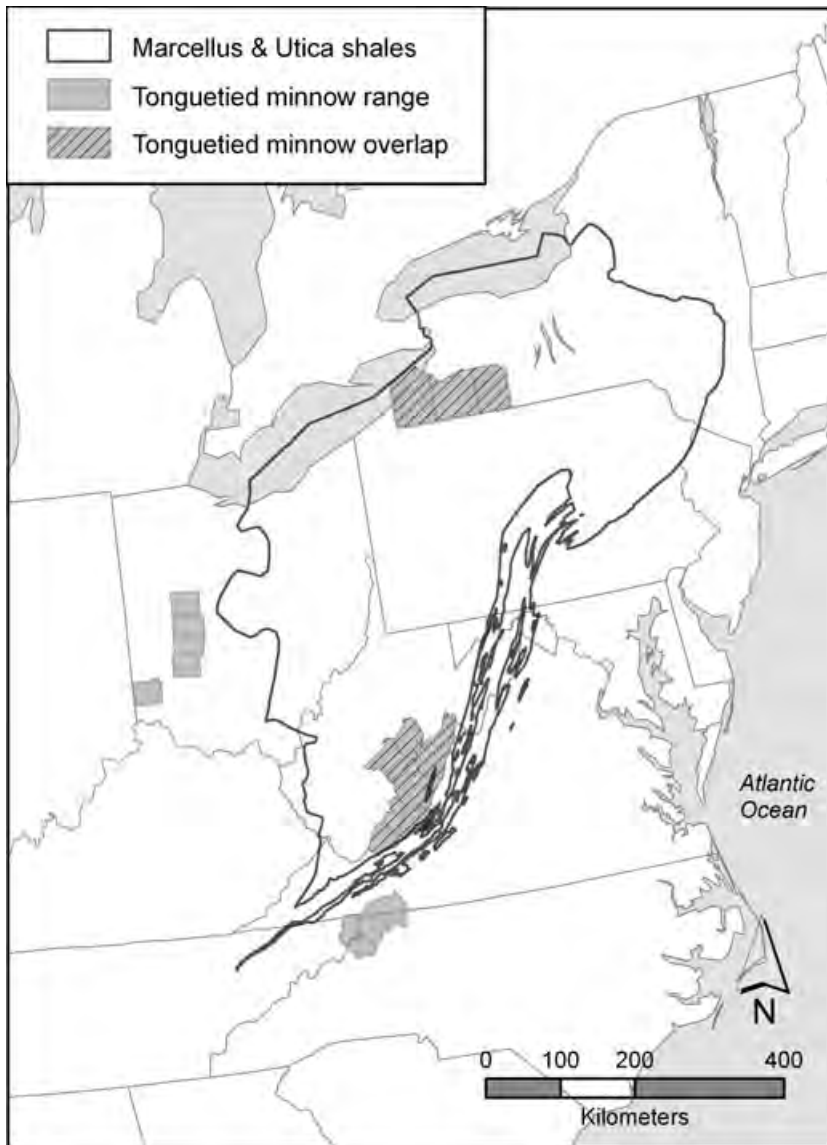
common species and ecological generalists. Rare or sensitive species that are small or require only small habitat patches (e.g., land snails, millipedes, certain insects) may persist in forest patches between wellpads, and some organisms might escape predators or competitors in fragments.

#### *Cumulative impacts*

In the Marcellus–Utica region, HVHFF constitutes landscape- and regional-scale activities and impacts.

Many thousands of wellpads will be distributed across the 280,000 km<sup>2</sup> region. Each wellpad will likely be drilled several times, and successful wells will be fractured multiple times during their 40- to 50-year life span.

Widespread environmental changes other than those produced by HVHFF also affect eastern biodiversity,<sup>6,122</sup> including coal mining, logging, agriculture, urban sprawl, accelerated climate change, acidification, eutrophication, chemical



**Figure 3.** Distribution of tongue-tied minnow (*Exoglossum laurae*) in relation to the Marcellus–Utica shale region. Reprinted with the permission of Cambridge University Press.<sup>8</sup>

contamination, altered fire regimes, emerging pathogens and parasites, and nonnative species spread. For example, most tree species are not shifting latitudinal ranges to keep pace with climate warming, and the ranges of many species are shrinking.<sup>123</sup> Such large-scale changes could potentially interact synergistically with the HVHFF impacts on forest biota as they accumulate across space and time. One study suggested that the effects of HVHFF on stream water quality will accumulate

across watersheds.<sup>3</sup> In a meta-analysis of the effects of roads, power lines, and wind turbines on birds and mammals, bird populations were reduced as far as 1 km, and mammal populations were reduced as far as 5 km, from roads and infrastructure.<sup>124</sup> If this finding applies to the wellpads, gas compressors, and roads associated with HVHFF, the corresponding buffers around each installation needed to protect birds and mammals (3.1 km<sup>2</sup> and 78.5 km<sup>2</sup>) are larger than the current spacing units for well density

in Pennsylvania (1–2.5 km<sup>2</sup>) and those projected for New York (2.6 km<sup>2</sup>).<sup>16</sup>

## Discussion and conclusions

Biodiversity impacts of HVHFF are similar to the impacts of many industries, although the chemical complexity and geographic extent are unusual. The major, long-term effects on biota likely to propagate through landscapes are habitat loss and fragmentation, chemical pollution, degradation of water quality, and hydrological alteration; other impacts, including noise, light, and air quality, may be more local and short-term. Biota vulnerable to HVHFF impacts include many native organisms that are important either for subsistence or in broader markets, such as medicinal plants (e.g., goldenseal (*Hydrastis canadensis*)),<sup>125</sup> edible fungi, brook trout and other sport fishes,<sup>1</sup> game birds and mammals (e.g., wood duck (*Aix sponsa*)), furbearers (American mink (*Mustela vison*), river otter (*Lontra canadensis*), common muskrat (*Ondatra zibethicus*)), and “watchable” wildlife (e.g., many forest-breeding birds). For example, studies suggest that HVHFF may affect trout habitats via water temperature increase, siltation, and heavy metals.<sup>126,127</sup>

Many of the biodiversity impacts of HVHFF might be reduced by zero-loss management of chemicals, wastewater, soil, and other pollutants, but this is a challenge considering the record of leaks, spills, fugitive emissions, and disposal. Water use and truck traffic can be reduced by reusing more wastewater, but similar amounts of pollutants will require disposal. If it eventually becomes possible to drill horizontally several kilometers, fewer wellpads would be needed, thus reducing fragmentation, and allowing more wells to be sited next to highways or on derelict lands, such as abandoned strip mines. However, pipelines would still fragment forests and impinge on sensitive habitats.

Forest loss and fragmentation are considered among the most serious threats to biodiversity.<sup>128,129</sup> Many forest species, particularly birds, require extensive tracts of continuous forest to maintain viable breeding populations. Inasmuch as the eastern United States was extensively deforested during the 1800s, one might ask whether current deforestation and fragmentation matter to biodiversity. At a maximum, only half of the east was deforested at once because clearing was not concurrent across the region; asynchronous deforestation prob-

ably prevented extinction of many species.<sup>129</sup> Yet deforestation contributed greatly to the extinction of the passenger pigeon (*Ectopistes migratorius*)<sup>130</sup> and the temporary loss or rarity of red-shouldered hawk (*Buteo lineatus*), wild turkey (*Meleagris gallopavo*), pileated woodpecker (*Dryocopus pileatus*), American beaver, black bear (*Ursus americanus*), fisher (*Martes pennanti*), and white-tailed deer from most of New York State and probably large regions elsewhere in the eastern United States.<sup>131</sup> Most of these species have recovered with the redevelopment of extensive forests, even to the point of overabundance of deer, bear, and turkey. Forest cover in the east is decreasing again,<sup>132</sup> and forests of the conterminous United States are fragmented to the degree that edge effects occur throughout most forested landscapes.<sup>133</sup> Fragmentation also affects grasslands and their breeding birds.<sup>16,134</sup> The many other stressors affecting freshwater organisms<sup>135</sup> may be compounded by water pollution and hydrological alteration from HVHFF.

Biotas are impoverished in industrial and urban areas, although many species thrive, including some rare species.<sup>136–138</sup> Few empirical data are available on biodiversity impacts of eastern HVHFF, although activities are already widespread and potentially will occur throughout 280,000 km<sup>2</sup>. HVHFF is also intensive, causing great changes to habitats at HVHFF installations and to the intervening landscapes. Consideration of a broad spectrum of taxa and guilds suggests potential HVHFF risks to biodiversity, particularly organisms that are specialized in their habitat, require unpolluted freshwater with natural hydroperiods, or have small geographic ranges concentrated in the Appalachian Basin. Impoverishment of species assemblages likely will lead to diminution of ecosystem functions and services.<sup>139</sup>

It is expected that an HVHFF installation will be decommissioned and the site restored after 40–50 years; procedures may include regrading, removing roads and impoundments, restoring topsoil, and native planting.<sup>21</sup> Restoration will accomplish more if it is targeted at habitats and species of conservation concern, rather than simply restoring forest or grassland. For example, CWD is important for salamanders, snakes, invertebrates, bryophytes, and lichens. Coarse woody debris could be stockpiled when a site is cleared and used for restoration of a nearby site that is being decommissioned. Construction,

operation, and decommissioning of HVVHF facilities, if viewed as a mosaic across the landscape, could be better managed to reduce impacts on biodiversity. Most research on wild organisms is restricted in space and time; thus, we are not well equipped to understand and conserve on large scales.<sup>140</sup> Most regulation of HVVHF has occurred at the level of the individual wellpad; however, to protect biodiversity and ecosystem services, it may be necessary to plan and regulate at the level of the whole Marcellus–Utica region.

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## Conflicts of interest

The author declares no competing financial interest.

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## Hydraulic Fracturing Threats to Species with Restricted Geographic Ranges in the Eastern United States

Jennifer L. Gillen, Erik Kiviat

**High-volume horizontal hydraulic fracturing (*fracking*) is a new technology that poses many threats to biodiversity. Species that have small geographic ranges and a large overlap with the extensively industrializing Marcellus and Utica shale-gas region are vulnerable to environmental impacts of fracking, including salinization and forest fragmentation. We reviewed the ranges and ecological requirements of 15 species (1 mammal, 8 salamanders, 2 fishes, 1 butterfly, and 3 vascular plants), with 36%–100% range overlaps with the Marcellus-Utica region to determine their susceptibility to shale-gas activities. Most of these species are sensitive to forest fragmentation and loss or to degradation of water quality, two notable impacts of fracking. Moreover, most are rare or poorly studied and should be targeted for research and management to prevent their reduction, extirpation, or extinction from human-caused impacts.**

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The new technology of high-volume horizontal hydraulic fracturing to extract natural gas, known as *fracking*, has gained attention in the past few years. Fracking is the process of drilling vertically and then horizontally through deeply buried shale beds, and pumping water, sand, and chemicals at high pressures into the shales to release the natural gas. Part of this chemical and water mixture returns to the surface as *frack water*, which contains toxicants such as benzene and toluene from the fracking fluids, as well as radium and salt from the shales (Rowan et al., 2011; Schmidt, 2011). Although the impacts of fracking in the eastern states on drinking-water supplies and public health have been discussed extensively, little

attention has been paid to the effects of toxic chemicals, salt, habitat fragmentation, truck traffic, air pollution, noise, night lighting, and water withdrawals on ecosystems and their wild animals and plants (Davis and Robinson, 2012; Entekin et al., 2011; Kiviat and Schneller-McDonald, 2011). The great spatial extent of industrialization and the rapid pace of development of shale-gas resources associated with fracking in the eastern United States (US) may result in environmental impacts disproportionate to economic benefits (Davis and Robinson, 2012). Many serious impacts of gas and oil mining on biodiversity have been documented in the US and Canadian West (Naugle, 2011). For example, compressor noise from gas-drilling installations was found to interfere with ovenbird (*Seiurus aurocapilla*) pairing success and alter population age structure (Habib, Bayne, and Boutin, 2007). In the Marcellus shale-gas region, it is expected that fracking will exacerbate the natural migration of salt from the deep shale beds into shallow aquifers (Warner et al., 2012), which could adversely affect wild species adapted to strictly fresh groundwaters or to surface waters into which groundwaters discharge.

The largest occurrence of commercially exploitable gas shales—the Marcellus and Utica shale-gas region—extends beneath approximately 285,000 km<sup>2</sup> of the Appalachian Basin (calculated from the US agency maps cited in this article's Methods section). This region supports high species diversity and many endemic species with small geographic ranges and narrow habitat affinities. The Appalachian region is a global megadiversity region for salamanders, stream fishes, freshwater mussels, and crayfishes, and is home to more than 150 imperiled species (Stein, Kutner, and Adams, 2000). Because organisms with geographic ranges concentrated in shale-gas regions are at greater risk from fracking impacts (Kiviat and Schneller-McDonald, 2011), we reviewed the potential impacts of fracking on animal and plant species with ranges substantially restricted to areas underlain by the Marcellus and Utica shale-gas region.

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## Methods

We focused on species that have geographic ranges of which 35% or more is underlain by the Marcellus and Utica shale-gas region; we refer to these species as *quasi-endemic* to the Marcellus-Utica region. The cutoff of 35% has precedent in conservation science and is considered a high percentage overlap in the Natural Capital Project's habitat risk assessment model (Arkema, Bernhardt, and Verutes, 2011). By reviewing publicly available range maps, we selected 15 species that met the 35% criterion and are currently accepted as full species in standard taxonomic treatments [e.g., US Department of Agriculture (USDA), 2012].

We then studied each species' natural history, habitat needs, and legal status for indications of vulnerability to the physical and chemical effects of fracking. For example, eight species are salamanders in the family Plethodontidae. These lungless salamanders are particularly sensitive to environmental changes because they respire through their skin and require constant contact with moisture (Welsh and Droege, 2001). After selecting species, geographic information system (GIS) software was used to calculate the percentage overlap with the gas shales. We obtained geographic range data for mammals and amphibians from the International Union for Conservation of Nature (IUCN) Red List Spatial Data Download website (2012), for plants from the USDA (2012), for fishes from NatureServe (2011), and for butterflies from Butterflies and Moths of North America (BAMONA, 2012). We combined digital maps of the Marcellus and Utica shale formations obtained from the US Energy Information Administration (2012) and the US Geological Survey (2002) to create a single map layer showing the region underlain by both formations. We used ArcMap 10.0 (ESRI, Redlands, CA) to establish the overlap between each species' range and the shale boundary, to calculate the percentage overlap, and to create the maps depicting the species ranges in relation to the Marcellus and Utica shale-gas region.

Various federal agency maps indicate that the area of the combined Marcellus and Utica shales is in the range of 268,000 to 340,000 km<sup>2</sup>. We use the conservative figure of 285,000 km<sup>2</sup> for our analyses.

One of the selected species, Bailey's sedge, extends northward into a small area of Québec, yet we have analyzed only the US portion of its range. Because Canadian and US practices differ with regard to managing this rare species, and the species undoubtedly varies genetically in different

portions of its range, we believe it is important to protect this plant within the US regardless of its status in Canada. Another species, northern blue monkshood, which occurs in small areas of Wisconsin, Iowa, Ohio, and New York (USDA, 2012), may be part of a widespread western species, Columbian monkshood (*Aconitum columbianum*; Cole and Kuchenreuther, 2001). However, because there is a disjunction of 800 km between the Ohio and Wisconsin populations, suggesting the potential for evolutionary divergence, we have included only the Ohio–New York populations in our analysis. Evolutionary potential must also be considered when determining the ecological effects of fracking. We assessed potential impacts at the species level, but genetic variation below the species level may have an even higher overlap with the shales.

## Results and Discussion

We reviewed 15 species with restricted geographic ranges having 35%–100% overlap with the Marcellus and Utica shale-gas region (Table 1 and Figure 1). Of the 15 species selected, there are 8 plethodontid salamanders, 2 stream fishes, 1 mammal, 1 butterfly, and 3 plants. The total geographic range size varies from 3 to 292,261 km<sup>2</sup>, with a mean of 91,075.3 km<sup>2</sup> and median of 59,988 km<sup>2</sup>. The mean overlap with the shale-gas region is 64.4%, and the median is 68%. Ten species have 50% or greater overlaps with the shales, and four have 40%–49% overlap. These overlap figures indicate the potential for impacts to occur over large portions of these species' ranges and, given the cumulative impacts of other intensive land uses such as coal mining, agriculture, residential development, and logging, raise substantial concerns about species survival. The sensitivities of these species to habitat degradation at the landscape and regional levels are suggested by the data in Table 1. Of the 15 species, 4 are listed as endangered or threatened at the federal level or in at least one state where the species occurs. Of the 15 species, 11 are stated to depend on good water quality, 10 to be sensitive to habitat fragmentation, 13 are either stenotopic (have narrow habitat affinities) or are sensitive to changes in habitat, and 11 are threatened by deforestation (Table 1).

Species with smaller geographic ranges are more vulnerable to extinction than are species with larger ranges (Payne and Finnegan, 2007), and species with smaller populations (numbers of individuals) are more vulnerable than are species with larger populations (Noss and Cooperrider, 1994; Slobodkin, 1986). Thus, reductions in range size are expected to make a species more vulnerable to extinction. Reductions in

**Table 1.** Selected species of animals and plants with restricted geographic ranges and a high degree of overlap with the combined Marcellus and Utica shale-gas region.

Species	Range (km <sup>2</sup> ) <sup>a</sup>	Shale (%) <sup>b</sup>	Status <sup>c</sup>	Water quality <sup>d</sup>	Fragmentation <sup>e</sup>	Stenotopic <sup>f</sup>	Forest <sup>g</sup>	References
Appalachian cottontail ( <i>Sylvilagus obscurus</i> )	94,345	46			X		X	Barry and Lazell, 2008
Allegheny mountain dusky salamander ( <i>Desmognathus ochrophaeus</i> )	292,261	70		X	X	X	X	Duncan et al., 2011 Gibbs et al., 2007
West Virginia spring salamander ( <i>Gyrinophilus subterraneus</i> )	3	100	E (WV)	X	X	X	X	Welsh and Droege, 2001
Wehrle's salamander ( <i>Plethodon wehrlei</i> )	114,481	82		X	X	X	X	Welsh and Droege, 2001 Duncan et al., 2011 Hammerman, 2004 Welsh and Droege, 2001 Wyman, 2003
Valley and ridge salamander ( <i>Plethodon hoffmani</i> )	59,988	68		X	X	X	X	Duncan et al., 2011 Welsh and Droege, 2001 Wyman, 2003
Cheat Mountain salamander ( <i>Plethodon nettingi</i> )	1,286	100	T (federal)	X	X	X	X	Wyman, 2003 Duncan et al., 2011 Welsh and Droege, 2001
White-spotted salamander ( <i>Plethodon punctatus</i> )	11,143	45		X	X	X	X	Wyman, 2003 Duncan et al., 2011 Welsh and Droege, 2001 Wyman, 2003
Shenandoah Mountain salamander ( <i>Plethodon virginia</i> )	2,472	77		X	X	X	X	Duncan et al., 2011 Welsh and Droege, 2001 Wyman, 2003
Northern ravine salamander ( <i>Plethodon electromorphus</i> )	113,396	58		X	X	X	X	Duncan et al., 2011 Welsh and Droege, 2001 Wyman, 2003
Tonguetied minnow ( <i>Exoglossum laurae</i> )	31,622	67		X		?		Wyman, 2003 USEPA, 2010
Bluebreast darter ( <i>Etheostoma camurum</i> )	75,917	51	C (NY) I (OH, VA)	X	X	X	X	USEPA, 2010 Losey, Roble, and Hammerman, 2011
Appalachian azure ( <i>Celastrina neglectamajor</i> )	244,038	36			X	X	X	NYNHP, 2011
Shale-barrens pimpernel ( <i>Taenidia montana</i> )	29,310	42	E (PA)			X		USDA, 2012
Bailey's sedge ( <i>Carex baileyi</i> )	279,581	44		?	?	X	?	Walton, Ormes, and Morse, 2012 MNHESP, 2009
Northern blue monkshood ( <i>Aconitum noveboracense</i> )	16,281	81	E (OH) T (federal, NY)	X	X	X	X	Edmondson et al., 2009 ONHP, 2007

<sup>a</sup> Total area of geographic range (calculations do not account for the fragmented ranges of some species, thus area occupied may be smaller than the figures shown).

<sup>b</sup> Percentage of geographic range that overlaps the Marcellus-Utica shale-gas region.

<sup>c</sup> E (endangered) or T (threatened) listing by federal or state agencies; C (critically imperiled) or I (impaired) ranking by NatureServe (see references cited).

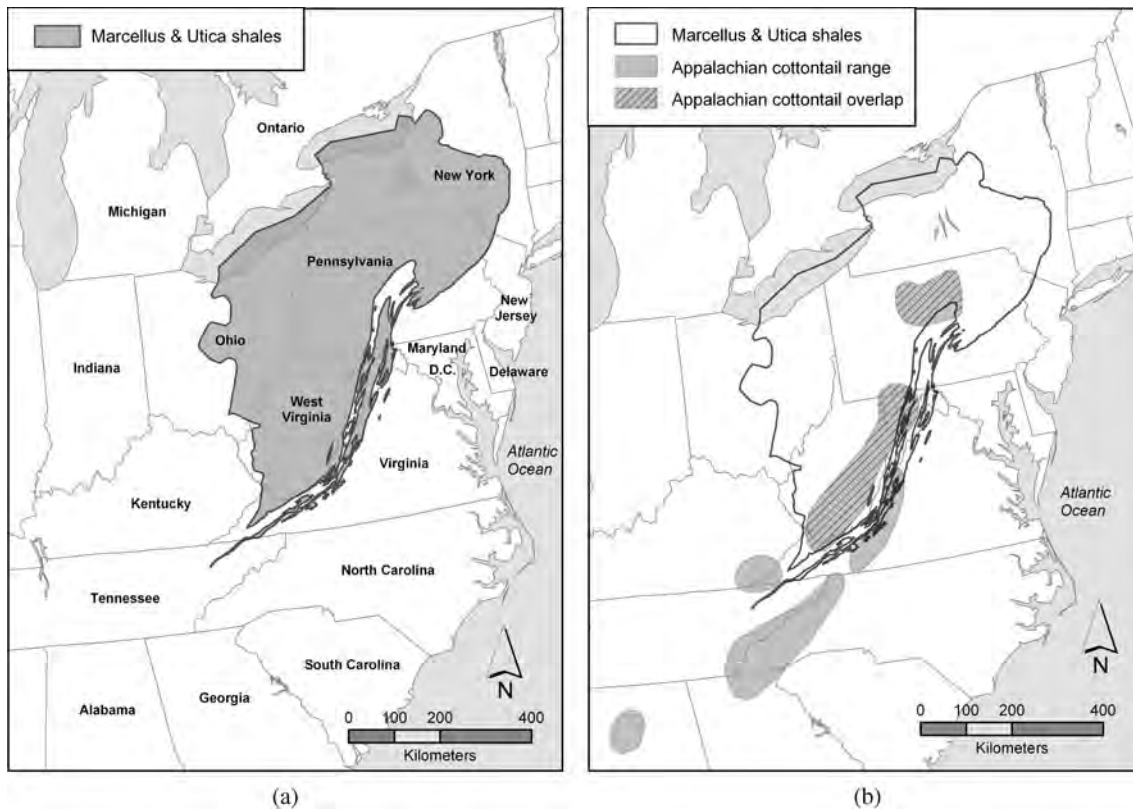
<sup>d</sup> Reported as sensitive to water quality (see references cited).

<sup>e</sup> Reported as sensitive to habitat fragmentation (see references cited).

<sup>f</sup> Reported as having narrow habitat affinities or as sensitive to habitat change (see references cited).

<sup>g</sup> Reported as dependent on forested environments or sensitive to deforestation (see references cited).

MNHESP, Massachusetts Natural Heritage and Endangered Species Program; NYNHP, New York Natural Heritage Program; ONHP, Ohio Natural Heritage Program; USDA, US Department of Agriculture; USEPA, US Environmental Protection Agency.



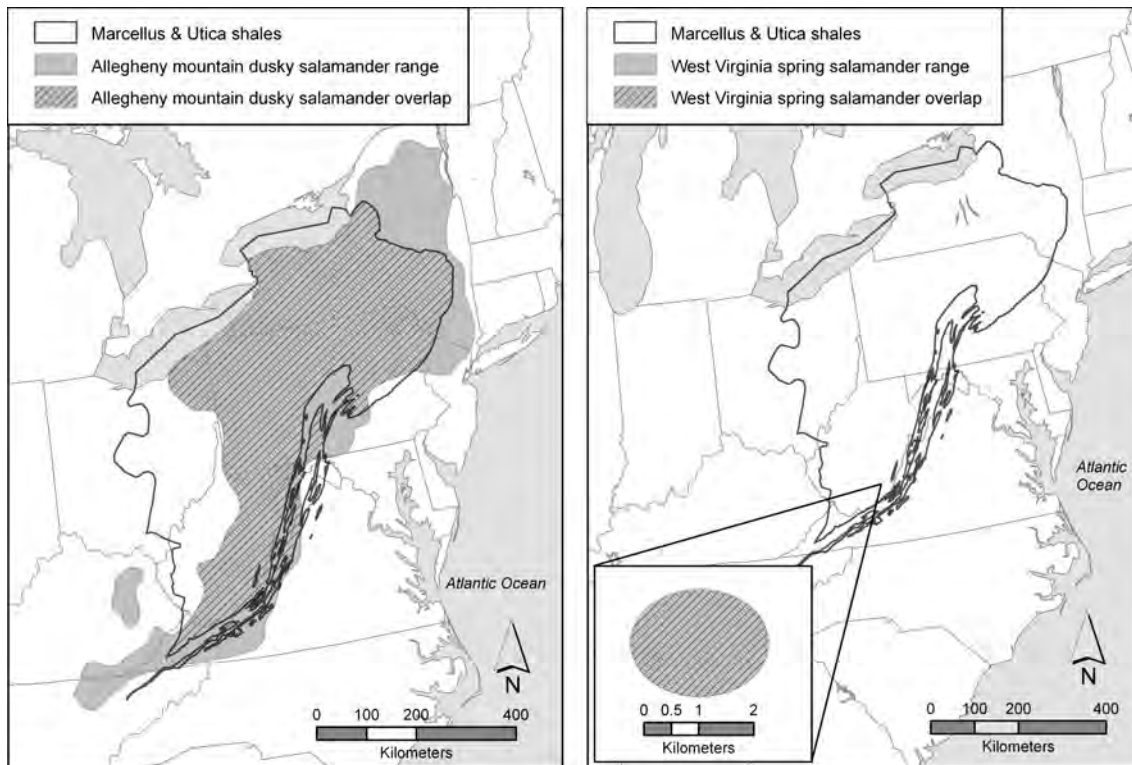
**Figure 1.** Maps showing the area underlain collectively by the Marcellus and Utica shale-gas region, the geographic ranges of selected species, and the overlap between shales and species: (a) Marcellus–Utica Shale outline, (b) Appalachian cottontail, (c) Allegheny mountain dusky salamander, (d) West Virginia spring salamander, (e) Wehrle’s salamander, (f) valley and ridge salamander, (g) Cheat Mountain salamander, (h) white-spotted salamander, (i) Shenandoah Mountain salamander, (j) northern ravine salamander, (k) tonguetied minnow, (l) bluebreast darter, (m) Appalachian azure, (n) shale-barrens pimperl, (o) Bailey’s sedge, and (p) northern blue monkshood. Range maps for species are from the International Union for Conservation of Nature (2011), the US Department of Agriculture (2012), and Butterflies and Moths of North America (2012). See Table 1 for calculated areas of the geographic ranges and percentage overlaps with the shales.

forest area may result in great reductions of the number of species (Drakare, Lennon, and Hillebrand, 2006), and most of the species in our sample are closely associated with forests. The remainder of this discussion addresses the ecological requirements of the various groups of organisms that may make them vulnerable to fracking impacts.

#### Mammals

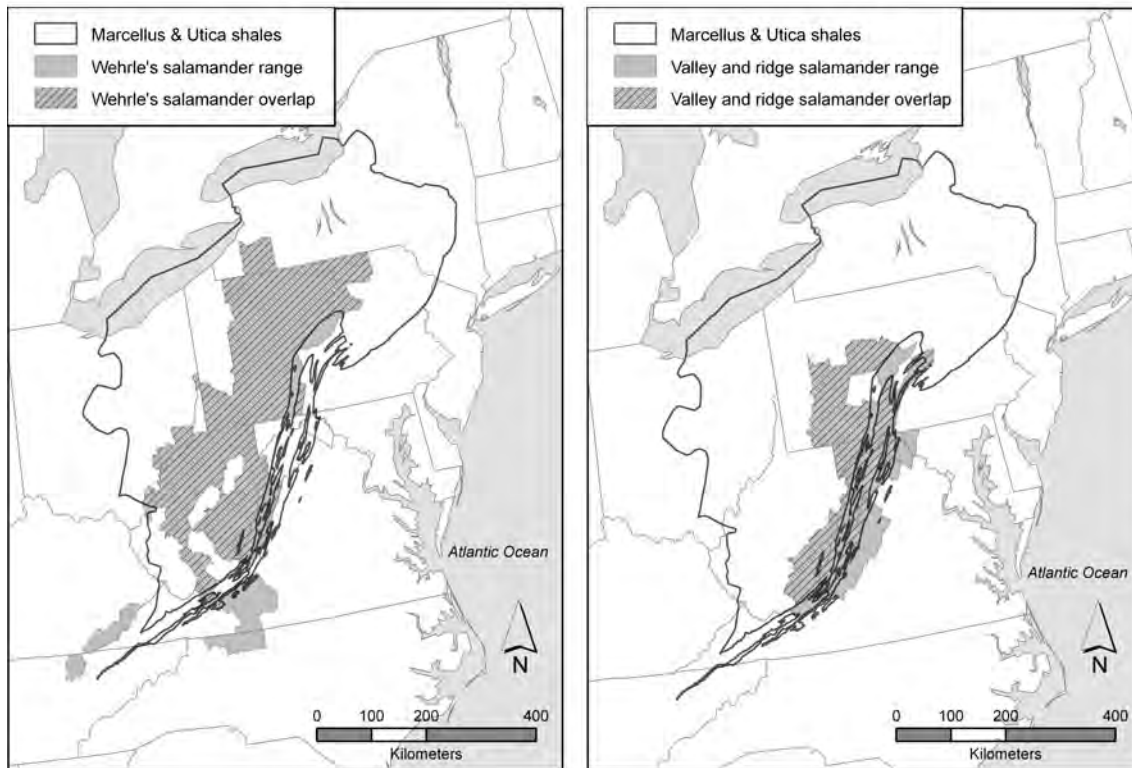
The Appalachian cottontail, recently separated by systematists from the New England cottontail, is found in mixed-oak forests with ericaceous (heath family) shrub cover (Bunch et al., 2012) and has a highly fragmented range, extending from Pennsylvania to Alabama (Barry and Lazell, 2008). Habitat needs are most likely different from those of the New England cottontail, but because this is not known, the

species cannot yet be managed in a targeted way (Bunch et al., 2012). The Appalachian cottontail is declining and the number of local populations is decreasing due to habitat destruction, fragmentation, and forest maturation (Barry and Lazell, 2008; Harnishfeger, 2010). Fracking uses large areas of land for drill pads and pipelines, and roads must be constructed to enable truck traffic back and forth from drill sites. An average of 8.8 acres of forest is cleared for each Marcellus drill site and, with an additional indirect impact (through edge effects) on 21.2 acres, an average of 30 acres of forest is impacted at each site (Johnson, 2010). For a species that is threatened by habitat destruction and fragmentation, fracking could further reduce population and cause endangerment. The IUCN lists the Dolly Sods Wilderness Area, West Virginia, as a major source population for smaller populations of Appalachian cottontails



(c)

(d)



(e)

(f)

Figure 1. Continued





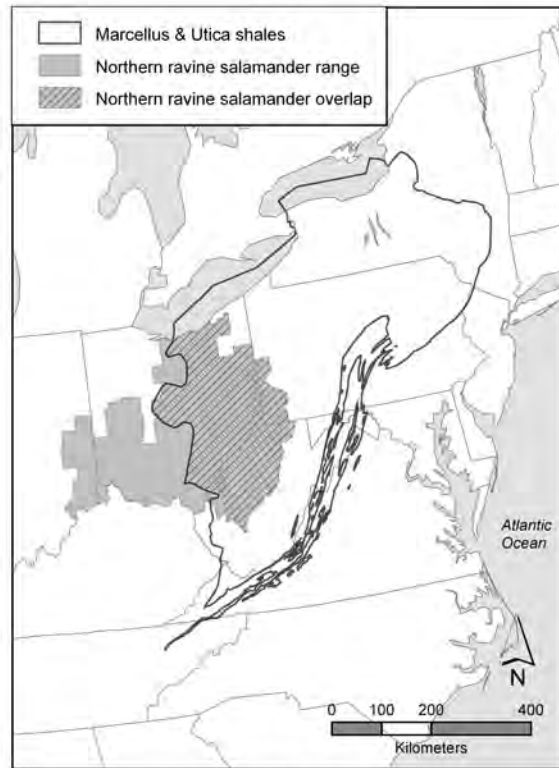
(g)



(h)



(i)

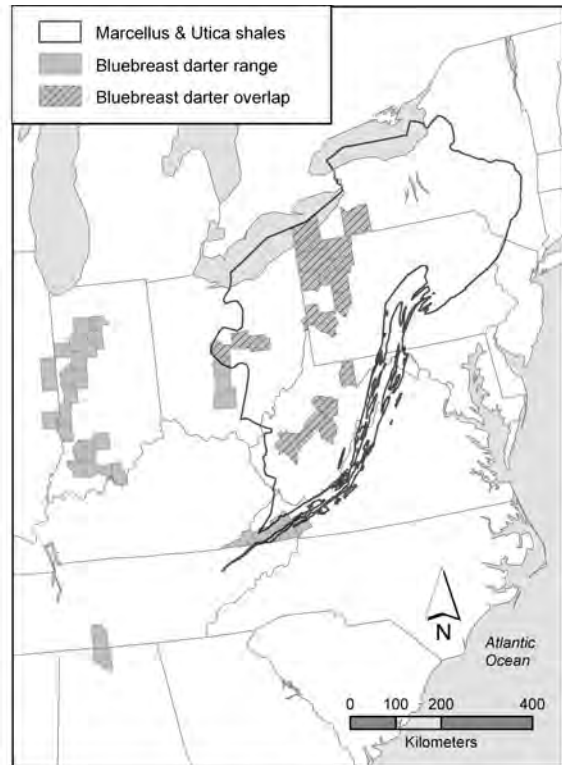


(j)

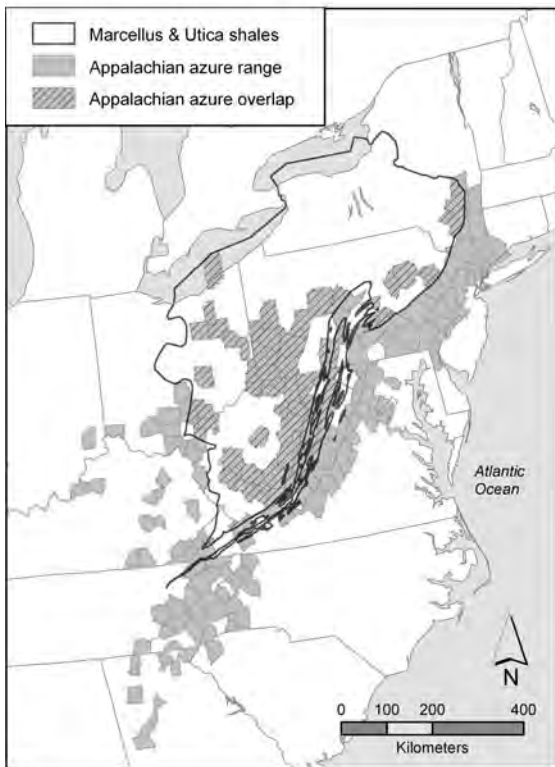
Figure 1. Continued



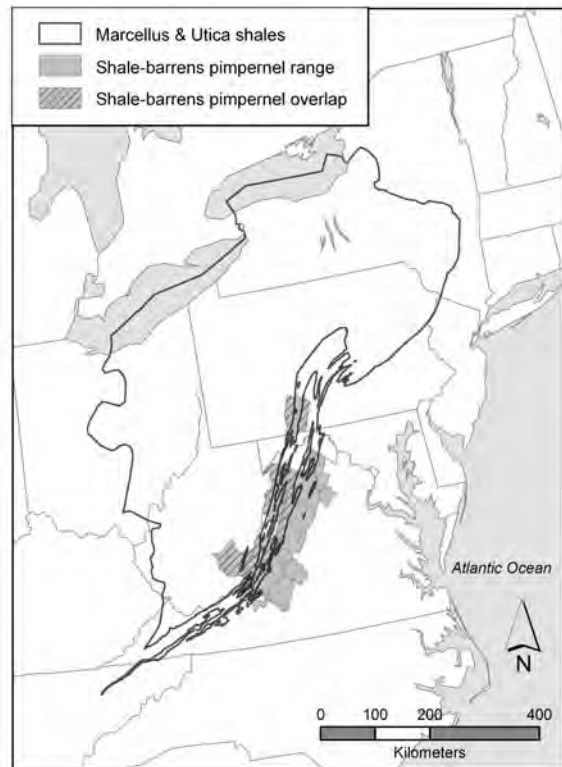
(k)



(l)



(m)



(n)

Figure 1. Continued

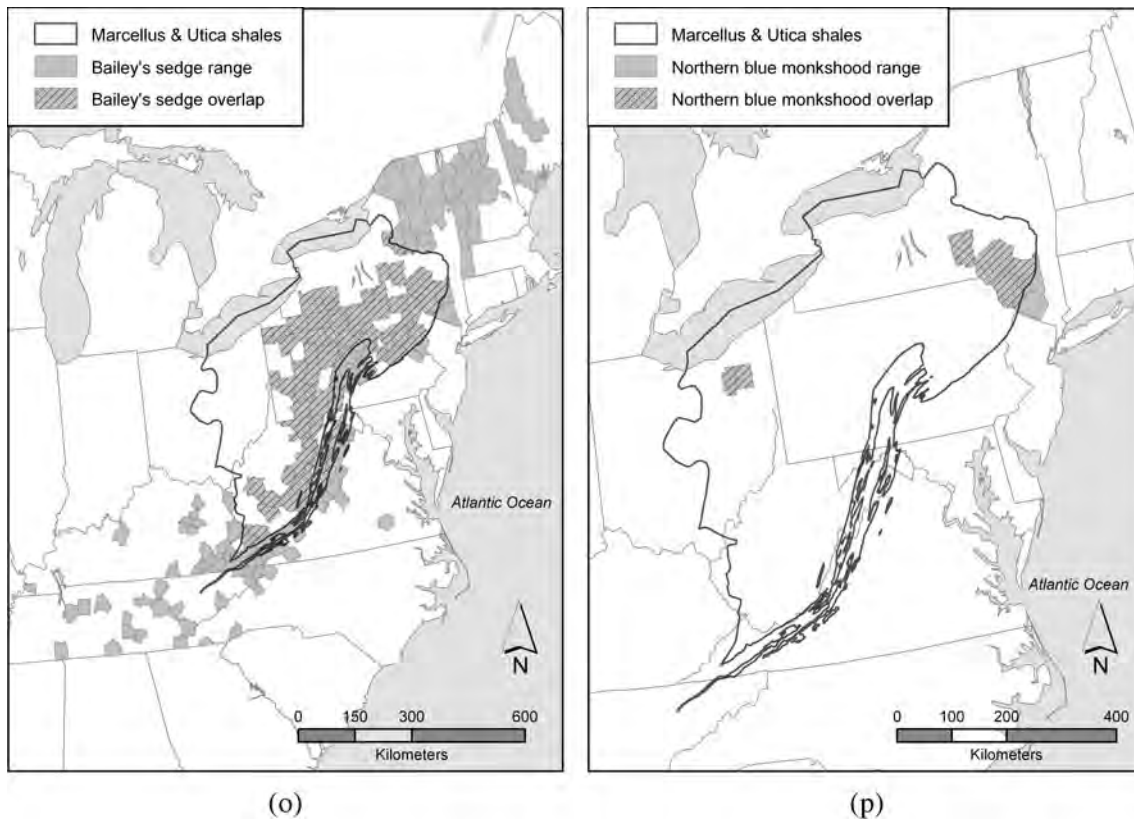


Figure 1. *Continued*

(Barry and Lazell, 2008), and if this population were severely affected by habitat destruction or fragmentation caused by fracking, those populations that depend on Dolly Sods for gene flow would be negatively impacted.

### Salamanders

The Plethodontidae, which is the largest family of salamanders, represents significant diversity (Petranka, 1998). Plethodontids are rapidly evolving, and too little is known about 43% of species to manage them successfully (Wyman, 2003). Many plethodontids, such as the Shenandoah Mountain salamander and the northern ravine salamander (Table 1), have only recently been recognized as species, and their habitat requirements and management needs are poorly understood (Highton, 1999). There is especially a lack of knowledge about the vulnerable juvenile terrestrial plethodontids (Wyman, 2003).

Terrestrial salamanders have difficulty crossing roads, and roads may reduce both their abundance and genetic diversity. Roads not only fragment habitats but may also be obstacles to salamanders (Wyman, 2003). Forest roads have

been shown to reduce terrestrial salamander movement by 51%, and multiple roads could reduce dispersal by up to 97%. Although roads may not have major implications for species with large ranges and high abundances, species with limited ranges and low abundances may be severely affected by new roads because they are already impacted by fragmentation, logging, and other human activities (Marsh, Gorham, and Beckman, 2005). Plethodontids such as the white-spotted salamander and the Cheat Mountain salamander have small distributions and are currently affected by fragmentation and deforestation (Hammerson, 2004; Hammerson and Mitchell, 2004); multiple roads and truck traffic, when compounded with many other destructive factors, could imperil these species' survival. After clear-cutting, salamander communities take decades to recover from the drying of soils in logged areas, changes in the prey community, and the difficulty many salamander species have in crossing nonforested habitats (e.g., Ash, 1997; Bratton and Meier, 1998; Mitchell, Wicknick, and Anthony, 1996; Petranka, Eldridge, and Haley, 1993). The perforation of forests by well pads, access roads, and pipeline rights-of-way, with associated microclimatic drying, salinization, and other changes, presumably reduces or eliminates local

populations of many salamander species in fracking landscapes, and this could contribute cumulatively to a decline or loss of species over large areas.

The wastewater from fracking installations is another potential threat to salamanders. After well fracking is completed, 30%–70% of the water injected into the well returns to the surface with contaminants from the shales and the fracking chemicals (Schmidt, 2011). In Pennsylvania and West Virginia, frack water has been sprayed on land, diluted in municipal sewage treatment plants, stored in open pits, partially reused, leaked, and spilled (Kiviat and Schneller-McDonald, 2011). Preliminary data from Pennsylvania streams indicate that conductivity was higher and biotic diversity (including salamanders) was lower in small watersheds where fracking had occurred (Anonymous, 2010). Saline wastewater can pollute streams and other bodies of water, and many stream-dwelling and water-dependent organisms are salt sensitive. Salamanders, especially those with aquatic larvae, are sensitive to water quality (Duncan et al., 2011). The West Virginia spring salamander has been found in a single cave in Greenbrier County, West Virginia; the adults reside in the mud banks next to the stream passage, and the aquatic larvae develop in the stream (Besharse and Holsinger, 1977). Fewer than 250 mature individuals of this species exist, and all of these salamanders are dependent on the stream that runs through the General Davis Cave (Hammerson and Beachy, 2004)—if this stream were to be polluted by salt or fracking chemicals, the species would be in danger of extinction. Although much of the toxicological research has been conducted on frogs rather than salamanders, amphibians in general are vulnerable to many contaminants, including organic chemicals, heavy metals, and metalloids (Herfenist et al., 1989).

## Fishes

There is a high probability of water pollution from spills of fracking wastewater (Rozell and Reaven, 2012), and stream fishes are vulnerable to this impact. The tongue-tied minnow is intolerant of water pollution (US Environmental Protection Agency, 2010), although there is not enough information on this species to determine how it would be affected by fracking. The bluebreast darter is critically imperiled in New York, imperiled in both Ohio and Virginia, and vulnerable in West Virginia and requires good water quality (Losey, Roble, and Hammerson, 2011; Pennsylvania Natural Heritage Program, 2012), making it particularly vulnerable to fracking activities.

## Butterflies

The Appalachian azure inhabits deciduous forests, and its larval food plant is black cohosh (*Actaea racemosa*). The butterfly is scarce and has difficulty moving between forest fragments. Black cohosh is potentially threatened by non-native plants and white-tailed deer (*Odocoileus virginianus*) (New York Natural Heritage Program, 2011), both of which are likely to benefit from fracking.

## Plants

Plants will also be affected by fracking through fragmentation, increased salinity levels, and pollution by toxic chemicals. The northern wild monkshood is a federally threatened plant at risk of soil contamination, drying due to canopy loss, and nonnative plants. The monkshood occurs in only four states, of which New York and Ohio overlap with the Marcellus and Utica shale-gas region. Monkshood has narrow habitat affinities, grows slowly, is very sensitive to disturbance, and there is probably little gene flow among the isolated populations (Edmondson et al., 2009; Ohio Natural Heritage Program, 2007); forest fragmentation and increased salinity caused by fracking could imperil an already threatened species. Forest fragmentation is known to facilitate the spread of nonnative, potentially invasive, plants (e.g., Yates, Levia, and Williams, 2003).

## Potential Benefits to Biodiversity

Fracking may benefit some species as well as harm others. Industrial activity creates habitats that may be used by rare or economically important species. For example, Noel et al. (1998) documented caribou (*Rangifer tarandus*) using gravel pads associated with oil drilling for insect relief habitat. Schmidt and Kiviat (2007) found a globally rare clam shrimp [*Cyzicus (Caenestheriella) gynecia*] in rain pools on a gas pipeline road in New Jersey. However, artificial industrial habitats tend to support common species that are ecological generalists (E. Kiviat, personal observations) rather than species of conservation concern. We expect that fracking installations will provide habitats for a few noteworthy species while degrading the environment for many others. Appalachian cottontail is known to use shrublands and several-year-old clear-cuts (Cannings and Hammerson, 2012); thus, gas-pipeline rights-of-way and abandoned well pads might provide acceptable habitat. Undoubtedly, other species of conservation concern could be managed for in fracking landscapes, and research to provide the basis for such management is urgently needed. Forest fragmenta-

tion in fracking landscapes, because of the dispersed character of the industry, cannot be avoided.

## Summary

Hydraulic fracturing poses serious threats to a diverse group of species, including plants, butterflies, fishes, and salamanders, that have restricted geographic ranges overlapping substantially with the Marcellus and Utica gas shales. Of the 15 species we reviewed, many are so little known that targeted management would be based on insufficient evidence. Of these, 13 have narrow habitat affinities and 11 are dependent on good water quality (Table 1), making them particularly vulnerable to fracking effects such as elevated salinity and other pollution.

## Conclusions

Although fracking will likely be permitted in most states underlain with gas shales, if biodiversity and human impacts are well studied, appropriate regulations can be implemented. Because New York has not yet permitted high-volume horizontal hydraulic fracturing, there is an opportunity to protect the quasi-endemic species whose ranges extend into New York, including northern blue monkshood, Wehrle's salamander, Allegheny mountain dusky salamander, and Appalachian azure. Many organisms are undergoing poleward range shifts caused by climate change, but because changes in range limits are species specific and subject to many biological and abiotic interactions (Wyman, 1991), we cannot know whether overlap percentages with gas shales will increase or decrease. Range contraction (local or regional extirpation) due to other causes may increase the percentage overlap of the remaining range with the Marcellus-Utica region, thus cumulatively increasing the risk posed by fracking; the Allegheny woodrat (*Neotoma magister*; LoGiudice, 2003) may be an example.

We reviewed species for which range maps are available; there are many more species with no range maps or so little ecological information that it would be impossible to assess how fracking may affect them. There are almost certainly many species of invertebrates, plants, lichens, and other organisms that are quasi-endemic to the Marcellus-Utica region, but lack of access to range maps and ecological information prohibited their inclusion in our study. The species selected in this study may actually have a much greater overlap with the shales (because habitat range maps are generalized or out of date), and thus potential effects of

fracking could be greater than the percentages in Table 1 suggest. Also, ecological impacts like mountaintop-removal mining, logging, climate change, and other industrial activities will compound the effects of fracking, making these species vulnerable to decline and extinction. Future studies should include a broader range of taxa and field research that can measure the impacts of fracking while considering how these impacts may be compounded by other threats to biodiversity.

Biodiversity at all levels, from genes to ecosystems, constitutes many important values to human society and ecosystem functions, as well as the intrinsic importance of each species (Wilson, 1992). Conserving biodiversity is important because each species has unique compounds, behaviors, and other information that we may be able to use to improve human health, biotechnology, and enjoyment. Biodiversity is also of great value to the function of ecosystems—and we do not know how the elimination of certain species will affect ecosystem function. Many of the species selected not only have restricted geographic ranges, but live in small, isolated populations that would be negatively affected by further fragmentation. A number of these species are also recently described species, and most are little known ecologically. Intensive industrial activities such as fracking that potentially affect an almost 300,000-km<sup>2</sup> region need to be thoroughly studied so that researchers and natural resource managers can assess impacts on biodiversity and humanity.

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**NEW SOLUTIONS**  
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**SCIENTIFIC, ECONOMIC, SOCIAL, ENVIRONMENTAL, AND  
HEALTH POLICY CONCERNS RELATED TO SHALE GAS EXTRACTION**

*Guest editors:* Robert Oswald and Michelle Bamberger

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*Editorial*

**AN ENERGY POLICY THAT PROVIDES CLEAN  
AND GREEN POWER**

**CRAIG SLATIN  
CHARLES LEVENSTEIN**

The oil and gas industry's current promise of cheap natural gas supplies for the next century sounds remarkably like the promises of the 1950s about nuclear power. We were to gain cheap, abundant, and safe electricity for our homes, to expand industry for jobs, and to advance modern living. Nuclear electricity generation, however, has brought us the burden of subsidizing the high cost of nuclear facility construction and liability insurance, denial of ongoing radioactive releases, additional cancer burden, decades of fights over the transport and disposal of radioactive wastes, secrecy and lies from the industry and its government regulators, and multiple actual and near meltdowns.

Now shale gas extraction conducted through the technological process commonly referred to as "fracking" is touted by the oil and gas industry as the next great energy boon. They tell us that gas will be so plentiful that it will answer all of our energy-related problems. Best yet, it will end the unemployment crisis that lingers past the Great Recession, leading to millions of jobs over the next several decades. Its promoters claim that we can have energy independence and a fuel that burns cleaner than coal—while they spread denial that the threat of catastrophic climate change is real or has much to do with human activity.

Let's not be deceived: shale gas extraction will neither fulfill the prophecies nor be useful in the transition to just, democratic, and ecologically sustainable economies across the globe. It is business as usual [1]. It is owned and operated by industries with more than a century's legacy of greed, corruption, war provocation, pollution, illness, injury and death, environmental degradation, and a steady stream of propaganda and lobbying to limit its regulation by

governments. The U.S. Energy Information Agency (EIA) had touted the Marcellus Shale deposit as containing an estimated 410 trillion cubic feet of recoverable natural gas. In 2011, however, the U.S. Geological Survey (USGS) reported that the deposit “contains about 84 trillion cubic feet of undiscovered, technically recoverable natural gas and 3.4 billion barrels of undiscovered, technically recoverable natural gas liquids” [2]. Though an increase from the 2002 USGS estimates, this figure was 80 percent less than the EIA estimate that the industry had used to sell expansion of the shale gas extraction projects. This revision came while some members of the U.S. Congress were calling for investigation of the EIA’s use of consultants with ties to industry to produce estimates of shale gas [3].

The subterfuges are likely to continue. In December 2012, the *Boston Globe* reported that Phil Flynn, a Chicago commodities trader for Price Futures Group, was confident that shale gas extraction was a key to U.S. energy independence. He stated that it would create:

... millions upon millions of jobs for the next 10 to 30 years. What is going to drive us in this next decade? What is going to create good, high-paying jobs? Really fracking and natural gas have been an answer to our prayers, so hopefully we’re going to embrace it and move in that direction [4].

In response to a journalist’s question about whether or not abundant natural gas could jeopardize development of renewable technologies, he replied:

If they can’t compete, maybe they shouldn’t. Fracking and new production have made a lot of these other technologies obsolete. You can throw billions of dollars at some of these technologies and they’ll never be able to compete, unless you’re going to subsidize them for the next 50 to 100 years. We’ve got over 100 years of [natural gas] supply, maybe more [4].

Keep in mind that this interview was reported at a time when the gas industry sought to obtain permission to establish a pipeline from the Marcellus Shale to New England, which it hopes will be a prime consuming region of this gas. Mr. Flynn neglected to note that U.S. oil and gas industries have received federal government subsidies dating back to 1916 [5]. The point isn’t for renewable energy technologies to compete with natural gas. Rather, it is to replace gas and all fossil fuels if we are to have any chance of avoiding catastrophic climate change.

Another end-of-2012 news report from Bloomberg.com criticized U.S. Senator Ron Wyden (D-OR) for suggesting that the U.S. government should “. . . direct trade in energy according to its determination of the national interest” [6]. The editorial criticized Wyden for “protectionism” because of his suggestion that liquefied natural gas exports would lead to domestic gas price increases. Bloomberg.com stated:

Natural gas is hardly a private product, in Wyden's understanding, but rather a national resource whose price, quantity and use are best determined by the federal government. What's so troubling about Wyden's view, however, is the potentially enormous cost to economic efficiency from substituting market mechanisms with political decision-making.

Wyden is wrong: The federal government should not be exercising a heavy hand in this case. Liberal capitalist democracies [*sic*] should not allocate resources through regulatory determinations of the national interest. They should encourage free trade. If the domestic manufacturing and chemical industries require natural gas, they should place competitive bids for it [6].

Pennsylvania, a prime area above the Marcellus Shale and a state that produces a significant percentage of the nation's shale gas, passed Act 13 in early 2012. The law imposed a tax, an impact fee, on shale gas production. Although it toughened some safety standards to protect the environment and public health, the limited fee is primarily to compensate communities for the prior and ongoing damages that result from shale gas extraction operations. Several pro-industry provisions of the law are being challenged in the courts, including limitations on local zoning of drilling operations and protection of industry chemical use disclosure. These are hardly reasonable trade-offs for limited reparations funding, but "[b]y October (2012), \$204 million from gas industry payments were being distributed to state agencies and counties and municipalities that host gas wells" [7]. Pennsylvania and Ohio have both passed laws allowing state institutions of higher education to receive a percentage of revenues from shale gas sales when gas companies are given the right to set up wells on school premises [8]. Shale gas extraction fees/taxes will increasingly be proposed to offset the impact of 30 years of cutting taxes at all levels of government and the resultant reduction and privatization of public services and infrastructure. In the case of public higher education facilities, these revenues will also create disincentives against critical examination of the consequences of using shale gas for fuel. This will be the latest phase of the blackmail of working-class communities—the offer of jobs and public services at the cost of safe and clean natural resources of water and air that sustain good health.

Since its inception, *New Solutions* has been a forum for discussions of a "just transition" toward ecologically sustainable modes of production and consumption. The well-being of workers and communities is at stake when industries and operations that threaten environmental and ecological destruction as well as human illness and injury are closed and in some cases transformed. Communities long suffering environmental injustices and often poverty due to racist and classist policies that placed polluting facilities in their midst must be made whole and provided priority status in this planned transition. Yes, planned, not the free market model of "liberal capitalist democracies" touted by Bloomberg.com.

With this special issue of *New Solutions*, so excellently organized by guest editors Robert Oswald and Michelle Bamberger, we address a range of social, economic, environmental, and public health risks that have emerged from energy companies' push to extract shale gas. The industry claims that the benefits of shale gas extraction far outweigh the costs, and that harms are mostly imagined by the usual collection of NIMBY environmentalists and public health police. We believe, however, that enough evidence has been provided in support of taking extraordinary caution during all phases of shale gas operations. Though this special issue barely addresses the health and safety concerns for workers in this industry, the hazardous exposures involved in this work are another key factor that requires taking extraordinary caution. We can no longer afford to have industry use deeply hazardous technologies—with government encouragement—while public health is consigned to surveillance of the sick and dead.

Whatever short-term assistance the American economy gains from the continued use of fossil fuels, the highest priority must be placed on establishing a national energy policy, coordinated with an international set of energy policies, that aims for immediate measures to avert catastrophic climate change and establish a transition toward producing and delivering clean, green, and sufficient energy as part of the foundation for sustainable development. Attention to the health and welfare of workers and communities affected by these changes must be an essential priority of this new energy policy.

#### AUTHORS' BIOGRAPHIES

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*Introduction*

**SCIENCE AND POLITICS OF SHALE GAS EXTRACTION**

**MICHELLE BAMBERGER  
ROBERT E. OSWALD**

**ABSTRACT- Please supply 50-100 word abstract**

**Keywords: Please supply 3-5 key words**

Although humans have exploited natural resources to produce energy throughout recorded history, the modern age of fossil fuels didn't begin until the first half of the 19th century, when oil and natural gas wells were used to extract hydrocarbons for heating in China and for illumination in the northeast United States. Our addiction to oil and gas began in earnest with the introduction of the internal combustion engine for cars and trucks, and the switch from coal to gas in heating our homes in the 1950s. In the 1940s, hydraulic fracturing was introduced to stimulate the production of gas and oil trapped in rocks with

limited porosity; such stimulation opened up a whole new avenue for the extraction of oil and gas. Conventional wells were drilled to search for pockets of hydrocarbons buried deep within the earth; with hydraulic fracturing, oil and gas could be coaxed out of even very dense rock, such as shales. The initial applications for hydraulic fracturing were on vertical wells where relatively small quantities of water and comparatively low pressures were used to stimulate the flow of oil or gas. The problem with this is that the shale layers are relatively thin (50 to 200 feet in thickness), so that even with hydraulic fracturing, only a small amount of hydrocarbons could be extracted from vertical wells. The solution was to drill down and then turn the bit horizontally and continue drilling. The horizontal length of the well can then be hydraulically fractured, and much more oil or gas can be extracted. This process requires much larger quantities of water (approximately 5 million gallons for each fracturing), which contains sand to keep the fractures open (i.e., sand is used as proppant) and a variety of chemicals, some benign and some highly toxic. The transition from a conventional vertical well to a horizontal well that is hydraulically fractured is a huge step from a relatively minor insult to the rural landscape to major industrialization of the landscape.

Although concerns about this process had been raised in Colorado [1] and Alberta [2], among other places, the realization [3] that a large portion of the heavily populated and farmed areas of the eastern United States rests above large deposits of shale oil and gas (the Marcellus and Utica Shales) has sparked an enormous interest in the consequences of drilling near homes and on farmland. Historically, Pennsylvania is the origin of the U.S. oil industry, with the first well in Titusville in 1859, and New York is the origin of the natural gas industry, with the first well in Fredonia in 1821. Tens of thousands of gas wells have been drilled throughout Pennsylvania and New York over the last 150 years, with little protest. The advent of high-volume hydraulic fracturing of horizontal wells has been perceived as a qualitatively and quantitatively different process that has transformed the landscape and communities. Notably, this recent concern is not limited to the eastern United States; high-volume hydraulically fractured horizontal wells are proposed for shale plays throughout the world, and grassroots organizations have sprung up to question the wisdom of large-scale industrialized drilling. It was in this context that this special edition of *New Solutions* was conceived. A paper in a previous issue of *New Solutions* [4] explored the use of animals as sentinels for the health effects of large-scale drilling and outlined the reasons for the lack of strong evidence to prove or disprove the safety of the process. This issue casts a wider net and explores a range of topics associated with unconventional gas drilling. The intention was to describe important public health, economic, and socio-ecological issues, to present available data, and to define topics that need further study. In the call for papers, all points of view were welcomed. After extensive peer review, a range of topics was included in this issue.



Entitled *Scientific, Economic, Social, Environmental, and Health Policy Concerns Related to Shale Gas Extraction*, the issue opens with an editorial by Charles Levenstein and Craig Slatin discussing the broader need for sustainable production and consumption—in particular, the need to make sure that our energy policies and plans help us move to a greener economy that eliminates poverty, promotes public health, and establishes the primacy of renewable and non-toxic energy sources. Next, Katrina Korfmacher and collaborators provide a comprehensive discussion of exposure pathways and describe a resolution on the use of hydraulic fracturing in shale gas extraction that was approved by the American Public Health Association at its meeting in San Francisco in November of 2012. This resolution proposes a number of commonsense recommendations and a series of action steps to minimize the public health effects of this process.

In the Scientific Solutions section, Simona Perry describes an ethnographic approach to studying the community health implications of unconventional oil and gas development. The work concentrates on hard-to-monitor factors (e.g., psychological, sociocultural) that are associated with chronic stress. A great deal of emphasis has been placed on measuring environmental impacts using air and water testing, but little has been done to monitor scientifically the psychological and sociocultural changes transforming individuals and communities living and working near large-scale industrial gas drilling. Dr. Perry explores how ethnography, with its rigorous methods of fieldwork and analysis, is useful in not only evaluating and monitoring psychological and sociocultural changes within these communities, but also in describing and assessing the short- and long-term environmental health and social justice implications of these changes.

Also in the Solutions section, Nadia Steinzor, Wilma Subra, and Lisa Sumi report on a survey of perceived health effects coupled with water and air monitoring in the Marcellus Shale regions of Pennsylvania. They find that perceived health effects were greater for individuals living within 1,500 feet of a well pad relative to those living beyond that distance. Their findings demonstrate the utility of community-based research designs, especially when industrial and commercial interests inhibit public health and environmental impact studies that could jeopardize profitable gas and oil drilling.

The Features section begins with an economic analysis by Janette Barth. Dr. Barth considers the conventional wisdom that hydrocarbon gas extraction will bring economic prosperity to state and local governments and critically reviews the literature on the subject. Her analysis includes both the positive and negative drivers and looks at both the long- and short-term effects. She concludes that, despite many uncertainties, the long-term economic impacts from shale gas extraction may not be positive for most communities.

Ronald Bishop then addresses the important public health and safety, ecological protection, and greenhouse gas emission concerns related to abandoned oil and gas wells. Using the example of New York State, he shows that the majority of abandoned wells in New York have not been plugged, that the number

of unplugged wells has increased since 1992 due to inadequate enforcement, and that no program exists to monitor the integrity of those that have been plugged. Because of the potential for abandoned wells to disintegrate and leak, stronger regulations and additional resources are required not only to complete plugging of the current inventory of abandoned wells but also to provide adequate regulation for the expected increase in the number of new wells within the next few years.

The shale layers containing oil and gas also harbor naturally occurring radioactive material that can be brought to the surface along with the hydrocarbons. Alisa Rich and Earnest Crosby analyzed the radioactive materials found in two reserve sludge pits and found radioactive elements of the thallium and radium decay series. The health effects of the individual radionuclides, along with the regulation (or exemption from regulation) of technologically enhanced naturally occurring radioactive materials (referred to as TENORMs) in federal and state regulations, are discussed.

To understand the impacts of gas drilling on water resources, extensive pre-drilling testing should be performed. The nonprofit Community Science Institute, headed by Stephen Penningroth, has developed an innovative program that partners with community volunteers to sample streams in 50 locations across the Marcellus and Utica Shale regions in New York State. This is combined with more detailed testing of individual water wells by the Institute's certified water quality testing laboratory. This unique approach to water sampling is a small step toward understanding changes in water quality from a variety of sources and will be useful in understanding impacts from both agriculture and industrial drilling in New York State.

In the next piece, Madeleine Scammell and collaborators review the regulations surrounding the disclosure of the chemical additives in hydraulic fracturing fluid. Since disclosure is not mandated by the federal government except on federal lands (and then only after well completion), it is regulated by laws that vary from state to state. The shortcomings cited in this paper include permitted nondisclosure of proprietary chemicals and mixtures, insufficient penalties for inaccurate or incomplete information, and timelines that allow disclosure after well completion. The authors suggest that lax and varying regulations on disclosure leave lawmakers, public health officials, and regulators uninformed of the potential hazards and ill-prepared to take steps to protect public health. Exemptions from federal regulations and efforts to mandate chemical disclosure are discussed.

The question of whether industrialized gas drilling has affected our food supply is an important unresolved issue. One of the reasons for our lack of information about this issue is that farming is by definition a decentralized process without detailed public recordkeeping. Madelon Finkel and collaborators have used what data are available to study the changes in the dairy industry in Pennsylvania, comparing those counties with extensive gas drilling to those

with little or none. Using data from the United States Department of Agriculture's National Agricultural Statistics Service and the Pennsylvania Department of Environmental Protection, the authors showed that both milk production and numbers of dairy cows began decreasing in 1996, but that larger decreases were seen between 2007 and 2011 in those counties with intensive gas drilling compared to those with little drilling. Although causal relationships are difficult to establish in studies such as this, the paper emphasizes the importance of considering the effects on the dairy industry when hydrocarbon extraction impacts large portions of a particular region of the country (e.g., the Marcellus and Utica Shales in the northeast United States).

The next section of the issue, *Voices*, includes an interview of Anthony Ingraffea by Adam Law. Both are founding members of Physicians, Scientists & Engineers for Healthy Energy. Dr. Law is a practicing endocrinologist in Ithaca, New York, and approaches the subject from a medical perspective. Dr. Ingraffea, an engineering professor at Cornell University, is one of the world's foremost experts in fracture mechanics; his simulations have provided important insights into hydraulic fracturing. Ingraffea and Law discuss the importance of studying the process of gas drilling and hydraulic fracturing from a variety of perspectives, including geological engineering, hydrology, and medicine. This interview was originally done as a part of a project funded by the Heinz Endowment, and the transcript is included here with permission of the Endowment. The original interview can be viewed at: [http://www.heinz.org/grants\\_spotlight\\_entry.aspx?entry=982](http://www.heinz.org/grants_spotlight_entry.aspx?entry=982).

Health practitioners in communities that may suffer health effects of large-scale gas drilling need to obtain accurate medical histories from individuals with potential exposures. In the *Movement Solutions* section, Pouné Saberi, a practicing physician, describes the process of taking an environmental exposure history in areas that are being intensively drilled, and the issues surrounding detection of possible environmental exposure clusters.

This special issue of *New Solutions* cannot establish firm conclusions, largely because the data are not available to make firm conclusions. Rather, our goal is to add to and review current knowledge and to point out areas where data are lacking and where regulations are lax or nonexistent. In the United States, gas drilling with high-volume hydraulic fracturing is regulated by a patchwork of state laws, varying from comparatively little regulation in Pennsylvania to an outright ban in Vermont. Regulations are largely based on political considerations rather than on sound scientific evidence. However, what passes for "sound scientific evidence" is sometimes in the eye of the beholder. On one hand, an oft-stated refrain is that in the 60-odd years since the introduction of hydraulic fracturing to extract hydrocarbons, no drinking water has been proven to be contaminated. This statement parses the issue into a small part of the process (hydraulic fracturing) and ignores the complete life cycle from drilling to production to consumption. It perpetuates misplacement of the burden

of proof, with disdain for the precautionary principle. Ample evidence exists from more than a century and a half of a fossil-fueled industrial economy that it is wrong to assume that the technological processes related to extracting, processing, and using these substances are safe unless proven otherwise by those impacted. In the case of high-volume hydraulic fracturing we are all best served, in the short and long terms, by demanding proof of safety prior to expanding the practice to new areas. The uncertainties and existing evidence make a strong argument for caution and for strong, well crafted, and strictly enforced regulations.

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*Comment and Controversy*

**PUBLIC HEALTH AND HIGH VOLUME HYDRAULIC  
FRACTURING**

**KATRINA SMITH KORFMACHER  
WALTER A. JONES  
SAMANTHA L. MALONE  
LEON F. VINCI**

**ABSTRACT**

High-volume horizontal hydraulic fracturing (HVHF) in unconventional gas reserves has vastly increased the potential for domestic natural gas production. HVHF has been promoted as a way to decrease dependence on foreign energy sources, replace dirtier energy sources like coal, and generate economic development. At the same time, activities related to expanded HVHF pose potential risks including ground- and surface water contamination, climate change, air pollution, and effects on worker health. HVHF has been largely approached as an issue of energy economics and environmental regulation, but it also has significant implications for public health. We argue that public health provides an important perspective on policy-making in this arena. The American Public Health Association (APHA) recently adopted a policy position for involvement of public health professionals in this issue. Building on that foundation, this commentary lays out a series of five principles to guide how public health can contribute to this conversation.

**Keywords:** environmental health, hydrofracking, public health

The recent growth of high-volume horizontal hydraulic fracturing (HVHF) to extract natural gas from unconventional gas reserves has been framed largely as an issue of economics and environment. Proponents emphasize the potential to bring prosperity to economically depressed communities and to vastly increase domestic natural gas production, decrease dependence on foreign energy sources, and replace dirtier energy sources, such as coal. At the same time, concerns have been raised that HVHF could result in ground- and surface water contamination, contributions to climate change, and increased air pollution. These concerns have focused attention on the inadequacy of existing regulations to protect the environment in the face of dynamic energy extraction technologies and practices.

Until recently, the public health perspective on this issue has received relatively little attention. Goldstein et al. [1] analyzed state and federal advisory committees related to HVHF in the Marcellus Shale region of the United States and concluded that public health was “missing from the table.” But what would it mean to have public health voices “at the table,” and what would they say? The American Public Health Association took an important first step by adopting a policy position on HFVH in October 2012, and has finalized a resolution as this article goes to press in January 2013 (<http://www.apha.org/advocacy/policy/policysearch/default.htm?id=1439>). Other public health organizations such as Physicians, Scientists, and Engineers for Healthy Energy (<http://www.psehealthyenergy.org>) are currently working on similar actions. In this commentary, we lay out a framework for the role of public health in decisions related to HVHF in the United States.

The public health framework for addressing issues that affect people’s health is holistic, multidisciplinary, and oriented toward prevention. Bringing this perspective to the issue of HVHF may help identify areas of concern that are not encompassed by existing environmental regulations. In contrast to the lack of public health expertise among the membership of HVHF advisory committees, Goldstein et al. note that in one public hearing, nearly two-thirds of speakers mentioned health [1]. Thus, framing HVHF as an issue of public health may also help decision-makers address the public’s concerns. Perhaps most importantly, the public health perspective has the potential to guide policy and management despite the persistent uncertainties about impacts of HVHF. Principles of public health emphasize the need for transparency in research and policy, a precautionary approach in the face of uncertainty, baseline and continued monitoring, and adapting management as understanding of risks increases.

This commentary considers the entire life cycle of, and processes involved in, the expansion of HVHF, including site preparation, drilling and casing, well completion, production, processing, transportation, storage and disposal of wastewater and chemicals, sand mining, and site remediation. The rapid socioeconomic changes, scale of development, and pace of extraction made possible by HVHF could affect health directly or indirectly through changes

in vehicular traffic, community dynamics, unequal distribution of economic benefits, demands on public services, health care system effects, impacts on agriculture, and increased housing costs. At the same time, economic growth resulting from HVHF may contribute to improvements in individual health status, health care systems, and local public health resources. The public health perspective also requires assessing the long-term and cumulative impacts of this dispersed-site extractive industry, as well as the distribution of these impacts, particularly within low-income rural populations.

### **HEALTH AND HVHF: OVERVIEW OF THE POTENTIAL IMPACTS**

As discussed in this special issue of *New Solutions*, high-volume horizontal hydraulic fracturing in unconventional gas reserves (often referred to as “fracing” or “fracking”) has expanded rapidly since 2007 [2]. HVHF is a technology that injects water, solids, and fluids into wells drilled into the earth’s crust as a means to enhance the extraction of natural gas from deep geologic formations, primarily shale, tight sands, and coal seam gas that underlie many regions of the United States [3]. Important unconventional natural gas reserves in the United States include: Barnett (Texas), Fayetteville (Arkansas), Haynesville (Louisiana and Texas), Antrim (Minnesota, Indiana, and Ohio), Marcellus (New York, Pennsylvania, and West Virginia), Bakken (North Dakota), Woodford (Oklahoma), and Eagle Ford (Texas). The basic technology of hydraulic fracturing has existed since the 1860s. However, its recent expansion arose from technological innovations that allowed for horizontal drilling, facilitating greater access to gas in certain shale formations than do conventional vertical wells. HVHF also uses vastly greater quantities of water and chemicals than conventional operations. These horizontal wells are often hydraulically fractured in a number of stages, greatly expanding the potential duration and scale of impacts at each individual site [4, 5].

The rapid expansion of HVHF, both in communities with a long history of natural gas development and in those with limited natural gas industry experience, has the potential to impact public health in numerous ways [1, 6]. These impacts range from direct health impacts for workers or residents who are exposed to harmful chemicals in air, surface water, or groundwater, to indirect effects such as those resulting from rapid community change (e.g., increased traffic and demand for housing), as well as off-site impacts, such as mining the sand required for the HVHF process. Some of these impacts may be positive—for example, from economic growth resulting in better nutrition and health care—while others may be negative.

The distribution of these health impacts varies by proximity to drilling operations, involvement in the industry (worker, property owner, neighboring community member), individual characteristics (children versus adults, asthmatics,

etc.), and income (e.g., low income people may be more adversely affected by inflation of housing rental rates). Unequal distribution of benefits may contribute to community conflict and stress, thus indirectly affecting health [7]. Below, we summarize some of the potential health impacts of HVHF in greater detail to set the stage for considering the role of public health in anticipating and managing risks.

### **Surface and Ground Water Quality**

Impacts on water quality and quantity are some of the most highly publicized environmental effects of HVHF with potential human health consequences [8, 9]. HVHF increases the amount of fresh water used by each natural gas well by as much as 100 times the quantity used in conventional drilling [10]. Additionally, wells can be hydraulically fractured more than once, each time using up to 5 million gallons of water [11, 12]. Between 25 and 100 percent of the fluids used in drilling may return to the surface; these “flowback” or “produced” fluids may contain hydraulic fracturing chemicals, as well as heavy metals, salts, and naturally occurring radioactive material (NORM), from below ground [13]. Therefore, this water must be treated, recycled, or disposed of safely [14].

The chemicals and proppants that are added to the water used in HVHF have raised public health concerns related to surface water and groundwater quality [2, 15]. Chemical additives used in fracturing fluids typically make up less than 2 percent by weight of the total fluid [16]. Over the life of a well this may amount to 100,000 gallons of chemical additives. These additives include proppants, biocides, surfactants, viscosity modifiers, and emulsifiers. The chemicals vary in toxicity. Some are known to be safe. However, others are known or suspected carcinogens, endocrine disruptors, or are otherwise toxic to humans—including silica, benzene, lead, ethylene glycol, methanol, boric acid, and gamma-emitting isotopes [16]. Manufacturers of hydraulic fracturing fluids are allowed to protect the precise identity and mixture of the fluids under “proprietary” or “trade secret” designations. From a public health perspective, this prevents effective baseline monitoring prior to hydraulic fracturing, as well as documenting of changes over time. In addition, without this information, it is difficult to apprise workers and the public of potential health hazards.

The manner in which wastewater from HVHF is handled and treated is another water quality concern. The disposal methods used for the “produced water” and brine extracted from the shale have the potential to affect the water quality of lakes, rivers, and streams, damage public water supplies, and overwhelm public wastewater treatment plants [17]. Surface water may be contaminated by leaking on-site storage ponds, surface runoff, spills, or flood events. Even if contaminated surface water does not directly impact drinking water supplies, it can affect human health through consumption of contaminated wildlife, livestock, or agricultural products [18].



Disposal through class II injection wells has traditionally been the primary option for oil- and gas-produced water [19]. Several recent earthquakes near Youngstown, Ohio, were linked to deep injection of HVHF wastewater, raising concerns about this practice under certain geologic conditions [20]. Produced water has also been treated in self-contained wastewater treatment systems at well sites, through local municipal wastewater treatment plants, and by commercial treatment facilities [14]. Because most municipal wastewater treatment plants cannot adequately treat wastewater from HVHF, some states (such as Pennsylvania) require treatment at industrial waste treatment plants [21]. However, the quantity of wastewater needing treatment and the capacity of existing plants to properly treat these wastes may be an issue in some areas [17]. For example, brine in Pennsylvania is permitted to be sprayed for road maintenance purposes, raising concerns about contamination of surface waters [21].

The potential for HVHF to cause methane to seep into drinking water supplies has received considerable media attention [10, 22]. While many of the assertions regarding flammability of drinking and surface water have yet to be substantiated, a study published in the *Proceedings of the National Academies of the Sciences* indicates that drinking-water wells within a one-kilometer radius of a drilling site have methane concentrations 17 times higher than wells outside of a one-kilometer radius [23]. The potential for health impacts from human exposure to methane released into household air from domestic water use is not well understood [23, 24].

Finally, on a local basis, using large volumes of fresh water for HVHF may consume a scarce commodity needed for agriculture, recreation, wildlife, environmental recharge, and drinking water supplies. Disrupting or displacing these pre-existing uses could have additional indirect public health impacts. Drilling fluids that do not return to the surface and remain below ground are effectively removed from the surface water cycle. Especially in areas with limited water resources, the impact of HVHF on the quantity of surface water available for other uses related to public health is a concern. Technological developments, such as gel-based fracking or closed-loop systems, could reduce water use in the future; however, the current practice of HVHF is water-intensive [25].

### **Air Quality**

Globally, replacing coal with natural gas may result in reduced air pollution. However, combustion connected with extraction processes and fugitive emissions may increase air-quality-related health problems in HVHF production areas. Levels of ozone (including wintertime ozone) and concentrations of particulate matter (PM<sub>10</sub> and PM<sub>2.5</sub>) have been found to be elevated near gas activity [26]. Wintertime ozone caused by the release of volatile organic compounds (VOCs) mixed with the conditions of sunlight and snow cover has been noted in Utah, New Mexico, and Wyoming. Hydrocarbon emissions from gas drilling

activity have also been found to be high in Colorado, where researchers found that twice as much methane was being leaked into the atmosphere from oil and gas activity as was originally estimated [27]. Researchers in Colorado have documented a wide range of air pollutants near an HVHF operation [28]. One study has found that residents living near well pads have a higher risk of health impacts from air emissions than those living farther away [29]. Domestic animals may also be affected [18].

### **Quality of Life**

Noise and light have been cited as health concerns for residents and animals living near drilling operations [30, 31]. Excessive and/or continuous noise, such as that typically experienced near drilling sites, has documented health impacts [32]. According to community reports near these sites, some residents may experience deafening noise; light pollution that affects sleeping patterns; noxious odors from venting, gases, and standing wastewater; and livestock impacts [33]. Both noise and light can contribute to stress among residents.

Expansion of HVHF in rural communities may result in significant rapid population changes. These changes may create health care needs that overwhelm the capacity of existing public health systems to care for existing populations. Similarly, both the number and nature of emergency response resources needed in local communities may increase due to accidents, blowouts, or spills at drilling sites, as well as accidents during the transportation of supplies and waste through rural communities. Some areas have reported inadequate emergency medical services (EMS) training and insufficient communication between drilling operators and emergency responders. Pipeline construction and maintenance may also pose security and safety issues [34].

In addition to these environmental health threats, the rapid socioeconomic changes, scale of development, and pace of extraction made possible by HVHF may impact health. HVHF has the potential to significantly change the nature of communities, particularly in rural areas [34]. There have been reports of increased crime associated with the influx of natural gas workers [35, 36]. A study by the County Commissioners Association of Pennsylvania found that Pennsylvania was experiencing deficits in emergency management and hazardous materials response planning in drilling areas; courts and corrections impacts; human services burdens in areas such as drugs and alcohol, domestic relations, and children and youth; and effects on affordable housing, among others [37]. The stresses of social change, uncertainty, isolation, inadequate housing and infrastructure, and substandard services may combine in ways that significantly affect communities' quality of life [33]. Chronic psychological stress has been linked to respiratory health, both independently and in combination with air pollution exposures [38]. Therefore, social stressors, such as those seen with the changes that natural gas drilling brings to an area, may have a cumulative impact on public health.

## Worker Health

Historically, natural gas extraction has been a dangerous occupation [39]. Many of the safety issues involved are well understood and regulated. According to the Bureau of Labor Statistics (BLS), transportation incidents are consistently the leading cause of fatalities, followed closely by contact with equipment [40]. However, the rapid pace and geographic scope of expansion into remote locations inhibits monitoring of worker protection at drill sites [41]. This environment creates significant challenges for protecting oil and gas extraction workers.

The industry is characterized by a high rate of fatal injury when compared to all U.S. industries. Worker safety in this industry is highly variable, both over time and across individual companies. The risk of fatality is higher among workers employed by contractors and small companies [42]. During times of high demand, the number of small companies and inexperienced workers entering the industry increase. The annual rate of fatalities is also associated with the number of drill rigs in operation [42]. This pattern of risk suggests particular attention should be paid to small operations during periods of rapid industry expansion, especially in rural areas with roadways unsuited to industrial traffic.

In addition to risks typical of the oil and gas industry, there may also be unique worker health concerns associated with HVHF, such as the potential for exposure to chemical constituents of hydraulic fracturing fluids, diesel exhaust, BTEX (benzene, toluene, ethylbenzene, and xylenes), particulate matter (PM), glutaraldehyde, and the sand used as a proppant that have not been fully characterized and are still poorly understood [43].

## Sand Mining and Transport

HVHF operations typically involve hundreds of thousands of pounds of “frac sand,” the sand used as proppant during the hydraulic fracturing process. Transporting, moving, and filling thousands of pounds of sand onto and through sand movers, along transfer belts, and into blenders generates dust containing respirable crystalline silica. Inhalation of fine dusts of respirable crystalline silica can cause silicosis [35]. Crystalline silica has also been determined to be an occupational lung carcinogen [44]. This exposure is of concern for workers and also for other individuals near the mining operations and well pads.

The National Institute for Occupational Safety and Health (NIOSH) recently collected air samples at 11 different HVHF sites in five different states (AR, CO, ND, PA and TX) to evaluate worker risks, including exposure to crystalline silica [43]. At each of the 11 sites, NIOSH consistently found levels that exceeded relevant occupational health criteria (e.g., the Occupational Safety and Health Administration (OSHA) Permissible Exposure Limit (PEL) and the NIOSH Recommended Exposure Limit (REL)). At these sites, 47 percent of the samples collected exceeded the calculated OSHA PELs; 79 percent of samples exceeded the NIOSH RELs. The magnitude of the exposures is particularly

important: 31 percent of samples exceeded the NIOSH REL by a factor of 10 or more. This study indicates that hydraulic fracturing workers are potentially exposed to inhalation health hazards from dust containing silica when open air mixing of sand is done on site.

There may also be impacts on workers and communities affected by the vastly increased production and transport of sand for HVHF in other areas of the country. NIOSH concluded that there continues to be a need to evaluate and characterize exposures to these and other chemical hazards in hydraulic fracturing fluids, which include hydrocarbons, lead, naturally occurring radioactive materials (NORM), and diesel particulate matter [26, 43].

### **Climate Change**

Uncertainty remains over the potential for HVFH to affect climate change. Climate change is predicted to significantly affect health in numerous direct and indirect ways [45]. Natural gas is more efficient and cleaner-burning than coal. When burned, natural gas releases 58 percent less carbon dioxide (CO<sub>2</sub>) than coal and 33 percent less CO<sub>2</sub> than oil [46]. Because of that, natural gas has been promoted as a transitional fuel to begin a conversion to greener energy such as wind and solar [11, 47]. However, some projections suggest that obtaining natural gas through HVHF actually produces more greenhouse gas emissions than does coal production and burning [48]. The impacts of HVHF on overall greenhouse gas emissions depend on actual fugitive emissions, the quantity of fossil fuels combusted during production processes (by compressors, trucks, machinery, etc.), and whether natural gas produced by HVHF reduces the use of other more greenhouse-gas-intensive fuels. Burning natural gas obtained through HVHF will result in a net increase of greenhouse gas emissions over time if it simply delays the burning of coal reserves.

The list of potential public health impacts outlined above is not comprehensive. However, it provides an overview of the diversity, extent, and nature of the issues that might be addressed by taking a public health perspective on HVHF. It is clear that while natural gas extraction is a long-standing and important part of our nation's energy portfolio, the rapid implementation of large-scale HVHF in many parts of the country has presented a new industrial, environmental, and land use development pattern with significant potential for public health effects.

## **PUBLIC HEALTH RESPONSE**

In 2008, Howard Frumkin and colleagues set forth a framework for public health responses to the challenge of climate change [45]. Both climate change and HVHF are usually considered issues characterized by tradeoffs between economic growth and environmental protection. As a policy problem, climate change is similar to the rapid expansion of HVHF in several key ways, including

wide-ranging uncertainties, the potential for impacts in diverse sectors, and the need to address the issue through multidisciplinary investigation and at local, state, and federal levels (as well as internationally). For both issues, public health brings an important perspective, and public health professionals have an important role to play. Here, we adapt Frumkin's framework for climate change to the issue of HVHF to provide guidance for a constructive role for public health in future practice and policy.

Frumkin et al. describe five public health perspectives that inform responses to the challenges of climate change [45]:

- prevention;
- risk management;
- co-benefits;
- economic impacts; and
- ethical issues.

These perspectives are also salient for the many challenges facing public health professionals in addressing HVHF. Below, we discuss each perspective in turn as a source of guidance for what public health voices can add to the ongoing public dialogue about managing HVHF to promote the public good.

Central to each of these perspectives is the uncertainty surrounding the potential impacts of HVHF. Uncertainty is frequently cited as one of the primary barriers to determining whether—and if so how—HVHF can be managed in a manner that promotes public health. While instances of health problems have been reported in various communities where HVHF has occurred across the country, to date there has been little peer-reviewed literature on the nature or extent of these impacts [18]. This dearth of research is due to the limited number of years HVHF has been practiced, as well as to fundamental challenges in studying its health impacts. These include the lack of identified unique health indicators, latency of effects, limited baseline and monitoring data, cumulative impacts, low population densities, and, in some cases, industry practices and non-disclosure agreements that limit access to relevant information. Understanding of health effects is further complicated by the variations in HVHF operations geographically and over time. Many of these significant uncertainties are unlikely to be overcome in the foreseeable future. However, the public health community has extensive experience in situations that are rife with unknowns. The precautionary principle is often invoked to guide decision-making, so as to prevent suspected environmental or health risks when there is significant uncertainty. The theme of taking action despite remaining uncertainties carries through each of the principles discussed below.

### **Prevention**

As Frumkin et al. [45] point out, public health professionals distinguish between primary prevention (taking action to avoid a harm) and secondary

prevention (anticipating and taking action to reduce existing impacts). Principles of prevention suggest that public health professionals should urge federal, state, and local environment, health, and development agencies to adopt a precautionary approach in the face of uncertainty regarding the long-term environmental health impacts of HVHF. Such an approach might include:

- discouraging the use of chemicals or chemical mixtures with unknown health effects, particularly those with the potential for long-term or endocrine-disrupting potential, and favoring safer substitutes;
- requiring gas development companies to disclose and receive approval of the chemicals proposed in each HVHF operation, before drilling and completion;
- conducting baseline monitoring of air quality, water quantity and quality, land resources, and human health before drilling begins, throughout the extraction process, and after active operations cease;
- modeling and predicting cumulative environmental health impacts under various extraction scenarios;
- conducting health impact assessments that address multiple health effects at a local and regional scale prior to expansion of HVHF;
- insisting on the use of commonly accepted industry best practices to lower worker exposures, for example, dust controls, traffic control plans, closed chemical delivery systems, reduced worker exposure to produced water, and employer provision of personal protective equipment (PPE), training and monitoring;
- proceeding at a scale and pace that allow for effective monitoring, surveillance, and adaptation of regulation to anticipate/prevent negative health effects; and
- should negative health or environmental effects be observed, ceasing extraction until further evidence indicates that operations may resume safely.

Geological, geographic, climatological, technological, economic, social, and political differences between communities in which HVHF occurs result in widely varied potential for health impacts. The public health community should advocate for planning and policy approaches that take into account this variability.

### **Risk Management**

The framework of risk management guides the systematic identification, assessment, and reduction of risks. Public health professionals should advocate for and participate in efforts to manage the risks of HVHF. These efforts should examine the full life cycle of the process at local, regional, and global levels.

This implies explicitly modeling the cumulative impacts of HVHF over time. For example, individual drilling operations are unlikely to produce enough pollution to trigger regulation under existing environmental laws. However, the cumulative impacts of emissions from drilling-associated activities at multiple

sites may create significant public health threats for local communities or regions. Therefore, projections of aggregate emissions under expected extraction scenarios should be the basis for regulation of individual sources. Overall density and projected development over time should be considered.

Air pollution is just one type of impact to which the risk management approach should be applied. Health impact assessment (HIA) provides a framework for identifying and prioritizing multiple impacts. Only one HIA of HVHF has been conducted to date, and public health professionals and others have advocated for additional HIAs to be conducted in other areas [30].

### **Co-Benefits**

Frumkin et al. invoke the principle of co-benefits to guide a public health response to climate change [45]. Co-benefits result when actions yield benefits in multiple arenas. Focusing on actions with co-benefits is particularly appropriate when resources are limited and uncertainties are high.

Public health professionals can look to the list of 10 essential services of public health, developed by the Public Health Functions Steering Committee in 1994 (see Figure 1) to help identify actions within their purview that may both reduce risks from HVHF and benefit health in other ways [49]. For example, monitoring private drinking water wells for baseline data prior to the onset of HVHF may identify pre-existing drinking water quality problems that would otherwise have gone undetected. Community partnerships forged to address the issues raised by HVHF may also be able to confront other local environmental public health problems. Training public health professionals, health care providers, and emergency responders to deal with potential spills, explosions, or accidents related to HVHF may improve local capacity to respond to other types of public health emergencies.

### **Economic Impacts**

Public health planning aims to protect the public at the lowest possible cost. In the case of HVHF, this suggests the following:

- Both long- and short-term costs and benefits should be considered. The history of environmental health includes many examples long-term remediation costing more than prevention.
- The timing of HVHF has major implications for the economics of shale gas extraction because of expected changes in the price of natural gas. Policies regarding HVHF should explicitly compare tradeoffs between the economic, strategic, public health, and global climatological implications of energy alternatives under different extraction scenarios over the long term.
- The distribution of costs and benefits from HVHF is highly variable. While HVHF undoubtedly brings economic growth, the benefits do not accrue

1. Monitor health status to identify and solve community health problems.
2. Diagnose and investigate health problems and health hazards in the community.
3. Inform, educate, and empower people about health issues.
4. Mobilize community partnerships and action to identify and solve health problems.
5. Develop policies and plans that support individual and community health efforts.
6. Enforce laws and regulations that protect health and ensure safety.
7. Link people to needed personal health services and assure the provision of health care when otherwise unavailable.
8. Assure competent public and personal health care workforce.
9. Evaluate effectiveness, accessibility, and quality of personal and population-based health services.
10. Research for new insights and innovative solutions to health problems.

Figure 1. Ten essential services of public health.

**Source:** U.S. Centers for Disease Control and Prevention, National Public Health Performance Standards Program (NPHPSP), “10 Essential Public Health Services,” <http://www.cdc.gov/nphpsp/essentialservices.html>

equally within communities, nor do the burdens. Because of public health’s focus on eliminating health disparities and the close association between economic and health status, the distribution of economic impacts has public health implications.

- The impacts of the boom-and-bust cycle of economics associated with extraction of nonrenewable resources like shale gas has significant implications for community health over the long-term.
- Many economic costs are not included in simple calculations of jobs and economic growth generated by new industry. These externalities may include losses to existing businesses (tourism, agriculture, etc.), damage to roads and increased costs of road maintenance, and days of work or school missed by asthmatics who suffer more when air pollution increases.

For these reasons, public health professionals should advocate for economic analyses that account for long-term costs, identify externalities, and clarify the distribution of costs and benefits. Such analyses may provide a basis for designing fee structures, prioritizing research needs, creating monitoring systems, and developing public health programs that reflect the true costs and benefits of HVHF.



## Ethical Issues

The ethics of public health have been codified into 12 “principles for practice.” In addition, Frumkin et al. [45] point to several ethical foundations that may inform public health responses in a given situation. Building on these principles, ethical considerations relevant to the public health perspective on HVHF include:

- *Future generations*: As noted above, the potential long-term costs of environmental and health damage should be considered. Given the long latency of diseases like cancer, intergenerational impacts of endocrine disruptors, and slow migration of groundwater, it is appropriate to advocate for a long-term perspective on health effects of HVHF.
- *Vulnerable populations*: Some individuals or populations may be more vulnerable to environmental health impacts of HVHF. Children, the elderly, and those with existing disease (for example, asthma) may be more susceptible to impacts such as air pollution. Workers (both on-site and in related industries) are another population that may be particularly affected due to their proximity to operations.
- *Environmental justice*: Public health ethics point to protection of those who have fewer resources to avoid or mitigate impacts, already bear disproportionate environmental risks, or have historically lacked a voice in policy decisions. By this definition, isolated and economically disadvantaged rural communities are of concern as a whole, and lower-income members of these communities may need particular consideration.
- *Public participation*: Informed, ongoing, and meaningful participation by affected communities is often advocated as a strategy to promote ethical decision processes and outcomes. Public health professionals have the tools and experience to communicate information, develop partnerships, and process the public’s input in a meaningful way. The extent of public concern about health in discussions of HVHF points to the importance of public participation in decisions on this issue.

Public health professionals have a role to play in making sure that these ethical principles are considered in decision-making related to HVHF.

## CONCLUSIONS

Natural gas development is regulated under local, state, and federal land use and environmental laws. However, implementing new natural gas extraction technologies on a large scale poses potential public health threats that existing regulatory systems may not adequately anticipate, monitor, or protect against. Therefore, it is essential that public health professionals be included in deliberation of administrative, programmatic, and policy approaches to natural

gas extraction at all levels of government. Federal, state, and local commissions and agencies charged with regulating the natural gas industry should include strong representation by professionals with training and experience in public health. In addition, the role of local and state public health professionals in responding to public health concerns arising from HVHF should be recognized and supported accordingly.

Training of local health departments, health care providers, and occupational health centers, as well as open ongoing communication between health professionals and the gas extraction industry, are essential to protecting worker and public health. The implementation of new natural gas extraction technologies, continual changes in the gas development industry, rapid growth of drilling operations in new areas, and variations in operations between companies pose significant challenges for occupational health. Public health professionals should support training for workers and local health care providers to anticipate these challenges and the provision of resources to subsidize these additional needs.

There are clearly many uncertainties surrounding the nature, distribution, and extent of health effects from HVHF. However, as Frumkin et al. [45] note, "Preparedness often occurs in the face of scientific uncertainty." Based on past experiences with emergency response, offshore oil and gas production, nonpoint sources of air and water pollution, and occupational health, public health professionals have a wealth of experience relevant to many aspects of HVHF. Policies that anticipate potential public health threats, use a precautionary approach in the face of uncertainty, provide for monitoring, and promote adaptation as understanding increases may significantly reduce the negative public health impacts of this approach to natural gas extraction.

To help accomplish this goal, the public health workforce should become better educated about natural gas development and its potential for public health impacts. In particular, local public health agencies in areas of active natural gas development should receive adequate resources to support education, outreach, surveillance and monitoring, needs assessment, and prevention activities related to natural gas extraction. Federal and state legislatures should provide funding for the training and staffing of local public health agencies in areas of active natural gas development. Public health professionals should also reach out to health care providers and community partners to increase their capacity and involvement in this area.

Such awareness, education, and support may help public health professionals more actively engage in protecting public health from the potential impacts of HVHF. Policy position statements such as that recently adopted by the APHA provide a platform from which public health professionals can continue to engage in decision-making processes related to HVHF. This special issue of *New Solutions* offers additional information and inspiration for next steps.

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**USING ETHNOGRAPHY TO MONITOR THE COMMUNITY HEALTH IMPLICATIONS OF ONSHORE UNCONVENTIONAL OIL AND GAS DEVELOPMENTS: EXAMPLES FROM PENNSYLVANIA'S MARCELLUS SHALE**

**SIMONA L. PERRY**

**ABSTRACT**

The ethnographer's toolbox has within it a variety of methods for describing and analyzing the everyday lives of human beings that can be useful to public health practitioners and policymakers. These methods can be employed to uncover information on some of the harder-to-monitor psychological, sociocultural, and environmental factors that may lead to chronic stress in individuals and communities. In addition, because most ethnographic research studies involve deep and long-term engagement with local communities, the information collected by ethnographic researchers can be useful in tracking long- and short-term changes in overall well-being and health. Set within an environmental justice framework, this article uses examples from ongoing ethnographic fieldwork in the Marcellus Shale gas fields of Pennsylvania to describe and justify using an ethnographic approach to monitor the psychological and sociocultural determinants of community health as they relate to unconventional oil and gas development projects in the United States.

**Keywords:** environmental justice, unconventional oil and gas, Marcellus Shale, community health, chronic stress, ethnography, fracking



The term *onshore unconventional oil and gas developments* refers broadly to the activities and technologies used for extracting hydrocarbon resources from oil and gas shale, tight gas and tar sands, heavy oil reservoirs, and coal beds [1]. As the pace of exploration, drilling, extraction, and processing of shale oil and gas across North America has increased, medical doctors, research scientists, and federal agencies have raised concerns about the public health implications of the environmental and social changes that result from these developments [2-8]. Many of these public health concerns relate to air and water pollution from industrial facilities and accidents related to these developments. However, perhaps just as significant is the risk that such changes may lead to psychological and social (psychosocial) stress that can make individuals more susceptible to disease and chronic health problems [9-11].

Ethnography, the process of observing, interpreting, describing, and writing about local cultures [12], is an important social science method for systematically documenting and describing environmental and sociocultural factors and changes that may impact community health. Ethnographic methods can also be used to inform local public health research agendas, including carrying out health impact assessments and planning for or responding to emergencies, and making culturally appropriate health policy recommendations. Ethnographic methods as part of community health studies can also be used within an environmental justice framework. A hallmark of these environmental justice studies using ethnography is their grounded, systematic description of the persistent environmental inequalities within communities of color and the poor who are exposed to greater environmental hazards at the same time as they experience higher rates of poverty, malnutrition, social isolation, political powerlessness, and discrimination [13-15]. This article expands on this application and describes how ethnography can be used as an important community health monitoring tool in rural, urban, and suburban areas where unconventional oil and gas developments are taking place.

Concrete examples are drawn from an ongoing ethnographic study in Bradford County, Pennsylvania, where Marcellus Shale gas exploration and development is taking place. Data collected from interviews, focus groups, and participant observations in 2009, 2010, and 2011 confirm that rapid environmental and social changes were happening in the county as a result of Marcellus Shale developments. A total of 31 landowners and 68 other residents of the county were interviewed during this time period, and most spoke about experiencing what was later classified during data analysis as psychosocial stress. The majority of this stress was articulated by landowners or observed in the field as resulting from the environmental and social changes taking place over such a short period of time. These psychosocial stress factors were then analytically sorted into three themes with direct relevance to understanding the psychological and sociocultural determinants of community health outcomes: anticipated or perceived changes to quality of life; economic inequalities; and acts of violence.

These themes raise new questions about the risks posed by unconventional oil and gas development and lead to new avenues for investigation of the links among such developments, environmental and social changes, chronic stress, and community health outcomes.

### **AN ENVIRONMENTAL JUSTICE FRAMEWORK FOR ASSESSING COMMUNITY HEALTH IMPLICATIONS OF UNCONVENTIONAL OIL AND GAS DEVELOPMENTS**

The rapid rise in onshore unconventional oil and gas developments has new and serious implications for local communities, particularly in poorer rural areas, making this an emerging environmental justice issue. Compared to the offshore oil and gas developments of the 1970s and 1980s in the Gulf of Mexico [16], these onshore developments, particularly in the Marcellus Shale in Pennsylvania and Ohio, occur in closer proximity to people's water wells, homes, schools, places of work and worship, playgrounds, and historic locations. There is increased competition and direct conflict with existing and future private and public land uses, particularly where new natural gas pipelines are being constructed. Adding to these tensions are unknown risks regarding the use of chemical compounds and other materials labeled "trade secrets" by the industry and used in the drilling, extraction, and production processes. The Energy Policy Act of 2005 and the Energy Independence and Security Act of 2007 created environmental and right-to-know regulatory exemptions for hydraulic fracturing and added tax breaks and government subsidies to encourage domestic exploration of unconventional oil and gas resources. In addition, the U.S. Environmental Protection Agency is investigating concerns about the amount and type of waste materials that are generated from drilling and production and their appropriate disposal [17].

This article applies an environmental justice framework that incorporates the public health model of prevention and the precautionary principle [18] to the assessment of the community health implications of onshore unconventional oil and gas developments. The public health model of prevention focuses on eliminating a threat before harm can occur. This approach shifts the focus from treatment to prevention and demands that affected communities not have to wait for conclusive proof of causation before preventive action is taken [18, pp. 19, 20, 26]. The precautionary principle says that if there is scientific uncertainty about the harms posed by an activity, then those proposing that activity have the duty to prevent harm. The burden of proof lies on those who propose to use risky technologies, not those who may be harmed by such technologies [18, pp. 19, 28].

In the United States, the use of ethnography to study environmental pollution as it relates to public health has its roots in the environmental justice movement, looking at the social, geographic, and procedural burdens disproportionately

placed on communities of color and the poor, particularly in urban areas [18, pp. 30-31]. The bottom-up, grounded approach that ethnographic fieldwork takes provides information on the cultural context: where people live, work, play, and attend school and how they interact with the physical and natural world on a daily and lifetime basis. Ethnographic analysis, and use of the iterative process of returning to the fieldwork location to verify and check analytical themes, also provides a means to track environmental and social changes and their impact on the psychological, social, and physical health of individuals and communities over time.

### **THE ROLE OF PSYCHOLOGICAL AND SOCIAL STRESS IN DETERMINING COMMUNITY HEALTH OUTCOMES**

Since at least the mid-1950s public health scientists, psychologists, and sociologists have studied how psychological, social, and environmental stressors impact individual and community susceptibility to disease or changes in overall health. In this previous work, a stress or stressor is defined as “any environmental, social, or internal demand which requires the individual to readjust his/her usual behavior patterns” [11, p. 54], having a negative influence on a person’s overall well-being and quality of life, and in some cases triggering physiological mechanisms that in turn may determine an individual’s or a community’s susceptibility to disease, environmental pollution, or toxic substances [11, 18, 21].

In their study of abandoned coal mine communities Liu et al. [22] found that economic deprivation was significantly associated with a greater number of abandoned mines in rural Pennsylvania. And, while they do not draw definitive conclusions regarding the community health implications of their results, they do identify important interactions between sociocultural characteristics and available material and institutional resources that may result in poor overall health outcomes. Namely, they point to problems of industrial and social abandonment and landscape changes in addition to poverty and economic inequality that can limit access to health care, healthy food choices, and recreational spaces [22, p. 7]. Previous studies of the social determinants of health have also identified poverty and economic inequality as significant contributing factors to chronic stress that may lead to adverse health outcomes [23-28]. These economic metrics may sometimes be an inaccurate and culturally inappropriate way to identify and measure overall well-being and quality of life [29]; however, at least in studies conducted in the United States, personal and community economic status does seem to play a key role in determining levels of chronic stress, the overall health of individuals and groups, and susceptibility to disease.

Anecdotal reports by individuals in communities where onshore unconventional oil and gas developments are occurring describe rapid environmental changes related to well pad and pipeline construction, road damage, physical health problems, and deteriorating air and water quality [30]. In more rural areas,

there are also anecdotal reports of rapid social changes related to an increase in population numbers and density (especially of transient young men working in the oil and gas industry), an influx of new personal income from lease-signing bonuses and royalty income, a shortage of affordable housing, and increased crime [31, 32]. While anecdotal reports such as these may indicate that communities are experiencing increased psychological and social stress as a result of environmental and social changes, they do not provide systematic evidence that individuals and entire communities are experiencing the type of chronic stress that may lead to an increased susceptibility to disease or changes in overall health. To rigorously and systematically collect this type of information on chronic stress, we need a way to document both individual and collective experiences before, during, and after environmental and social changes take place. The practice of ethnography and its grounded data collection and iterative analysis methods offer a comprehensive way of doing just that.

### ETHNOGRAPHIC METHODS

Ethnographic research methods seek to describe everyday lives and practices through cultural interpretation. An ethnographer's goal is to explain how these descriptions represent what can be called "webs of meaning" [12, pp. 5, 33] in which we all live. To do this, ethnographers have developed a variety of methods for studying the everyday lives of humans and the systems and patterns (language, artifacts, visual symbols, etc.) connecting humans to each other, as well as to natural and built environments, institutional structures, and other constructs of traditional and contemporary society [34]. In contrast to other social science methods and approaches, ethnography takes what is known as an inductive and grounded perspective, meaning that categories and meanings of analysis emerge from data collection rather than being imposed from existing models or hypotheses. Done correctly, this grounded perspective ensures that the data emerging from ethnographic fieldwork can be used to develop further research questions and hypotheses that have local salience. A closer look at the methods used in the Bradford County study illustrates these points.

The objective of the ethnographic study conducted in Bradford County was to describe the cultural world views and personal and social interactions of rural landowners, specifically related to their land, water resources, and the rapid industrial developments taking place as a result of the potential boom in Marcellus Shale gas production [35]. The study utilized mixed-methods data collection and analysis, including a community-integrated geographic information system (GIS) process [36, 37], focus group meetings [38, 39], questionnaires, photo-voice (described below) [40, 41], oral history interviews, ethnographic interviews, participant observations, and archival document analysis.

To develop a plan for recruiting landowners and other interviewees, conversations and informal interviews were held with individuals at the County

Conservation District and the Planning and Grants Office, County Commissioners, township supervisors, and several Bradford County residents who had lived 10 or more years along the Susquehanna River. Observations were also conducted at various meetings of landowners and concerned citizens in the county and north-central and northeastern Pennsylvania to understand the diverse types of landowners and other residents. Based on this early fieldwork, a decision was made to focus on landowners owning close to 100 acres, or more, and who were actively using their land for farming, timber, and other forest uses. Specific names of possible participants in the focus groups were drawn from word-of-mouth referrals from county staff and other farmers and forest landowners. The successful recruitment of focus group participants took four months longer than anticipated. Two things caused this delay: difficulties in gaining the trust of a diversity of rural landowners in the county and the inability to guarantee complete anonymity to potential focus group participants who had signed previous legal agreements (non-disclosure agreements) or were in legal proceedings with a shale gas company. These difficulties required the scaling back of the number and size of focus groups. It was a trade-off that favored the collection of deeper, richer data from a smaller group of participants instead of broader, more representative data from a larger group of participants. To capture some of the diversity of landowners that was lost in the smaller focus groups, individual interviews were conducted with the landowners who could not participate because of anonymity concerns (but who still wanted to participate), and with those landowners who were unable to make the meetings, felt uncomfortable in a group setting, or who no longer actively used their land for farming or forest uses. These individual landowner interviews, plus additional interviews with county residents who were recruited by word of mouth referrals and identified during participant observations, were used both on their own and as a supplement to the analysis of the focus group data.

Seven landowners participated in two focus groups, each of which met four times. The two separate groups were based on their primary land use, one group of four crop and livestock (primarily corn, hay, dairy, horse) farmers and the other group of three woodland (timber, hunting, wildlife watching) landowners. The focus group participants were involved in the community-integrated GIS process during which they selected geographic places of special importance to them in the county, mapped their land, and identified their neighbors, all the while discussing their relationship to place and community. Focus group participants were also involved in a photo-voice process that involved taking photographs of things and places that exemplified their relationship with their land, the county, and the changes they were experiencing, and then writing about those photographs and sharing them with others in the group. To supplement this group work, individual oral histories were conducted with each of these seven landowners.

Twenty-four landowners and 68 other local residents, including a county commissioner, agricultural extension specialist, town residents, small business

owners, township supervisors, oil and gas contractors, and school teachers, participated in individual ethnographic interviews. Participant observations were conducted at community events such as local fairs and church dinners, at public meetings such as monthly township meetings and weekly county commissioner meetings, at public hearings related to Pennsylvania Department of Environmental Protection Marcellus Shale regulations, and at private meetings such as gas industry community advisory panels.

The ethnographic data from the Bradford County study includes audio and video of focus groups and interviews, photographs and writings from the photo-voice process, spatial data and maps from the GIS process, informational brochures and handouts from meetings, field notes of participant observations and interviews, as well as historic photographs and documents from archival research. Even though all the data were collected in the same county, the data cannot be analyzed for generalizations about the entire county, a township, a specific type of landowner, the region, or the state. Instead, data was analyzed to differentiate and describe particular aspects of the relationships humans have to their local environments and to each other; in other words, the data were used to discern the various cultural worldviews and “webs of meaning” held by those who participated as interviewees or under observation as part of the study [42].

### **ETHNOGRAPHIC ANALYSIS: THEMES OF CHANGE AND STRESS**

The interpretation of ethnographic data and its analysis is an iterative process. It involves coding of interviews and observational notes, re-entering the field and asking new questions where necessary to refine themes emerging from the coding, and finally developing a set of themes that can be used to convey a detailed cultural description of local places and local people who were the focus of the study. The iterative nature of the analysis process ensures that an ethnographic study remains grounded in the local cultural context over time. This refining of themes and descriptions over time is critical to documenting and describing real-time environmental and social changes and the impact of those changes on local individuals and communities.

In the Bradford County study, cultural analysis revealed three themes directly related to environmental and social changes and what were articulated by local participants as increased levels of psychological and social stress: anticipated or perceived changes to quality of life, economic inequalities, and acts of violence. These themes are being used in continued ethnographic fieldwork in the county to ask new questions and form hypotheses. But these themes can also serve in planning future ethnographic studies on community health in other rural, suburban, and urban locations where unconventional oil and gas developments are located or are being planned and to inform preventive public

health policies. How each theme emerged from the ethnographic data, and each theme's significance to understanding the community health implications of unconventional oil and gas development, are described below.

### **Changes in Quality of Life**

The seven rural landowners who participated in focus groups in Bradford County identified six components to what quality of life meant to them: clean water, fresh air, fertile soil, rural way of life, economic security, and family and personal histories with the land in the present time and for their grandchildren. This local meaning of quality of life was probed for relevance in ethnographic interviews with the 24 individual landowners and it was found to resonate with them as well. When focus group discussions, or individual interviews, turned to how these qualities of life were either currently being changed or anticipated to change as a result of the Marcellus Shale gas developments, landowners spoke of many changes, including these: destruction of their dirt and gravel roadways (which were described as “arteries of rural community life” and the boundaries of family lands); a noticeable increase in “dust” in the air that gets on laundry hung out to dry, porches, and even inside their houses; an increase in loud noises from trucks applying their brakes and from drilling rigs at all hours of the day and night; bright lights in the night sky from construction activities and drilling rigs; visual and odor changes in the appearance or odor of their drinking water (all landowners who participated have private water wells); the number of strange new faces and non-English-speakers at local stores and gas stations; chemical spills into landowners' ponds and crop fields; and expectations of greater economic security as a result of signing a lease to allow a gas well, compressor station, or pipeline on their property.

When matching emotions to these changes, one landowner in a focus group described a feeling of “dread in the pit of my stomach,” and all the landowners interviewed said they felt that as a result of the development of the Marcellus Shale in the county they were losing certain aspects of their quality of life, especially the fresh air and rural feel. Most landowners also expressed great uncertainty about whether these changes in quality of life would be temporary or permanent. This uncertainty turned to fear, anxiety, and depression in some landowners, particularly regarding what the changes would mean for their future well-being and the well-being of their children and grandchildren.

Uncovering and naming what quality of life meant to them allowed landowners to name and describe some of the psychological, social, and environmental factors that they felt may be leading to improvements or declines in their quality of life and overall well-being as a result of both external and internal forces, including state or national farming policies, environmental regulations, the shale gas industry, local politics, family and social relationships, and many others. Landowners said this helped them name, sometimes for the first time, what their

quality of life meant to them. They reported feeling more aware of what was important to them, and this gave them a greater will to fight to keep their quality of life and help their neighbors do the same; however, they also reported that this greater awareness left them at times with a greater sense of loss and sadness. Ethnographic methods, with the focus on asking questions that directly relate to accessing local culture through understanding the language and behaviors of locals, put interviewees' cultural viewpoints above the researchers' and thereby allow for this sort of awareness-raising in ways that other social science methods cannot.

The concept of quality of life is closely associated with what people report as a sense of well-being. Behavioral economists and political scientists have found that among individuals, families, and communities, this sense of well-being can lead to overall improvements in quality of life and society [43-46]. During a speech at the University of Kansas in 1968, Robert F. Kennedy famously said,

“... the gross national product does not allow for the health of our children, the quality of their education, or the joy of their play. It does not include the beauty of our poetry or the strength of our marriages; the intelligence of our public debate or the integrity of our public officials. It measures neither our wit nor our courage; neither our wisdom nor our learning; neither our compassion nor our devotion to our country; it measures everything, in short, except that which makes life worthwhile” [47].

Today international development agencies and national governments are developing indicators that seek to measure the sense of well-being that Kennedy spoke of in his speech. Measurements such as the United Nation's Human Development Index [29, 48] look not just at income or financial indicators but also levels of health, education, political freedom, and inequality. These types of quality-of-life measures have also been used in epidemiologic studies to assess the impact of industrial development, specifically fossil fuel developments, on local communities [22]. Ethnography offers a set of methodological and analytical tools that allow for the rigorous documentation, description, and analysis of what quality of life means to local communities faced with periods of rapid change.

### **Economic Inequality**

All participants interviewed or observed as part of the ethnographic study in Bradford County expressed the belief that crop/livestock landowners tend to have less money than landowners who own only woodlands. But would a crop/livestock landowner who needs annual or semi-annual supplemental income to meet expenses be more eager to sign a lease for locating a shale gas well pad, water impoundment pond, compressor station, or pipeline on his or her property than a woodland landowner or other type of landowner who does not rely on supplemental income to meet his or her financial obligations?



In focus group meetings of the crop/livestock landowners, all four landowners said that they would allow Marcellus Shale gas development on their properties if the “price was right.” At the time of the focus groups (January 2010–August 2010) all four of the crop/livestock landowners had active gas leases on their properties. In individual interviews these same landowners expressed more specific concerns regarding how the property would be treated during the developments (e.g., spills of hazardous wastes, accidents, destruction of prime pasture, etc.), but as in guided conversations in the focus group meetings, they individually conceded that if enough money was offered they would consider agreeing to development.

In contrast, the three landowners in the woodland focus group said that what was most important to them was not the price they would be offered or paid by the gas company to develop their land, but instead how the land would be developed and if the gas company would allow them to negotiate protection of their water, timber, wildlife, and access. In individual interviews with these landowners, one of these landowners admitted that price was an important consideration although certainly not the only thing to be considered in signing an agreement to allow shale gas development on his land. The other two woodland owners had no interest in the money, but only in the preservation of their land and water resources. At the time of the focus groups (February 2010–August 2010), none of the three woodland owners had a gas lease on his/her property.

Responses to a socioeconomic questionnaire given to the focus group participants indicated that income, not land use, was the main factor separating the four crop/livestock landowners from the three woodland owners. All landowners in the crop/livestock group reported annual household incomes (minus the salaries of minors and dependents) of less than \$40,000, with two reporting less than \$20,000. All woodland landowners reported annual household incomes of greater than \$40,000. These responses are within the same range of estimates for mean household income in the entire county as reported in federal census statistics from 2006-2010. The 2006-2010 mean household income for the county was \$51,372, with 30.2 percent of all total households in the county reporting less than \$24,999, 29.9 percent reporting between \$25,000 and \$49,999, and 40.3 percent reporting over \$50,000 [49]. In addition, the crop/livestock group participants responded that an average of 67 percent of their annual household income is derived from agricultural activities, while in the woodland group the percentage from agriculture was reported as only 2 percent.

Differences in household income revealed in such a small sample cannot lead to conclusive evidence regarding the impact that economic differences or inequalities may have on the psychological, sociocultural, and environmental indicators of community health. However, data confirming these income disparities was also collected during open-ended ethnographic interviews with individual landowners and in participant observations at a 2011 meeting of the

Bradford-Sullivan Forest Landowners' Association. Specifically, the point was made in these open-ended interviews and observations that supplemental income from both harvest of timber resources and off-the-farm jobs may be more important for crop/livestock landowners than for woodland owners. In addition to this income disparity between different types of rural landowners in Bradford County, the differences in occupation and employment status between landowners raises questions about differential access to affordable and timely health services. For example, all of the crop/livestock landowners in the focus groups and the majority of crop/livestock landowners and active farmers who were interviewed individually reported having no health insurance coverage. Current evidence or lack of evidence for the health effects of employment status are reviewed in detail by Catalano et al. [50], with a recommendation that more research is needed to understand how job and income loss in families and individuals may impact well-being, anxiety, and overall health outcomes [50, p. 445]. Clearly, given what the data collected during this ethnographic research say about economic inequalities and rural landowner types in Bradford County, more research needs to be done to understand how rural landowners' economic status influences their well-being, anxiety, and overall health and what this may mean in light of new shale gas developments.

This ethnographic data on economic inequalities between different types of landowners raises important questions with regard to the geographic locations of shale gas facilities and what this may mean with regard to the uneven psychological, social, and environmental stressors faced by different landowners, or even an entire region and the nation. For example, could income differences between landowners have implications for where unconventional oil and gas facilities are located in the first place given different landowners' willingness to either accept "the right price" or preserve their land and water resources regardless of the price? If certain types of landowners, such as crop and livestock farmers, are more willing or eager to have development on their land, does this put them and their families and other farm workers at a greater risk of exposure to industrial accidents and hazardous materials related to shale gas development? If landowners who own cropland or livestock and are actively farming are more willing to have shale gas developments, does this mean the products that come from those farms also run a greater risk of being contaminated by hazardous materials? Do shale gas developments on farmland pose a threat to the nation's food supply? And, if there is a threat, what does this mean to the livelihoods, incomes, and overall sense of well-being of farmers in Bradford County? To answer some of these questions environmental health and toxicology studies must be done. However, in drawing conclusions, and more importantly in offering management and policy recommendations, these environmental health studies must also rely on the psychological and sociocultural information that is being collected from the on-going ethnographic research described here and elsewhere [34].

## Acts of Violence

Violence is defined as “the intentional use of physical force or power, threatened or actual, against oneself, another person, or against a group or community that either results in or has a high likelihood of resulting in injury, death, psychological harm, mal-development or deprivation” [51]. Political scientists, psychologists, and social workers who research violence document how different types of violent acts (physical, sexual, psychological, deprivation or neglect, and environmental) can have long-term implications for individual, family, and community stress levels, leading to widespread abuses of power, racism, continuous cycles of abuse, and in the worst cases murder, civil war, and genocide [52-54].

During the first months of fieldwork among Bradford County landowners, local officials and residents of the county talked in open-ended ethnographic interviews about prior cases of beatings, rape, incest, murder, bullying, and intimidation that they had knowledge of or had been directly involved in. Analysis of these early interviews and field notes bears evidence that violence and violent behavior are a part of everyday life in the county. Sometimes particular stories of violence were brought up by interviewees when they wanted to illustrate their concerns about society or politics, such as a belief that lack of education and low-income conditions lead to social turpitudes. Other times, though, these violent stories told by Bradford County residents were very personal and conveyed individual feelings of fear, anxiety, disassociation, loss, and powerlessness, all found in other studies [55-58] to be feelings symptomatic of stress and psychological trauma.

In interviews with landowners and other residents of the county, and most notably in the focus group meetings with the seven rural landowners, these feelings surrounding personal experiences of violent behavior were spoken of as analogous to the way some participants felt they and their families were experiencing changes related to Marcellus Shale gas developments. For example, interviewees described being bullied or intimidated by gas industry employees and their agents, by their neighbors when there were disagreements about the pros and cons of gas development in the local community, and by local politicians when they denied or did not listen to residents' experiences with the shale gas industry and the severity of pollution events at particular locations. An article published in the anthropology journal *Culture, Food, Agriculture, and Environment* provides a more comprehensive discussion of these findings [35]. Confirming this, participant observation and interview data also contain descriptions of bullying and intimidation of landowners by gas company employees, local politicians, and other landowners related to leasing, siting, construction, and operation of shale gas facilities throughout the county [35]. The recall of past violent acts and the creation of new anxieties and feelings of powerlessness around the Marcellus Shale developments could increase the development of chronic stress patterns [56].

With regards to acts of physical violence in the county since unconventional gas developments began, there is preliminary evidence of an increase in overall physical violence, or threats of violence, from filings of Protection from Abuse (PFA) orders and arrests [59, 60]. However, the current ethnographic data from Bradford County does not allow for an analysis of the relationship between different levels of physical violence and unconventional oil and gas developments or other factors.

Anthropologists, geographers, and political scientists working in Africa, the United States, and other fossil-fuel-rich nations have documented the different acts of violence—physical, psychological, economic, political, environmental, and social—that exist in the context of large-scale oil and gas developments [61-63]. However, none of this research makes the explicit connection between such acts of violence, increased chronic stress, and community health outcomes. In urban settings, the relationship between environmental health and violence has been investigated by social epidemiologists. Epidemiological research in Boston showed that in neighborhoods where childhood asthma rates are higher, children tend to also be exposed to greater violence [64, 65]. While this urban epidemiological research shows that the two issues—asthma and violence—are spatially and temporally correlated, it does not answer the question of whether they are causally linked and, if so, what factors may link them. Using ethnography to describe and monitor the levels of violence in communities where unconventional oil and gas developments are taking place gives community health researchers and epidemiologists a way to track the spatial and temporal interactions between psychosocial stress factors, such as violence and violent behavior, and community health outcomes.

## CONCLUSION

Ethnography and ethnographic approaches for monitoring the community health implications of onshore unconventional oil and gas developments are not without their limitations. Several of the most important limitations are faced by all ethnographic researchers regardless of the topic. These involve lack of funding for qualitative, grounded, exploratory, or descriptive social science research, the enormous volumes of data produced from interviews and fieldwork and the amount of time and organizational skill required for analysis of the data, and the difficulty in recruiting and maintaining trust with a diversity of informants and interviewees for the duration of a project. An additional limitation is a lack of understanding of what ethnography is (and is not) and how it can be employed to understand environmental justice concerns, inform further research agendas, and make concrete policy recommendations. For example, ethnography uses qualitative and sometimes anecdotal information as part of a systematic approach to documenting and describing culture based on prescribed methodological and analytical practices. However, the results of this research

methodology are not anecdotal stories and information, but are defensible descriptions and analyses of the cultural worldviews and context within which specific people or places exist, which are documented and verified through intense immersion in those people's ways of life or a place. In spite of these limitations, ethnographic approaches to community health have much to offer other researchers, community health practitioners, policy makers, and communities.

To enhance understanding and communication about the potentially important role ethnography can play in gathering environmental health data in communities where unconventional oil and gas developments are taking place, ethnographic researchers must build a solid case for the usefulness and importance of both fieldwork methods and analytical tools by detailing what exactly ethnographic approaches look like on the ground, providing more information about the history of the method in addressing environmental health concerns where necessary, and justifying what sets ethnography apart from other social science approaches. The examples from Pennsylvania's Marcellus Shale described in this article are just one attempt to begin communication and build the case for more ethnographic and other community health research in shale gas areas. Clearly much more needs to be done in this regard.

In many of the rural and urban communities across North America where onshore unconventional oil and gas developments are being considered or already taking place there is a lack of scientific and clinical information on the local psychological and sociocultural factors that may directly influence community health outcomes [9]. Without such baseline information on the determinants of community health with particular emphasis on psychosocial stress factors, practitioners and policy makers have a difficult time determining the potential for harm to public health associated with these relatively new development projects and then enacting appropriate preventive measures. Thus, serious problems are raised regarding application of the precautionary principle and social, geographic, and procedural equity [18, pp. 30-31].

Ethnographic approaches can serve as one way to evaluate community health outcomes related to unconventional oil and gas developments, a growing need identified by health care practitioners, researchers, and government agencies [2, 3, 5, 7, 17]. As illustrated by the examples from ongoing ethnographic fieldwork in communities living near Marcellus Shale gas wells, compressor stations, and pipeline routes in northeastern Pennsylvania, these approaches show potential usefulness in systematically documenting the psychological, sociocultural, and environmental determinants of health.

While the exact causal mechanisms that link stress to disease may vary from case to case, there are some physiological mechanisms that do seem to be consistent in similar cases and offer models of how psychological, social, and environmental factors influence individual and community health outcomes. One of these mechanisms is known as allostatic load, or "the cumulative

physiological burden that results as the body adapts to environmental and psychosocial stressors” [66, p. 30]. Allostatic load has been implicated in poor health outcomes when social and environmental factors create chronic stress that elevates cortisol levels, which then work to biologically impact the body [67, 68]. There are physiologic indicators of this chronic stress that can be monitored, including high blood pressure, elevated blood sugar, and hormonal changes [69-72]. However, the psychological and behavioral indicators of chronic stress—such as higher rates of smoking, alcohol consumption, sleeping problems, accidents, and eating disorders—may be more difficult to track [10]. Ethnographic approaches, such as the ones described here, could be used to monitor some of these more difficult-to-track indicators and compare them over time in communities where unconventional oil and gas developments are occurring.

Ethnography also offers a way to collect data on the cumulative impacts of industrialization and chemical pollution on local communities. The assessment of cumulative risks and impacts to already overburdened local communities in the United States is the subject of scientific study and debate, and is also one of the top research priorities of environmental justice advocates [8, 73]. The close bonds and sometimes long-term engagements that ethnographic researchers have with the communities where they conduct fieldwork makes this approach to documenting localized changes in psychological, sociocultural, and environmental stress levels through time a valuable contribution to cumulative impact assessments.

The emergent themes described in this paper offer a possible starting point for further community health research by social epidemiologists and others into the impacts of onshore unconventional oil and gas developments. Studies can be designed to identify and describe some of the contributing factors to chronic stress by eliciting culturally and locally relevant meanings of quality of life and well-being and the factors that contribute to or detract from it. More research in rural communities can be conducted that provides data on the relationship between economic inequality and psychological, sociocultural, and environmental stress factors, including the impact on local livelihoods and incomes from public perceptions of food safety on farms near shale gas developments. And, psychological and anthropological studies could be undertaken that document and describe the ways that societal and individual forms of violence interact with psychological, social, and environmental factors that may contribute to chronic stress near unconventional oil and gas projects.

National and state decision-makers need to examine the solid scientific evidence on the psychological, social, and environmental determinants of community health. In collaboration with medical practitioners, researchers, and the communities they serve, strategies need to be developed that can address the large gaps still existing in our knowledge about the linkages between human health, ecosystem health, large-scale industrialization, and chemical pollution. The ethnographic approach introduced here, alongside an environmental justice

framework that includes the public health model of prevention and the precautionary principle, offers an opening to such collaboration, and the outline of a strategy to fill in some of those gaps. As others have suggested [3, 73], public-policy-makers and decision-makers in the United States must step beyond the political rhetoric over the community and environmental health impacts of energy policies and decisions to develop informed policies that prevent harm, embolden the precautionary principle, and ensure that environmental protection is a right, not a privilege.

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**INVESTIGATING LINKS BETWEEN SHALE GAS  
DEVELOPMENT AND HEALTH IMPACTS THROUGH A  
COMMUNITY SURVEY PROJECT IN PENNSYLVANIA**

**NADIA STEINZOR  
WILMA SUBRA  
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**ABSTRACT**

Across the United States, the race for new energy sources is picking up speed and reaching more places, with natural gas in the lead. While the toxic and polluting qualities of substances used and produced in shale gas development and the general health effects of exposure are well established, scientific evidence of causal links has been limited, creating an urgent need to understand health impacts. Self-reported survey research documenting the symptoms experienced by people living in proximity to gas facilities, coupled with environmental testing, can elucidate plausible links that warrant both response and further investigation. This method, recently applied to the gas development areas of Pennsylvania, indicates the need for a range of policy and research efforts to safeguard public health.

**Keywords:** health surveys, shale gas, toxic exposure, hydraulic fracturing, fracking

Public health was not brought into discussions about shale gas extraction at earlier stages; in consequence, the health system finds itself lacking critical information about environmental and public health impacts of the technologies and unable to address concerns by regulators at the federal and state levels, communities, and workers. . . .

—Institute of Medicine at the National Academies of Science [1]

For many years, extracting natural gas from deep shale formations across the United States (such as the Marcellus Shale in the East or the Barnett Shale in Texas) was considered economically and technologically infeasible. More recently, changes in hydraulic fracturing technology and its combination with horizontal drilling have made it possible to drill much deeper and further. Bolstered by declining global oil resources and a strong political push to expand domestic energy production, this has resulted in a boom in shale gas production nationwide and projections of tens or even hundreds of thousands of wells being drilled in the coming decades.

By mid-2012, there were nearly 490,000 producing natural gas wells in the United States, 60,000 more than in 2005 [2]. In Pennsylvania alone, more than 5,900 unconventional oil and gas wells had been drilled, and more than 11,700 had been permitted, between 2005 and September 2012; the pace of expansion has been rapid, with 75 percent of all unconventional wells drilled just in the last two years [3]. The rapid pace of industry expansion is increasingly divergent from the slower pace of scientific understanding of its impacts, as well as policy and regulatory measures to prevent them—in turn raising many questions that have yet to be answered [4]. Further, the limited availability of information has both contributed to public perception and supported industry assertions that health impacts related to oil and gas development are isolated and rare.

Modern-day industrial gas and oil development has many stages, uses a complex of chemicals, and produces large volumes of both wastewater and solid waste, which create the potential for numerous pathways of exposure to substances harmful to health, in particular to air and water pollution [5]. Many reports of negative health impacts by people living in proximity to wells and oil and gas facilities have been documented in the media and through research by organizations [6-8]. In addition, several self-reporting health survey and environmental testing projects have been conducted in response to complaints following pollution events or the establishment of facilities [9-12].

Such short-term projects have been initiated in a research context in which longer-term investigations—particularly ones that seek to establish causal links between health problems and oil and gas development—have historically been narrow and inconsistent [13]. Reflecting growing concern over the need to deepen knowledge among scientists, public agency representatives, and environmental and health professionals, four conferences on the links between shale gas development and human health were convened in just a one-year period (November 2011–November 2012), including those convened by the Graduate School of Public Health at the University of Pittsburgh; by Physicians, Scientists, and Engineers for Healthy Energy; and by the Institute of Medicine of the National Academy of Sciences.

In-depth research on the health impacts of oil and gas development has also begun to appear in the literature. In 2011, a review of more than 600 known chemicals used in natural gas operations concluded that many could cause cancer

and mutations and have long-term health impacts (including on the skin, eyes, and kidneys and on the respiratory, gastrointestinal, brain/nervous, immune, endocrine, and cardiovascular systems) [14]. In early 2012, a study by researchers at the University of Colorado concluded that the toxicity of air emissions near natural gas sites puts residents living close by at greater risk of health-related impacts than those living further away [15]. Also in 2012, a paper (published in this journal) documented numerous cases in which livestock and pets exposed to toxic substances from natural gas operations suffered negative health impacts and even death [16].

Public health has not been a priority for decision-makers confronting the expansion of natural gas development and consumption. Commissions to study the impacts of shale gas development have been established by Maryland and Pennsylvania and by the U.S. Secretary of Energy, but of the more than 50 members on these official bodies, none had health expertise [17]. In addition, state and federal agencies in charge of reviewing energy proposals and issuing permits do not require companies to provide information on potential health impacts, while only a few comprehensive health impact assessments (HIAs) on oil and gas development have ever been conducted in the United States [18]. Data on air and water quality near oil and gas facilities are also lacking because federal environmental testing and monitoring has long focused on a limited number of air contaminants and areas of high population density [19], while testing at oil and gas facilities in states like Pennsylvania began only recently [20]. Finally, only a few states (including Pennsylvania, Ohio, and Colorado) have any requirements for baseline air and water quality testing before drilling begins, making it difficult for researchers and regulators—as well as individuals who are directly impacted—to establish a clear connection afterwards.

### **SUMMARY OF THE RELEVANCE OF SELF-REPORTING HEALTH SURVEYS**

For many individuals and communities living amidst oil and gas development and experiencing rapid change in their environments, too much can be at stake to rely solely on the results of long-term studies, especially those that are just now being developed. Recent examples include a new study by Guthrie Health and the Geisinger Health System in Pennsylvania, set to take from 5 to 15 years [21], and research proposals solicited in April 2012 by the National Institute of Environmental Health Sciences [22].

In contrast, self-reporting health survey research facilitates the collection and analysis of data on current exposures and medical symptoms—thereby helping to bridge the prevailing knowledge gap and pointing the way toward possible policy changes needed to protect public health. Another premise throughout the various phases of this project (location selection, survey distribution and completion, environmental testing, report development and distribution, and

outreach to decision-makers) was the value of public participation in science and the engagement of a variety of actors and networks to both conduct the research and ensure its beneficial application [23].

With this in mind, this health and testing project reflects some of the core principles of community-based participatory research (CBPR), including an emphasis on community engagement, use of strengths and resources within communities, application of findings to help bring about change, and belief in the research relevance and validity of community knowledge [24]. For example, the current project selected areas for investigation based in part on the observations of change in environmental conditions by long-time residents, and upon completion, participants received resources on testing and reporting of drilling problems for use in their communities.

In addition, CBPR is often used by public agencies and academic researchers to gather information on health conditions that may be related to social or environmental factors manifested on the community as well as individual level [25]. Relevant examples include identification of linkages between environmental health and socioeconomic status [26], adverse health impacts associated with coal mining [27], and the perception of health problems from industrial wind turbines [28].

Community survey and environmental testing projects such as the current one are also valuable in identifying linkages and considerations that can be used to develop protocols for additional research and policy measures. For example, community survey projects similar to the current one have revealed the presence of toxic chemicals in water and air that were known to be associated with health symptoms reported by residents, resulting in the strengthening of state standards for the control of drilling-related odors in Texas [9], expansion of a groundwater contamination investigation by the U.S. Environmental Protection Agency in Wyoming [10], and relocation of residential communities away from nearby oil refineries and contaminated waste storage areas in Louisiana) [29].

## METHODS

Between August 2011 and July 2012, a self-reporting health survey and environmental testing project was undertaken in order to:

- investigate the extent and types of health symptoms experienced by people living in the “gas patches” (that is, gas development areas) of Pennsylvania;
- provide air and water quality testing to some of the participating households in need of such information;
- identify possible connections between health symptoms and proximity to gas extraction and production facilities;
- provide information to researchers, officials, regulators, and residents concerned about the impact of gas development on health and air and water quality; and



- make recommendations for both further research and the development of policy measures to prevent negative health and environmental impacts.

This project did not involve certain research elements, such as structured control groups in non-impacted areas and in-depth comparative health history research, that aim to show a direct cause-and-effect relationship or to rule out additional exposures and risks. Such work, while important, was beyond the scope of the project.

The primary routes of exposure to chemicals and other harmful substances used and generated by oil and gas facilities are inhalation, ingestion, and dermal absorption—of substances in air, drinking water, or surface water—which can lead to a range of symptoms. The health survey instrument explored such variations in exposure through checklists of health symptoms grouped into categories (skin, sinus/respiratory, digestive/stomach, vision/eyes, ear/nose/mouth, neurological, urinary/urological, muscles/joints, cardiac/circulatory, reproductive, behavioral/mood/energy, lymphatic/thyroid, and immunological). A similar structure was followed for different categories of problems in participants' disease history (kidney/urological, liver, bones/joints, ulcers, thyroid/lymphatic, heart/lungs, blood disorders, brain/neurological, skin/eyes/mouth, diabetes, and cancer). Questions were also asked about occupational background and related toxic exposure history. In addition, the survey included questions on proximity to three types of facilities (compressor and pipeline stations, gas-producing wells, and impoundment or waste pits) to explore possible sources of exposure. It also asked participants to describe the type and frequency of odors they observe, since odors can both indicate the presence of a pollutant and serve as warning signs of associated health risks [30].

As indicated in Table 1, the survey was completed by 108 individuals (in 55 households) in 14 counties across Pennsylvania, with the majority (85 percent) collected in Washington, Fayette, Bedford, Bradford, and Butler counties. Taken together, the counties represent a geographical range across the state and have active wells and other facilities that have increased in number in the past few years, allowing reports of health impacts and air and water quality concerns by residents to surface [31, 32]. The survey and testing locations were all in rural and suburban residential communities.

All survey participants were assured that their names, addresses, and other identifying information on both the surveys and environmental testing results would be kept confidential and used only for purposes related to this project, such as following up with clarifying questions, responding to requests for assistance, or providing resources. Due to expressed concerns about confidentiality, participants had the option of completing the surveys anonymously, which some chose to do. Most participants answered questions on their own. In some cases, spouses, parents, or neighbors completed surveys for participants, and a few provided answers to the project coordinator in person or over the phone.

Table 1. Survey Locations

County surveyed	Number of surveys collected and percent of all surveys
Washington	24 (22%)
Fayette	20 (18%)
Bedford	20 (18%)
Bradford	17 (16%)
Butler	12 (11%)
Jefferson	3 (3%)
Sullivan	2 (2%)
Greene	2 (2%)
Warren	2 (2%)
Elk	2 (2%)
Clearfield	1 (1%)
Erie	1 (1%)
Susquehanna	1 (1%)
Westmoreland	1 (1%)
Total	108

While less formal and structured, the approach taken to identifying project participants has similarities to established non-random research methods that are respondent-driven and rely on word-of-mouth and a chain of referrals to reach more participants, such as “snowball” and “network” sampling [33]. As in studies in which these methods are used, the current project had a specific purpose in mind, focused on a group of people that can be hard to identify or reach, and had limited resources available for recruitment [34].

The survey was distributed in print form either by hand or through the mail and was initiated through existing contacts in the target counties. These individuals then chose to participate in the project themselves and/or recommended prospective participants, who in turn provided additional contacts. The survey was also distributed to individuals who expressed interest in participating directly to the project coordinator at public events or through neighbors, family members, and friends who had already completed surveys.

A second phase of the project involved environmental testing conducted at the homes (i.e., in the yards, on porches, or at other locations close to houses) of a

subset of the survey participants (70 in total) in order to identify the presence of pollutants that may be coming from gas development facilities. In all, 34 air tests and nine water tests were conducted at 35 households. Test locations were selected based on household interest, the severity of symptoms reported, and proximity to gas facilities; results were made available to the households where the testing took place. The air tests were conducted with Summa Canisters put out for 24 hours by trained individuals and the results analyzed with TO-14 and TO-15 methods, which are used and approved by the U.S. Environmental Protection Agency to test for volatile organic compounds (VOCs) such as benzene, toluene, ethylbenzene, and xylene (known as BTEX chemicals). The water tests were based on samples drawn directly from household sinks or water wells by technicians employed by certified laboratories and covered the standard Tier 1, Tier 2, and Tier 3 (including VOCs/BTEX) and in one case, gross alpha/beta radiation, radon, and radium.

## FINDINGS

### Health Surveys

Among participants, 45 percent were male, ranging from 18 months to 79 years of age, and 55 percent were female, ranging from 7 to 77 years of age. The closest a participant lived to gas facilities was 350 feet and the farthest away was 5 miles.

Participants had a wide range of occupational backgrounds, including animal breeding and training, beautician, child care, construction, domestic work, farming, management, mechanic, medical professional, office work, painter, retail, teaching, and welding. About 20 percent of participants reported an occupation-related chemical exposure (for example, to cleaning products, fertilizers, pesticides, or solvents). At the time of survey completion, 80 percent of participants did not smoke and 20 percent did. More than 60 percent of the current nonsmokers had never smoked, although 20 percent of nonsmokers lived with smokers.

Almost half of the survey participants answered the question on whether they had any health problems prior to shale gas development. A little less than half of those responses indicated no health conditions before the development began and a little more than half reported having had one or just a few—in particular allergies, asthma, arthritis, cancer, high blood pressure, and heart, kidney, pulmonary, and thyroid conditions were named by respondents.

While not asked specifically in the survey, some participants volunteered (verbally or in writing) additional information that points to health-related concerns warranting further investigation. For example, five reported that their existing health symptoms became worse after shale gas development started and 15 that their symptoms lessened or disappeared when they were away from home. Participants in 22 households reported that pets and/or livestock had unexplained symptoms (such as seizures or losing hair) or suddenly fell ill and died after gas development began nearby.

Some variation was noted with regard to the specific symptoms reported for each category surveyed, and some symptoms were reported to a notable degree in only one or a few locations. However, as seen in Table 2, the same overall categories of problems reported by survey participants garnered high response rates among survey participants regardless of region or county. For example, sinus/respiratory problems garnered the highest percentage of responses by participants overall, as well as in four of the five focus counties; the second top complaint category, behavioral/mood/energy, was the first in one county, second in three, and fourth in one. The total number of symptoms reported by individual participants ranged from 2 to 111; more than half reported having more than 20 symptoms and nearly one-quarter reported more than 50 symptoms. The highest numbers were reported by a 26-year-old female in Fayette County (90), a 51-year-old female in Bradford County (94), and a 59-year-old female in Warren County (111).

The 25 most prevalent individual symptoms among all participants were increased fatigue (62%), nasal irritation (61%), throat irritation (60%), sinus problems (58%), eyes burning (53%), shortness of breath (52%), joint pain (52%), feeling weak and tired (52%), severe headaches (51%), sleep disturbance (51%), lumbar pain (49%), forgetfulness (48%), muscle aches and pains (44%), difficulty breathing (41%), sleep disorders (41%), frequent irritation (39%), weakness (39%), frequent nausea (39%), skin irritation (38%), skin rashes (37%), depression (37%), memory problems (36%), severe anxiety (35%), tension (35%), and dizziness (34%).

Many symptoms were commonly reported regardless of the distance from the facility (in particular sinus problems, nasal irritation, increased fatigue, feeling weak and tired, joint pain, and shortness of breath). In addition, there was some variability in the percentage of respondents experiencing certain symptoms in relation to distance from facility, including higher rates at longer distances in a few instances. Possible influencing factors could include topography, weather conditions, participant reporting, the use of emission control technologies at facilities, or type of production (e.g., wet gas contains higher levels of liquid hydrocarbons than dry gas).

However, many symptoms showed a clearly identifiable pattern: as the distance from facilities increases, the percentage of respondents reporting the symptoms generally decreases [35]. For example, when a gas well, compressor station, and/or impoundment pit were 1500-4000 feet away, 27 percent of participants reported throat irritation; this increased to 63 percent at 501-1500 feet and to 74 percent at less than 500 feet. At the farther distance, 37 percent reported sinus problems; this increased to 53 percent at the middle distance and 70 percent at the shortest distance. Severe headaches were reported by 30 percent of respondents at the farther distance, but by about 60 percent at the middle and short distances.

Table 2. Percent of Participants Reporting Symptoms in the Most Prevalent Categories of Symptoms, by County

Symptom category	All counties	Percent of individuals reporting symptoms in category								
		Bedford	Bradford	Butler	Fayette	Washington	Others <sup>a</sup>			
Sinus/respiratory	88	80	82	75	85	95	87			
Behavioral/mood/energy	80	60	88	67	85	74	67			
Neurological	74	45	71	50	70	79	60			
Muscles/joints	70	55	82	67	70	74	47			
Digestive/stomach	64	55	65	58	75	63	33			
Ear/nose/mouth	66	40	59	50	75	68	47			
Skin reactions	64	45	70	67	75	63	27			
Vision/eyes	63	40	65	50	70	79	53			

<sup>a</sup>Includes Clearfield, Elk, Erie, Jefferson, Greene, Sullivan, Susquehanna, Warren, and Westmoreland counties. The surveys from these counties (15) were analyzed together to create a group comparable in number to each of the counties where more surveys were collected.

Figure 1 shows, for the top 20 symptoms, the percentage of residents living within 1500 feet of a natural gas facility (well, compressor, or impoundment) who reported the symptom, compared to the percentage among residents living more than 1500 feet from the facility. For 18 of the 20 symptoms, a higher percentage of those living within 1500 feet of a facility experienced the symptom than of those living farther away.

The difference in percentages reporting the symptom in the two groups (i.e., 1500 feet or closer vs. more than 1500 feet from a facility) was statistically significant for 10 of the 20 symptoms. Notably, this finding reinforces the value of data attained through self-reporting health surveys. It shows that, regardless of how symptom data were acquired, they suggest that increased proximity to gas facilities has a strong association with higher rates of symptoms reported.

When the most prevalent symptoms are broken out by age and distance from facility, some patterns stand out [35]. Within each age group, the subset living within 1500 feet of any oil and gas facility had a higher percentage of most symptoms than the age group as a whole.

Among the youngest respondents (1.5-16 years of age), for example, those within 1,500 feet experienced higher rates of throat irritation (57% vs. 69%) and severe headaches (52% vs. 69%). It is also notable that youngest group had the highest occurrence of frequent nosebleeds (perhaps reflective of the more sensitive mucosal membranes in the young), as well as experiencing conditions not typically associated with children, such as severe headaches, joint and lumbar pain, and forgetfulness.

Among 20- to 40-year-olds, those living within 1500 feet of a facility reported higher rates of nearly all symptoms; for example, 44 percent complained of frequent nosebleeds, compared to 29 percent of the entire age group. The same pattern existed among 41- to 55-year-olds with regard to several symptoms (e.g., throat and nasal irritation and increased fatigue), although with smaller differences and greater variability than in the other age groups.

The subset of participants in the oldest group (56- to 79-year-olds) living within 1,500 feet of facilities had much higher rates of several symptoms, including throat irritation (67% vs. 47%), sinus problems (72% vs. 56%), eye burning (83% vs. 56%), shortness of breath (78% vs. 64%), and skin rashes (50% vs. 33%).

In sum, while these data do not prove that living closer to oil and gas facilities causes health problems, they do suggest a strong association since symptoms are more prevalent in those living closer to facilities than those living further away. Symptoms such as headaches, nausea, and pounding of the heart are known to be the first indications of excessive exposure to air pollutants such as VOCs [36], while the higher level of nosebleeds in the youngest age group is also consistent with patterns identified in health survey projects in other states [9, 10].

The survey also asked respondents to indicate whether they were smokers. While the average number of symptoms for smokers was higher for smokers than nonsmokers (30 vs. 22), the most frequently reported symptoms were very

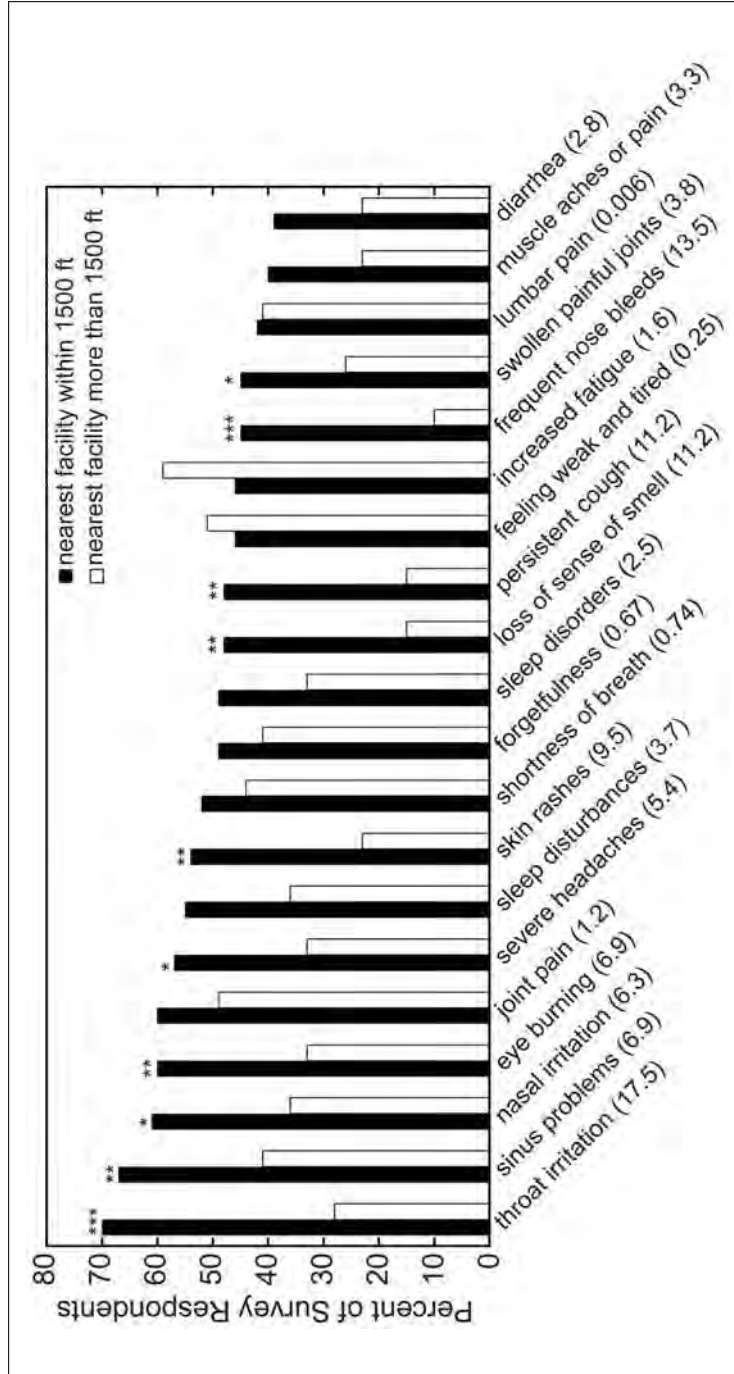


Figure 1. Association of symptoms and distance from facilities  
**Note:** The significance of the effect was tested using a two-way contingency table analysis, and the chi-square value is given in parenthesis after each symptom. Effects significant at  $p < 0.001$  are indicated by \*\*\*, those significant at  $p < 0.01$  by \*\*, and those significant at  $p < 0.05$  by \*.

similar (including forgetfulness, increased fatigue, lumbar pain, joint pain, eye burning, nasal irritation, sinus problems, sleep disturbances, severe headaches, throat irritation, shortness of breath, frequent nausea, muscle aches or pains, and weakness). The fact that the nonsmokers experienced symptoms that are commonly considered to be side effects of smoking (e.g., persistent hoarseness, throat irritation, sinus problems, nasal irritation, shortness of breath, and sleep disturbances) suggests that factors other than smoking were at play.

In addition, while the smoking subpopulation generally reported a larger number of symptoms, the symptoms most frequently reported by smokers and nonsmokers were remarkably similar within each age group [35]. For example, for 20- to 40-year-olds, increased fatigue, sinus problems, throat irritation, frequent nausea, and sleep problems were among the top symptoms for both smokers and nonsmokers. In the 41- to 55-year-old group, increased fatigue, throat irritation, eye burning, severe headaches, and nasal irritation were among the top symptoms for both smokers and nonsmokers, and in the over-55 age group, eye burning, sinus problems, increased fatigue, joint pain, and forgetfulness were among the top symptoms of both smokers and nonsmokers.

Participants were asked if they had noticed any odors and were asked whether they knew the source of the odors. In all but a few cases, survey participants mentioned only gas-related sources. Responses focused on locations, facilities, and processes, including drilling, gas wells, well pads, fracturing, compressor stations, condensate tanks, flaring, impoundments and pits, retention ponds, diesel engines, truck traffic, pipelines and pipeline stations, spills and leaks, subsurface ground events or migrations from underground, seismic testing, blue-colored particles in the air (possibly catalytic compounds or particulate matter), and water and stock wells. Odors were among the most common of complaints, with 81 percent of participants experiencing them sometimes or constantly. The frequency ranged from one to seven days per week and from several times per day to all day long; 18 percent said they could smell odors every day.

Participants were also asked to describe odors and whether they noticed any health symptoms when odor events occurred. The most prevalent links between odors and symptoms reported were:

- *nausea*: ammonia, chlorine, gas, propane, ozone, rotten gas;
- *dizziness*: chemical burning, chlorine, diesel, ozone, petrochemical smell, rotten/sour gas, sulfur;
- *headache*: chemical smell, chlorine, diesel, gasoline, ozone, petrochemical smell, propane, rotten/sour gas, sweet smell;
- *eye/vision problems*: chemical burning, chlorine, exhaust;
- *respiratory problems*: ammonia, chemical burning, chlorine, diesel, perfume smell, rotten gas, sulfur;
- *nose/throat problems*: chemical smell, chlorine, exhaust, gas, ozone, petrochemical smell, rotten gas, sulfur, sweet smell;



- *nosebleeds*: kerosene, petrochemical smell, propane, sour gas;
- *skin irritation*: chemical smell, chlorine, ozone, sulfur;
- *decreased energy/alertness*: chemical gas, ozone, rotten/sour gas, sweet smell; and
- *metallic/bad taste in mouth*: chemical burning, chlorine, turpentine.

### Environmental Testing

As detailed in Table 3, the air tests detected a total of 19 VOCs in ambient air sampled outside of homes.

The number of compounds detected in a single sample ranged from one to 25; there was some consistency with regard to the chemicals present in most of the samples, although the concentrations of VOCs detected varied across counties [35]. The highest numbers of VOCs were detected in air samples from Washington County (15), Butler County (15), Bradford County (12), and Fayette County (9). Washington County also had the highest measured concentration of five VOCs and the second highest concentration of 12 chemicals. Samples from Butler and Bradford Counties had the highest concentrations of five and three VOCs, respectively. Five chemicals were detected in all nine of the samples from Washington County and in the six samples from Butler County: 1,1,2-trichloro-1,2,2-trifluoroethane, carbon tetrachloride, chloromethane, toluene, and trichlorofluoromethane.

It is also possible that in some places, sampling did not occur at the precise times when facilities were emitting high concentrations of chemicals or when the wind was blowing contaminants toward canisters. Some of the additional variation in number of chemicals and concentrations could be due to differences in topography, the total number of active oil and gas wells, the types of wells (conventional versus unconventional), the use of emission control technologies, and the number of active drilling sites, compressor stations, and oil and gas waste impoundments located within a certain radius of the sampling locations.

In 2010, the Pennsylvania Department of Environmental Protection (DEP) conducted air testing around natural gas wells and facilities in three regions across the state, in part using the same canister sampling methods as in this project [37]. When compared to DEP's results, our results showed some striking similarities in both the chemicals detected and concentrations. In particular, BTEX chemicals that we measured in Butler and Washington counties were consistently higher than concentrations found at DEP control sites (ethylbenzene and *m*- and *p*-xylenes were not detected at any of the control sites). When compared to the sampling done by DEP around oil and gas facilities, the concentrations in Butler and Washington counties were in the same range for benzene, but were considerably higher for toluene, ethylbenzene and *m*- and *p*-xylenes. It is also striking that some of the concentrations of ethylbenzene and

Table 3. Volatile Organic Compounds (VOCs) in Ambient Air,  
Sorted by Percent Detection<sup>a</sup>

Compound	Total number of samples	Number of samples detecting VOCs	Percent of samples detecting VOCs	Minimum concentration	Maximum concentration	Chemical reporting limits for the three labs		
						Columbia	Con-Test	Pace <sup>b</sup>
2-Butanone	17	16	94	0.95	2.9	0.85-1.3	NA	NA
Acetone	17	15	88	8.0	19	6.5-10	NA	NA
Chloromethane	34	27	79	1.0	1.66	0.59-0.90	0.1	1.39-1.53
1,1,2-Trichloro-1,2,2-trifluoroethane	34	26	76	0.54	0.73	0.22-0.34	0.38	5.13-5.67
Carbon tetrachloride	34	26	76	0.4	0.76	0.091-0.14	0.31	4.21-4.65
Trichlorofluoromethane	34	26	76	0.6	1.8	0.81-1.2	0.28	3.32-3.66
Toluene	34	22	65	0.68	7.9	0.53-0.82	0.19	2.52-2.79
Dichlorodifluoromethane	17	9	63	1.9	2.8	NA	0.25	3.32-3.66
n-Hexane	8	3	38	3.03	7.04	NA	NA	2.37-2.61
Benzene	34	11	32	0.31	1.5	0.46-0.67	0.16	2.14-2.36

Methylene chloride	34	10	29	1.9	32.62	0.49-0.76	1.7	2.33-2.57
Total hydrocarbons (gas) <sup>c</sup>	8	2	25	49.8	146	NA	NA	46.9-52.2
Tetrachloroethylene	34	8	24	0.12	10.85	0.10-0.16	0.34	4.54-5.02
1,2,4-Trimethylbenzene	17	4	24	0.38	0.61	NA	0.25	3.30-3.64
Ethylbenzene	34	6	1	0.27	1.5	1.4-1.9	0.22	2.91-3.21
Trichloroethylene	34	6	18	0.17	5.37	0.08-0.12	0.27	3.60-3.98
Xylene ( <i>m</i> - and <i>p</i> -)	34	5	15	0.92	5.2	2.5-3.8	0.43	2.82-3.12
Xylene ( <i>o</i> )	34	5	15	0.39	1.9	1.2-1.9	0.22	2.91-3.21
1,2-Dichloroethane	34	1	3	0.64	0.64	0.59-0.90	0.2	2.71-2.99

<sup>a</sup>Concentrations are in micrograms per cubic meter, µg/m<sup>3</sup> (*n* = total number of canister samples that were analyzed for a particular chemical).

<sup>b</sup>Pace Lab's reporting limits were in parts per billion volume (ppbv). We converted to micrograms per cubic meters (µg/m<sup>3</sup>) using equations in the Air Unit Conversion Table (Torrent Labs, [www.torrentlab.com/torrent/Home/ResourceCenter.html](http://www.torrentlab.com/torrent/Home/ResourceCenter.html)).

<sup>c</sup>Total hydrocarbons reported as parts per billion volume (ppbv).

xylene measured at rural and suburban residential homes in Butler and Washington counties were higher than any concentration detected by the DEP at the Marcus Hook industrial site in 2010.

As stated above, several factors can influence air results. However, it is also highly possible that the poorer air quality in the areas where we tested—which were rural and residential, with little or no other industry nearby—can be attributed to gas facilities. While the DEP reports on the agency’s air testing indicated that some of the VOCs we found in our study may not be due to oil and gas development since they persist in the atmosphere and have been widely used (for example, as refrigerants), the agency also indicates that acetone and the BTEX chemicals can be attributed to gas development [37].

With regard to the water tests conducted, Table 4 shows the 26 parameters that were detected in at least one sample. More than half of the project water samples contained methane; although some groundwater contains low concentrations of methane under normal conditions, this finding could also indicate natural gas migration from casing failure or other structural integrity problems [38]. Four of the substances detected in water well samples in Bradford and Butler Counties—manganese, iron, arsenic, and lead—were found at levels that exceed the Maximum Contaminant Levels (MCLs) set by Pennsylvania DEP’s Division of Drinking Water Management [39]. Two of the water samples, both from Butler County, were more acidic than the recommended pH for drinking water.

Some metals, such as manganese and iron, are elevated in Pennsylvania surface waters and soils, either naturally or due to past industrial activities, and levels can vary regionally [40]. In 2012, Pennsylvania State University (PSU) researchers found that some drinking water wells in the state contained somewhat elevated concentrations of certain contaminants prior to any drilling in the area [41]. However, seven out of the nine water supplies sampled in our study (78%) had manganese levels above the state MCL—a much higher percentage than what was found in the pre-drilling samples in the PSU study (27%). Even where metals are naturally occurring or predate gas development, drilling and hydraulic fracturing can contribute to elevated concentrations of these contaminants [42] and have the potential to mobilize substances in formations such as Marcellus Shale, which is enriched with barium, uranium, chromium, zinc, and other metals [43].

### **LINKAGES BETWEEN SURVEYS AND ENVIRONMENTAL TESTING**

More research would be required to identify cause-and-effect connections between the chemicals present in air and water in Pennsylvania’s gas patches and symptoms reported by residents in specific locations. Nonetheless, such links are plausible since many of the chemicals detected in the testing are

known to be related both to oil and gas operations and to the health symptoms reported by individuals living at the sites where air and water testing was conducted [13-15].

The air tests together detected 19 chemicals that are known to cause sinus, skin, ear/nose/mouth, and neurological symptoms, 17 that may affect vision/eyes, and 16 that may induce behavioral effects; as well as 11 that have been associated with liver damage, nine with kidney damage, and eight with digestive/stomach problems. In addition, the brain and nervous system may be affected by five of the VOCs detected, the cardiac system by five, muscle by two, and blood cells by two [44, 45].

Using these sources [44, 45], we compared lists of the established health effects of the chemicals detected at households where testing occurred with lists of the symptoms reported in surveys by participants at those testing locations in order to identify associations. We then calculated the rate of association, in which the denominator is the total number of health impacts reported by an individual and the numerator is the total number of health impacts reported by that individual that are consistent with the known health impacts of the chemicals detected through air or water testing where they live.

Benzene, toluene, ethylbenzene, xylene, chloromethane, carbon disulfide, trichloroethylene (TCE), and acetone were detected through testing at the same households where survey participants reported symptoms established in the literature [13-15, 44, 45] as associated with these chemicals, including symptoms in the categories of sinus/respiratory, skin, vision/eyes, ear/nose/mouth, and neurological. Some of these chemicals, as well as others (such as carbon tetrachloride and tetrachloroethylene) were found at sites where survey participants reported known associated symptoms in the categories of digestion, kidney and liver damage, and muscle problems. Specific examples of chemicals and symptoms that are linked in the research literature, and were found together at households where testing and surveys were conducted, are: benzene and dizziness and nasal, eye, and throat irritation; carbon tetrachloride and nausea, headaches, and liver and kidney disease; and tetrachloroethylene and skin rashes, persistent cough, and nerve damage.

As shown in Table 5, health symptoms reported by the individuals living in a home where testing occurred matched the known health effects of chemicals detected in that home at an overall rate of 68 percent. Fayette and Washington counties had the highest match, followed by Greene, Bedford, and Butler counties.

In addition, the percent of individuals reporting symptoms that have been associated with chemicals detected in air testing at households participating in this study showed some consistency across counties with regard to the most significant categories of problems reported, as shown in Table 6—indicating that patterns in both chemicals detected and symptoms exist despite different geographic locations.

Table 4. Water Quality Results from Nine Private Water Wells in Bradford and Butler Counties, Pennsylvania

Parameter <sup>a</sup>	Units	Number of sample	Number above detection limit	Minimum <sup>b</sup>	Maximum	Mean <sup>c</sup>	PA DEP MCL <sup>d</sup>	Number of samples above MCL <sup>e</sup>
Barium	mg/L	9	9	0.029	0.5	0.25	2	0
Calcium	mg/L	9	9	33	66.2	43.7	None	
Magnesium	mg/L	9	9	4.5	16.8	9.1	None	
Sodium	mg/L	9	9	9.2	64.1	20.9	None	
Strontium	mg/L	9	9	0.126	1.7	0.5	None	
Hardness (total as CaCO <sub>3</sub> )	mg/L	9	9	120	234	147	None	
pH	Std Units	9	9	6	7.9	6.5	6.5-8.5	<i>f</i>
Alkalinity (total as CaCO <sub>3</sub> )	mg/L	9	9	38	285	130	None	
Total dissolved solids	mg/L	9	9	138	392	218	500	0
Sulfate	mg/L	9	9	6.7	231	33	250	0
Manganese	mg/L	9	7	<0.005	6.44	1.04	0.05	7
Chloride	mg/L	9	7	< 5.0	84.3	24.1	250	0
Iron	mg/L	9	6	<0.04	153	19.5	0.3	5
Potassium	mg/L	6	6	1.14	1.57	1.1	None	

Specific conductance	µmhos/cm	6	6	287	552	326	None
Methane	µg/L	9	5	1.06	57.4	10	0.3
Arsenic	mg/L	9	4	< 0.001	0.0282	0.005	0.010
Lead	mg/L	9	4	< 0.001	0.113	0.113	0.01
Total coliform	per 100 mL	9	4	Absent	Present		None
Total suspended solids	mg/L	6	4	< 5	448	118	None
Temperature, water	Degree/Celsius	3	3	25	29	28	None
Turbidity	NTU	3	3	0.22	5.7	2.3	None
Nitrate	mg/L	3	3	0.076	0.71	0.46	10
<i>E. coli</i>	per 100 mL	9	2	Absent	Present		None
Sulfur	µg/L	1	1	< 1,000	7,550	2,850	None
Bromide	mg/L	1	1	0.26	0.26	0.26	None

<sup>a</sup>Note: not all parameters were analyzed in every sample.

<sup>b</sup>Minimum values: If reports included non-detects of a particular chemical, the minimum value in the table was shown as being less than (<) the lowest laboratory detection limit.

<sup>c</sup>Mean values: Non-detected chemicals were assigned a concentration equal to half of the detection limit *only if* there were other samples that detected the chemical.

<sup>d</sup>MCL: Maximum Contaminant Levels published by the Pennsylvania Department of Environmental Protection Division of Drinking Water Management.

<sup>e</sup>No values are provided if MCLs for substances do not exist.

<sup>f</sup>Two samples had higher acidity (lower pH) than the value recommended by the PA DEP.

Table 5. Match between Health Symptoms Reported by Individuals at Air Testing Sites and Known Effects of Chemicals Detected

County	Number of individuals surveyed at homes where testing was conducted	Match between known health effects of chemicals detected and symptoms reported (percent) <sup>a</sup>	
		Average	Range
Overall	59	68	33-100
Fayette	16	73	33-100
Washington	15	73	33-100
Bradford	8	58	16-100
Butler	8	63	56-68
Bedford	6	69	63-100
Elk	2	64	53-74
Clearfield	1	none	none
Greene	1	70	70
Susquehanna	1	50	50

<sup>a</sup>When a health symptom was associated in the literature with more than one of the chemicals detected, only one match was counted for that symptom.

As mentioned above, levels of iron, manganese, arsenic, and lead were detected in our water well samples in Bradford and Butler Counties at levels that exceeded drinking water standards set by the Pennsylvania DEP. These substances are known to be associated with numerous symptoms reported by individuals living in the homes where these particular exceedances occurred, including symptoms in the categories of sinus/respiratory, skin reactions, digestive/stomach, vision/eyes, ear/nose/mouth, neurological, muscle/joint, behavioral/mood/energy, and liver and kidney damage. Survey participants in the homes where water samples contained methane reported health symptoms known to be associated with methane, including symptoms in the categories of sinus/respiratory, digestive/stomach, neurological, and behavioral/mood/energy. While the water samples taken for this project did not show detectable exceedances of safety standards for other substances, it is notable that no drinking water standards have been set for methane, bromide, sodium, strontium, or Total Suspended Solids (TSS)—and thus no exceedances would be indicated in laboratory reports.



Table 6. Percent of Individuals at Air Testing Sites Reporting Symptoms Associated in the Literature with Chemicals Detected at Those Sites, by Symptom Category and Primary Air

Symptom category	All	Testing counties							
		Bedford	Bradford	Butler	Fayette	Washington	Others <sup>a</sup>		
Sinus/respiratory	83	100	88	100	81	73	80		
Vision/eyes	73	—	100	63	69	67	60		
Digestive/stomach	69	50	63	88	75	80	—		
Skin reactions	63	50	63	88	69	53	40		
Neurological	60	50	88	75	44	53	60		
Behavioral/mood/energy	54	67	50	63	63	47	40		
Ear/nose/mouth	33	50	—	38	44	33	20		
Muscle problems	—	—	—	—	—	40	—		

<sup>a</sup>This includes air samples from Clearfield, Elk, Greene, and Susquehanna counties.

## DISCUSSION

Complete evidence regarding health impacts of gas drilling cannot be obtained due to incomplete testing and disclosure of chemicals, and non-disclosure agreements. Without rigorous scientific studies, the gas drilling boom sweeping the world will remain an uncontrolled health experiment on an enormous scale.

—Michelle Bamberger and Robert Oswald [16]

While the survey and testing results, and their related findings, do not constitute definitive proof of cause and effect, we believe they do indicate the strong likelihood that the health of people living in proximity to gas facilities is being affected by exposure to pollutants from those facilities. Most participants report a high number of health symptoms; similar patterns of symptoms were identified across project locations and distances from facilities; and consistency in symptoms reported exists regardless of age group or smoking history. In addition, contaminants that result from oil and gas development were detected in air and water samples in areas where residents are experiencing health symptoms that are established in the literature as consistent with such exposures.

Because of the short-term nature of the air-canister testing (24 hours) and the single water tests conducted at households, our results were contingent on conditions at particular “moments in time.” Thus additional chemicals, or the same chemicals at different concentrations, might be captured through expanded testing; and residents could be experiencing exposures that were not detected but would be detectable through such testing. In addition, some of the variation in the air test results may have been due to the different reporting protocols used by the laboratories used in this project. Although all the labs test for the same core suite of chemicals, both their reporting limits and the additional chemicals for which they test vary; these will be key considerations for future testing work.

Another consideration that warrants further exploration involves the established standards on both the state and federal levels for “safe” concentrations, which are set only for exposure to single contaminants. This prevailing regulatory approach can not adequately address the potential risks posed by chronic, long-term exposure to lower levels of multiple contaminants simultaneously—in other words, the experience of people living in oil and gas areas day in and day out, and of workers at job sites where toxic substances are continuously used. In addition, for many substances in the environment (including those that come from gas operations and were detected in our air and water sampling), data on health risks or safe exposure levels simply do not exist.

More research is also needed that focuses on the sources of odors and odor events experienced by residents living near gas facilities. In some cases, participants reported different health impacts associated with specific sources and odor events than those they reported in the overall health survey. Since odors are

a clear sign of the presence of airborne substances (such as fuel and chemicals), this aspect warrants tracking and analysis.

Although we did not investigate additional factors that can influence health conditions (e.g., through ordered control groups, in-depth health history research, or identification of other potential sources of contaminants), such factors may affect an individual's health independent of gas operations. The relationship between symptoms and distance from gas facilities also warrants more research.

At the same time, we strongly suggest that for individuals with a history of other health concerns (e.g., asthma or heart conditions) and who are already living with other exposures (e.g., traffic fumes or workplace chemicals), the presence of gas facilities and related pollution could have a strong “trigger effect” that can make existing problems worse and put individuals at higher risk of developing new ones.

## RECOMMENDATIONS

As discussed earlier, scientific knowledge about the health and environmental impacts of shale gas development—and also the adoption of policy and regulatory measures to prevent them—are proceeding at a far slower pace than the development itself. This timing mismatch creates situations (already being experienced by residents of Pennsylvania and other states) in which problems are widely reported but left unaddressed. Several measures can be taken to ensure that public health impacts are fully understood and given greater priority in decision-making about shale gas development.

1) *Elevate the role of public health considerations in gas development decisions.* A key measure would be to conduct health impact assessments before permitting begins. HIAs aim to minimize negative impacts and to improve health outcomes associated with land use decisions by analyzing problems that could arise over time as well as existing health and environmental risks that could be exacerbated by new activities [46]. HIAs can also have a strong preventive effect by identifying mitigation measures related to aspects such as toxic exposures, air and water pollution, and emergency response [47]. In addition, regulatory agencies could comprehensively plan the scope and pace of permits for wells and other facilities in order to reduce impacts on air and water quality, rather than continuing the permit-by-permit process currently being followed in Pennsylvania and other states. Information on where wells and facilities would be built in relation to places where health could be at risk (e.g., homes, schools, and hospitals) could also be required in permit applications.

2) *Increase the involvement of state departments of health in assessing the impacts of gas development.* Efforts should be increased to track and respond to health concerns, and a database should be established to document these problems and the agency response. Health departments could provide training for health and medical professionals on exposure pathways and health symptoms

related to gas operations, so that residents receive more informed advice and appropriate testing and care referrals. Financial aid mechanisms should be established to enable low-income residents to have blood and urine tests for chemical exposure.

3) *Conduct baseline water testing and continuous long-term monitoring of air quality.* Such testing would apply to private wells and public drinking water supplies prior to drilling and to the air at or near facilities during all phases of operations. Testing and monitoring should cover a full suite of chemicals, and contaminants and results should be reported regularly and made available to the public. Air quality testing in particular should be conducted at a range of facilities (e.g., compressor stations, impoundment pits, dehydrators) that cause emissions. These efforts could be carried out by the state regulatory agencies that issue permits or through an agreement between those agencies and health departments. Inter-agency agreements could also be developed to track potential health impacts that could result following spills of chemicals and waste, the underground migration of fracturing fluids, leaks, and other problems.

4) *Strengthen regulations for facilities to minimize air and water pollution risks.* These could include significantly increased setback distances; the installation of advanced technologies on all equipment to reduce emissions, odors, and noise; the use of closed-loop storage systems for waste and drilling fluids (rather than open pits); and the practice of “green completions” to reduce or eliminate flaring and venting of methane gas and other pollutants.

5) *Advance changes in testing parameters that determine “safe” exposure in order to account for low-level, chronic exposure and multiple chemical exposure in testing and monitoring.* Such changes are necessary to reflect impacts on people living in oil and gas development areas day in and day out, as well as workers at facilities. Under current testing parameters (which are based largely on acute episodes involving single contaminants), results may show below-threshold levels even though residents are negatively affected. For example, a recent paper showed that endocrine-disrupting chemicals can have different but still harmful effects at lower doses than at higher ones and concluded that fundamental changes in chemical testing and safety protocols are needed to protect human health [48]. Additionally, current health guidelines should be updated to capture more of the chemicals currently in use and to assess complex or indirect sources of contamination, such as oil and gas operations that rely on a variety of substances, equipment, and facilities at numerous stages of development.

## CONCLUSION

While we realize that human activities may involve hazards, people must proceed more carefully than has been the case in recent history. Corporations, government entities, organizations, communities, scientists, and other individuals must adopt a precautionary approach to all human endeavors. . . . When an activity raises threats of harm to human health or the environment,

precautionary measures should be taken even if some cause and effect relationships are not fully established scientifically.

—Wingspread Consensus Statement on the Precautionary Principle [49]

Across the gas patches of the United States, people experiencing health problems voice the simple wish to be believed. Many say that their health has worsened since gas development began in their communities and that they feel better when they are away from home. Often these conversations turn to what it will take for regulators and policymakers to view their stories not just as “anecdotes,” but as valid concerns worthy of an effective response.

There is no doubt that more research on the environmental and health impacts of shale gas development is needed and can play a critical role in making sound decisions about a complex and controversial issue. Yet an equally important consideration is how to respond to the presence of unanswered questions. For many proponents of unfettered gas development, the absence of definitive causal links between gas facilities and specific health impacts indicates the absence of a problem. But for impacted communities and others who believe health and the environment deserve protection and that water and air quality should be maintained, what we don’t yet know makes the need for caution even greater.

We believe that the findings of this survey and testing project in Pennsylvania, coupled with similar projects elsewhere and an emerging body of research, provide sufficient evidence for decision-makers to take action to slow the rush to drill, at least until the wide gaps in scientific knowledge, policies, and regulations are bridged. Much is already known about the chemicals used and pollution caused by oil and gas activities, which alone create the real potential for negative health effects in any area where development occurs [50]. The precautionary principle should be applied to decisions about shale gas development (both in existing gas patches and in areas slated for new development), and this should include shifting the burden of proof that harm does or does not occur to those proposing the action.

The status quo—in which science and policy changes proceed slowly while gas development accelerates rapidly—is likely to worsen air and water quality, resulting in negative health impacts and possibly a public health crisis. Greater understanding of the experiences reported by individuals living near gas facilities can play an important role in pointing the way forward to preventing these problems, both in Pennsylvania and nationwide.

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*Features*

**THE ECONOMIC IMPACT OF SHALE GAS  
DEVELOPMENT ON STATE AND LOCAL ECONOMIES:  
BENEFITS, COSTS, AND UNCERTAINTIES**

**JANNETTE M. BARTH**

**ABSTRACT**

It is often assumed that natural gas exploration and development in the Marcellus Shale will bring great economic prosperity to state and local economies. Policymakers need accurate economic information on which to base decisions regarding permitting and regulation of shale gas extraction. This paper provides a summary review of research findings on the economic impacts of extractive industries, with an emphasis on peer-reviewed studies. The conclusions from the studies are varied and imply that further research, on a case-by-case basis, is necessary before definitive conclusions can be made regarding both short- and long-term implications for state and local economies.

**Keywords:** economic impact; shale gas development; extractive industries; hydraulic fracturing, fracking

The combined technologies of horizontal drilling and hydraulic fracturing have made it possible to extract large amounts of natural gas from the Marcellus Shale, which underlies portions of five states in the Northeast. Many commentators have assumed that shale gas exploration and development in these states will be enormously beneficial to the state and local economies. While externalities, both positive and negative, are commonly experienced along with the direct

activities of extractive industries, the negative externalities and the overall net benefits are often overlooked in economic impact studies. Examples of negative externalities in connection with shale gas development include water, air and land contamination; related public health impacts; wear and tear on roads and other infrastructure; and costs to communities due to increased demand for services such as police, fire, first responders, and hospitals.

An understanding of economic impacts in the Marcellus Shale region can be enhanced by a wider knowledge of boom-bust cycles, the resource curse, and extractive industries generally. In an effort to investigate both the potential net benefits to state and local economies and how policymakers may evaluate them, this article offers a summary review of research findings and makes suggestions for further research that would be necessary to adequately analyze the net economic impact of shale gas development. It also offers a preliminary look at some economic measurements in the Barnett Shale play in Texas that are not often mentioned in relation to shale gas development. The first section provides a brief critique of some of the industry-sponsored, non-peer-reviewed studies, and it is followed by a summary of peer-reviewed literature and non-industry-funded studies that are relevant to extractive industries such as shale gas development. The final section discusses some of the costs and uncertainties inherent in any economic assessment of shale gas development.

### **STUDIES FUNDED BY INDUSTRY**

Numerous studies have been prepared by and/or funded by the gas industry [1-6]. They generally conclude that there will be large, positive economic impacts to both states and local communities. These studies primarily highlight benefits such as employment, income, and tax revenue growth. Kinnaman [7] has reviewed several of these industry-sponsored studies and observed that they are not peer-reviewed. He has raised a number of concerns about the industry-sponsored studies, and concluded that due to unrealistic assumptions regarding windfall gains to households, location of suppliers and property owners, and the methodology used, the estimates of economic benefits in the industry-sponsored studies are very likely overstated. Any economic activity, including shale gas development, will generate some level of state and local economic revenues and provide some number of state and local employment opportunities, but policymakers should recognize that the estimated gains in revenues and employment are probably exaggerated in the industry-funded studies and the long-term economic impact may be far different than expected. In addition to the points made by Kinnaman [7], the estimates in these studies may be further overstated if overly optimistic gas reserve and production assumptions were used. There have been widely differing estimates of Marcellus Shale gas reserves from various sources, including academicians and federal government agencies [8]. For all these reasons, it is possible that the net benefits cited

by industry-sponsored studies are overstated even before any adjustments are made for negative externalities.

Input-output analysis is frequently used by industry in their efforts to show direct, indirect, and induced economic impacts of shale gas development [1-3]. Using this technique, the industry-funded studies have captured some of the likely benefits of shale gas development, including the growth of ancillary and other industries. Input-output analysis relies on tables of coefficients that link each industry in a region to all other industries. An input-output matrix shows how much output from each industry is used as input into other industries. In a region where shale gas drilling has not existed in the past, it is impossible to know with certainty what the inter-industry coefficients will be, and “borrowing” them from other regions or industries may result in inaccurate impact conclusions [9].

An important fact to bear in mind when viewing the shale gas experience in Texas and trying to extrapolate it to other states, such as New York, is that Texas is likely to experience greater economic benefits from shale gas development than is New York. Texas has had a well-established oil and gas industry for many years and a labor force with the requisite skill sets. Oil and gas headquarters and main offices are more often in Texas than in New York. Many of the industries that are ancillary to gas exploration and development are also located in Texas, not in New York. New York will have to import skilled labor as well as materials and equipment, much of which is manufactured, managed, contracted for, and maintained in Texas. Economists at the Federal Reserve Bank of Dallas (Dallas Fed) have pointed out that due to the extensive oilfield machinery and energy services located in Texas, the state greatly benefits from oil and gas production throughout the world [10]. In addition, the Barnett Shale is in the Dallas–Fort Worth metroplex, a region that is much more urban than the Marcellus Shale region. The literature indicates that the impact of extractive industries in nonmetropolitan areas may be much different than in metropolitan areas [11]. Economic multipliers tend to be larger in metropolitan areas, such as the Dallas-Fort Worth metroplex, where there are larger populations and greater industrial diversity than in nonmetropolitan areas, such as the Marcellus Shale region of upstate New York [12].

Kinnaman has pointed out that “economic resources necessary to fuel a growing industry would either relocate from other regions of the country or shift from local industries within the region. . . . The IMPLAN model used . . . largely ignores the possibilities of direct spending crowding out other users of the resource” [7]. An additional weakness is the fact that environmental impacts are ignored. Wassily Leontief, who received the Nobel Prize in Economic Science for his model of input-output economics, had himself stressed as early as the 1970s that environmental repercussions and externalities should be incorporated into input-output analysis [13-15]. Leontief recommended that a pollution abatement industry be entered into the input-output matrix, and that the abatement industry be in the business of eliminating pollutants

generated by the productive sectors, consumers, and the abatement industry itself. And Wiedmann, Lenzen, Turner, and Barrett stated, “in the last few years models have emerged that use a more sophisticated multi-region, multi-sector input-output framework . . . in order to calculate environmental impacts. . . . Results demonstrate that it is important to explicitly consider the production recipe, land and energy use as well as emissions in a multi-region, multi-sector and multi-directional trade model with detailed sector disaggregation” [16]. The industry-sponsored studies have not addressed environmental repercussions, such as water and air contamination, or externalities such as damage to roads and costs to communities. Unless appropriate adjustments are made, input-output analysis tends to use unrealistic assumptions. Bess and Ambargis [17] and Lazarus, Platas, and Morse [18] discuss some of the limitations of input-output analysis. For example, Bess and Ambargis state, “Regional input-output models can be useful tools for estimating the total effects that an initial change in economic activity will have on a local economy. However, these models are not appropriate for all applications and care should be given to their use. . . . Key assumptions of these models typically include fixed production patterns and no supply constraints. Assumptions about the amount of inputs that are supplied from the local region are also important in these models. Ignoring these assumptions can lead to inaccurate estimates” [17]. There are several additional problems of particular relevance to the application of input-output analysis to the study of shale gas development. For example, while spending patterns in communities with an established drilling industry would probably be different than spending patterns in communities without an established drilling industry, this difference is not reflected. Input-output analysis implicitly assumes that all populations have identical spending patterns. This assumption exaggerates the estimated economic impact if new workers are transient. The gas industry frequently brings in transient workers and houses them in man-camps or rental housing on a short-term basis [19]. Such workers often send their wages to their families living elsewhere, improving the economies in those distant locations, not in the shale region, and thereby exaggerating the estimated economic impact. In addition, input-output analysis assumes “constant returns to scale.” This means that the gas industry would get no volume discounts on supplies. This is an unrealistic assumption, and it inflates estimates of industry spending and thus estimates of economic impacts from the industry’s activity in the community. Input-output models used in the industry-sponsored studies tend to be static in time, implying that there are no changes in coefficients over time and no allowance for price changes in factors of production such as supplies and labor. The production function is also assumed to be constant. This does not allow for input substitution or changes in the proportions of inputs as technology and/or prices change over time. Input-output models tend to be aspatial, implying that transportation costs are not fully reflected. Transportation costs in gas drilling areas may differ

due to differences in availability of and proximity to fresh water supplies and wastewater disposal wells.

In order to produce even somewhat accurate results using an input-output approach, inter-industry relationships must be known. There are several frequently used sources of input-output coefficients that indicate how the input and output of each industry in a given region are related [20, 21]. One cannot know what the true coefficient values are in a case where the industry being studied does not already exist in a region, as is the case for horizontal drilling and hydraulic fracturing in New York State. Even if the input-output coefficients could be known, the technique is of limited use. Input-output methodology estimates the positive impacts on variables such as employment, value added, and tax revenue, but as shown in the above discussion of assumptions, the estimates are often exaggerated; and the methodology does not capture the impacts of environmental degradation or the full costs to communities and society.

### **STUDIES NOT FUNDED BY INDUSTRY**

While studies not funded by the gas industry on the economic impact of shale gas drilling are in short supply, there is substantial peer-reviewed literature on the economic impact of extractive industries generally. There are also some studies that are not peer-reviewed but are not funded by the gas industry. Conclusions from peer-reviewed literature and from studies not funded by the gas industry should be considered in the analysis of shale gas development. The research summary below is categorized into three areas: the resource curse, boom and bust cycles, and socio economics.

#### **The Resource Curse**

Research by Sachs and Warner [22, 23] concluded that there is a “natural resource curse,” meaning that countries with great natural resource wealth tend to grow more slowly than resource-poor countries. The so-called “resource curse” has been the subject of several literature surveys and the peer-reviewed research indicates that the resource curse holds within the United States, particularly in regions where there was once a strong extractive industry. After reviewing much of the literature, Stevens [24] pointed out that while there has been some disagreement, the evidence appears to support a negative relationship between abundance of natural resources and economic growth. He concluded that there is no simple single explanation of what creates a “blessing” rather than a “curse,” and he argued for a case-by-case approach to analysis. His findings indicate that to decrease the likelihood of a “curse,” the resource should be developed at a slow pace, thereby improving the chances that the economy and society can adjust and the crowding-out effect may be reduced. Increased diversification is suggested as another way to decrease the “curse” effect. Key dimensions of the

resource curse that have been studied include negative impacts on economic growth, prevalence of poverty, and creation of greater conflicts in society. Regional and national impacts may be quite different. Stevens stated, “A final dimension of ‘resource curse’ is the regional impact of the projects. Thus while the effect at a national level might be debated, because of the heavy local impact of the projects, clear damage is done especially in terms of both the environment and human rights. Meanwhile, the benefits appear to flow to central rather than regional authority. However, this aspect of the ‘curse’ tends to be neglected in the economics literature” [24].

This dichotomy between benefits to a nation and damage to localities should be studied further in the case of shale gas development in the United States. Industry-funded studies [25, 26] have concluded that there will be large positive impacts on tax revenues and national employment levels, but they have ignored many negative impacts that would be incurred at the local and state levels. In the case of shale gas development, it is likely that policymakers at the state and local levels will have different interests than policymakers at the national level. One question that policymakers at all levels should consider is whether shale gas development, including its exploration, production, and exportation, is worth the costs to the states, communities, and individuals that are directly impacted.

Initial research on the natural resource curse was focused on how it impacts developing nations [22-24]. Such research includes extensive empirical analysis and speculation on what causes the resource curse. While there has been less research on the natural resource curse specific to the United States, Papyrakis and Gerlagh [27] focused on the United States. They concluded that even in the United States, natural resource abundance is a significant negative determinant of economic growth. James and Aadland [28] extended the research to a disaggregated level within the United States, by focusing on counties. Their results show “clear evidence that resource-dependent counties exhibit more anemic growth, even after controlling for state specific effects, socio-demographic differences, initial income, and spatial correlation” [28].

Headwaters Economics studied county-level impacts and concluded, “counties that were not focused on fossil fuel extraction as an economic development strategy experienced higher growth rates, more diverse economies, better educated populations, a smaller gap between high and low income households and more retirement and investment income” [29]. Peach and Starbuck [30] studied oil and gas extraction in New Mexico and found a small but positive effect on income, employment, and population.

It may be difficult to determine if extraction of a natural resource caused poorer economic performance in an affected region or if the region was already relatively poor or on the path to poverty prior to exploitation of the resource. In two cases that are specific to counties in the United States, and were cited above, James and Aadland [28] and Headwaters [30], attempts were made to control for initial income and other differing characteristics of the areas under study.

### **Boom and Bust**

Extractive industries are known for their boom-and-bust cycles [31], and the bust must be analyzed as well as the boom. Weber [32] focused on the short-term impact of a natural gas boom in Colorado, Texas, and Wyoming and found modest increases in employment, wage and salary income, and median household income. The negative economic consequences during the bust may exceed the positive direct economic impact during the boom. Black, McKinnish, and Sanders [33] studied the coal boom in the 1970s and the bust in the 1980s on local economies in the four-state region of Kentucky, Ohio, Pennsylvania, and West Virginia. They concluded, “for each 10 jobs produced in the coal sector during the boom, we estimate that fewer than 2 jobs were produced in the local-good sectors of construction, retail and services. The spillovers from the coal bust were larger. During the coal bust, we estimate that for each 10 jobs lost in the coal sector, 3.5 were lost in the construction, retail and services sector” [33]. Seydlitz and Laska studied boom-and-bust cycles of the petroleum industry in Louisiana and concluded that improved community economic health is transitory in areas with petroleum extraction, and “improvements can be lost as early as the second or third year after an increase in petroleum activity and will be lost during the bust if not sooner” [34]. They suggest that a diversified economy may help to prevent some of the loss in benefits. Christopherson and Rightor [35] have written about the boom and bust phenomenon as it impacts shale gas extraction, and they suggest that the boom and bust cycle can be controlled by slowing the pace and scale of shale gas development.

### **Socioeconomics**

Peer-reviewed sociology journals have published articles on the socioeconomic impact of extractive industries in the United States, and the results of this research should be considered by policymakers in their assessment of the economic impact of shale gas development. For example, Freudenburg and Wilson [11] analyzed 301 research findings regarding the impact of mining in the United States, and they concluded that adverse conditions are significantly more likely than positive outcomes. They also stated, “the areas of the United States having the highest levels of long-term poverty, outside of those having a history of racial inequalities, tend to be found in the very places that were once the site of thriving extractive industries” [11].

Wilson [36] studied the socioeconomic well-being of mining communities by comparing two communities in the Midwest and concluded that local well-being as a result of mining in a community is influenced by local circumstances such as “levels of economic dependence on mining, the geographic distribution of the workforce, and the options available to the companies to confront changes in minerals price.” Wilson’s research indicates that different mining communities within the same region of the United States can have different long-term employment impacts, and case-by-case research is required.



### **SOME COSTS AND UNCERTAINTIES SPECIFIC TO SHALE GAS**

The relevant peer-reviewed research, as described above, indicates that each extractive industry and its impacts on specific states and locations must be studied on a case-by-case basis. There are many uncertainties regarding the long-term impacts on local and regional economies. Long-term impacts on the number of jobs created, unemployment rates, and income and poverty levels should each be considered. There are likely to be significant local costs, and these must also be considered. As horizontal, high-volume slick-water hydraulic fracturing for natural gas is still in its early stages, it is premature to analyze and attempt to make definitive conclusions regarding the long-term economic impacts of shale gas development in the United States. However, since the Barnett Shale play in Texas has been active for about a decade, some early indications of economic health are emerging. According to the Texas Railroad Commission [37], there are four core gas-drilling counties in the Barnett Shale: Denton, Johnson, Tarrant, and Wise counties. While there are many reasons why economic data and trends in certain counties differ from state-level data, it is interesting to examine unemployment rates, growth in median household income, and the number of people in poverty in these core gas-drilling counties as compared to statewide data. The data indicate that the residents of these counties are not experiencing great economic prosperity relative to the rest of Texas. Data were obtained from the U.S. Census Bureau, Small Area Estimates Branch, and the Bureau of Labor Statistics [38, 39]. For the period from 2003 to 2010, median household income increased by 21.2 percent in the state of Texas, but in the four core counties, median household income increased between 10 percent and 16 percent. And for the same period, the increase in the unemployment rates for the four counties ranged from 1.8 to 2.4 percentage points, a little higher than the increase in the state-level unemployment rate, which was 1.5 percentage points. Finally, the number of people in poverty in the four-county areas increased, in percentage terms, just as much as statewide.

Significant costs that are associated with shale gas development and other extractive industries should be considered in any study of the economic impact of shale gas development. Such costs are often omitted in both peer-reviewed literature and in the industry-funded studies. Kinnaman [7] briefly discusses the implications of social costs and implementation of a tax on negative externalities, which is intended as an incentive to reduce the negative externality and may be used as a source of funds to help mitigate negative impacts. A few of the costs that have not been adequately addressed in the literature are summarized here.

Shale gas development may transform a previously pristine and quiet natural region, bringing increased industrialization to the region in the form of industrial contaminants, heavy truck traffic, and excessive noise. Due to concerns regarding potential water, air, and land contamination, industries that have been vital to

some of the communities in the shale region may decline. Industries that are incompatible with high levels of industrialization and potential environmental degradation include agriculture, tourism, organic farming, hunting, fishing, outdoor recreation, and wine and beer making. Each of these industries that rely on clean air, land, water, and/or a tranquil environment is currently important to the shale counties in upstate New York. Kauffman [40] has calculated that the net present value, using a discount rate of 3 percent over 100 years, of natural goods and services from ecosystems in the New York State portion of the Delaware River Basin is \$113.6 billion.

Tourism is an industry that been encouraged in many of the communities on the Marcellus Shale, and Rumbach [41] reported that in 2008, visitors spent more than \$239 million in three counties of New York State's Southern Tier, and the tourism and travel sector accounted for 3,335 direct jobs and nearly \$66 million in labor income. The Outdoor Industry Association [42] reports that 6.1 million American jobs are directly supported by the outdoor industry and that Americans spend \$646 billion each year on activities like camping, hunting, fishing, and snow sports, all of which are popular in the Marcellus Shale region.

Deller et al. [43] analyze economic growth due to tourism in areas with natural amenities that encourage outdoor recreation and conclude that rural areas that can take advantage of such amenities are in a position to expand their local economies. Public fears of water, air, and land contamination due to shale gas development, whether those fears are realistic or not, may forever negatively impact the public perception of the rural areas that currently enjoy tourism dollars. Another related sector of the economy in the shale region of New York centers around retirees and owners of second homes, both of whom may become less enamored of a region when it becomes industrialized. Such potential losses to communities should be reflected in an economic assessment.

Estimating the ignored costs is not a simple task, but there are ways to at least roughly estimate many of the costs that have been ignored to date. Rumbach [41] analyzed the potential impact of shale gas drilling on the New York tourism industry, and his work may assist in attempting to estimate impacts. He points out that tourism brings many non-monetary benefits to the region and its communities, and its amenities improve the quality of life for residents. He states, "Restaurants, shops, parks and outdoor recreation areas, campgrounds, wineries, festivals, museums and other related amenities are beneficial to local residents as well as visitors. These amenities also make a region more attractive for economic investment; they are some of the crucial resources that allow an area to attract economically mobile populations." He questions whether drilling will permanently damage the "brand" of the region as a pristine and picturesque destination. Brand image may also be affected for agricultural products from shale areas. In an open letter on the subject of shale gas development, the president of the Park Slope Food Coop, a very large food coop in Brooklyn, NY,

stated, “I guarantee that our members will not want the fruits and veggies that come from farms in an industrial area” [44]. The use of surveys and focus groups may help to estimate the extent of the impact of “brand” image on customers and the overall impact on some of the impacted industries. Probability or risk models, based on the likelihood of contamination, may also be employed. In the case of the impact on hunting and fishing, volume decreases can be estimated using surveys of businesses and customers together with official state data on game animal harvests and creel surveys in areas already experiencing shale gas development. The impact on outdoor recreation and related facilities can be estimated through surveys, attendance records at major facilities, and the loss to businesses that cater to such customers.

Additional costs that should be estimated are the costs to communities associated with increased demand for community social services, such as police and fire departments, first responders, and local hospitals. Such cost increases resulting from gas drilling have taken place in the Rocky Mountains [45, 46], and research from Pennsylvania shows that many municipalities have experienced increased costs [47]. As the shale gas industry imports labor from other states, transient workers will exert additional demand on community services and further upward pressure on costs.

There will be costs associated with traffic congestion and road damage. The heavy truck traffic required for shale gas development is known to cause air quality issues and significant road damage. It was recently reported that the Texas Department of Transportation told industry representatives and elected officials that “repairing roads damaged by drilling activity to bring them up to standard would ‘conservatively’ cost \$1 billion for farm-to-market roads and another \$1 billion for local roads. And that doesn’t include the costs of maintaining interstate and state highways” [48]. The New York State Department of Transportation made a preliminary statement that “the impacts of Marcellus Shale gas development on State transportation financing needs is likely to be profound. . . . The incremental costs to mitigate Marcellus impacts for the State range from \$90 million to \$156 million per year. The estimate for costs for local roads and bridges range from \$121 million to \$222 million per year, some of which may well flow from the State Transportation Budget” [49].

The impact on property values is uncertain and has been inadequately addressed in the literature. On the one hand, increased property valuations of large tracts may be expected due to potential income from gas drilling, and an influx of transient workers will probably increase the demand for and value of rental properties. The net impact on property values, however, is uncertain. Shale gas drilling is taking place in homeowners’ backyards, and such industrial activity and the presence of hazardous materials are in many cases in violation of residential mortgage conditions [50]. Boxall, Chan, and McMillan [51] studied the impact of oil and gas drilling on residential property values in

Alberta, Canada, and found a negative relationship. The authors note that three industry-funded studies did not find a negative relationship between gas drilling and residential property values [52-54]. Again, while the impact on property values is difficult to estimate, there is relevant literature. For example, Taylor, Phaneuf, and Liu [55] used an empirical model to identify the direct impact of environmental contamination on residential housing prices separate from land use externalities. Muehlenbachs, Spiller, and Timmins [56] demonstrated that the risk of groundwater contamination from natural gas extraction leads to “a large and significant reduction in house prices.” They further found that “these reductions offset any gains to the owners of groundwater-dependent properties from lease payments or improved local economic conditions, and may even lead to a net drop in prices. . . . To the extent that the net effect of drilling on groundwater-dependent houses might even be negative, we could see an increase in the likelihood of foreclosure in areas experiencing rapid growth of hydraulic fracturing.”

Recent reports indicate that obtaining insurance is likely to become increasingly difficult, if not impossible, for properties that may be impacted by shale gas drilling [57]. This will negatively impact property values, as residential mortgages require the property owner to carry homeowner’s insurance. A representative of Nationwide Insurance recently stated in email correspondence, “From an underwriting standpoint, we do not have a comfort level with the unique risks associated with the fracking process to provide coverage at a reasonable price” [58]. If available in the future, the cost of obtaining such insurance to protect against the substantial risks inherent in shale gas drilling using hydraulic fracturing techniques may become prohibitively high. This is another example of a cost that is omitted in the research to date. Data on trends in housing sales and prices in existing shale regions should be analyzed in detail to help identify the impact on property values.

Potential public health costs should be reflected in a thorough economic assessment. Multiple researchers have discussed potential negative health impacts that may result from water and air contamination. Various chemicals used in hydraulic fracturing include carcinogens and endocrine disruptors, which are related to serious diseases and birth defects, both involving significant costs. Bamberger and Oswald [59], Schmidt [60], Weinhold [61], and McKenzie, Witter, Newman, and Adgate [62] have investigated health impacts. In the case of humans, such costs can be estimated by measuring health services costs related to specific diseases and the loss of life and decreases in life expectancy. In the case of domestic and farm animals, values may be assigned based on market prices. All these health costs should be estimated using probabilities based on the likelihood of contamination by the various pathways.

An opportunity cost that should be factored into the analysis is the foregone economic development in areas where networks of gas pipelines are constructed.

As buildings cannot be placed on or adjacent to pipelines, shale gas development may cause future construction and economic development to be significantly curtailed [63]. This foregone regional development and the possibility of earthquake damage caused by disposing wastewater into deep injection wells [64] are uncertain costs that may be impossible to measure, but they may become enormous costs to communities in the long-run. Dutzik, Ridlington, and Rumpler [65] have outlined many of the economic costs, made a few suggestions regarding estimation of some of the costs, and shown that communities and states will bear many of the costs.

All potential benefits and costs of shale gas development should be considered during the decision-making process. Some questions that policymakers should ponder, in addition to the basic question of whether there will be net economic benefits to states and communities, are the following: (1) Are the potential benefits to the nation in the form of balance of payments gains from shale gas exports worth the risks to the environment, public health, and local economies? (2) Is the continued development of fossil fuels and their impact on climate change sensible in light of the uncertainty regarding the impacts on public health and state and local economies? One cannot answer such questions until a comprehensive analysis of net economic impacts has been completed. One way to view the net impacts and the many tradeoffs is to think of the benefits and costs to a region or a state as assets and liabilities in the form of a balance sheet for the region. As an example, Figure 1 presents such a balance sheet for New York State.

In conclusion, there are many uncertainties regarding the net benefits of shale gas development on state and local economies. There are sufficient independent research findings on extractive industry impacts to question the claims commonly propounded by the industry, and repeated by the press, that shale gas extraction will bring prosperity to local communities. The preponderance of independent research indicates that long-term prosperity for local communities is unlikely, but far more research is required in order to make a definitive conclusion. Policymakers should insist on unbiased, comprehensive economic assessments of shale gas development for each state and community that may be impacted.

#### **AUTHOR'S BIOGRAPHY**

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### A Balance Sheet for New York State: What is New York State's Net Equity from Shale Gas Development?

**► Assets\***

- Tax Revenue:
  - Direct from the gas industry based on future legislation
  - Increased income tax based on Royalty income to leaseholders
  - Lease income to landowners
- Stimulation of industries based on byproducts of natural gas
- Climate benefits from decreases in green house gases from burning shale gas
- Indirect benefit to NYS from improved Balance of Payments assuming substantial shale gas exports
- Short-term job gains in the gas industry and related industries
- Increased spending by leaseholders in New York State
- Lower cost of energy as long as it lasts

**TOTAL ASSETS**                      ???

**► Liabilities\***

- Tax Revenue Loss:
  - Income tax losses by leaseholders who vacate properties and relocate out-of-state
  - Income tax losses caused by decreases in tourism and other industries negatively affected by drilling
  - Property tax losses caused by negative impact of drilling on property values and financing
- Decreased spending by leaseholders if they move out of state, or buy second homes out of state
- Human health costs associated with:
  - Water contamination from frack fluids and wastewater
  - Air pollution from compressors, leaks, gas released at well-sites
- Costs due to impacts on animals (domestic, agricultural and game) of water, land and air contamination
- Climate costs associated with increases in greenhouse gases from methane leaks and venting
- Costs associated with declining quality of life due to the creation of an industrial landscape
- Costs associated with declines in tourism industry
- Costs associated with declines in organic farming and other agriculture and food manufacturing
- Costs associated with declines in outdoor recreation
- Costs associated with increased air pollution from increased truck traffic
- Costs associated with declines in fisheries and trout fishing industry
- Infrastructure costs due to use of and damage to roads and bridges from increased truck traffic
- Costs due to declines in numbers of retirees and retirement housing market
- Costs due to declines in numbers of second home owners and second home market
- Costs due to crowding out (loss of jobs to existing businesses and governments)
- Costs to communities due to increased demand for police, fire and first responder services
- Social costs associated with the gas drilling industry
- Costs to the mortgage industry and housing market, and related declines in property values and property tax revenue
- Costs associated with increased homelessness
- Costs associated with the postponement of investment in renewables
- Opportunity costs due to the prevention of future building and economic development
- Costs associated with a long-term bust, characteristic of extractive industries

**TOTAL LIABILITIES**                      ???

**NET EQUITY**                                      ???

\*These are not necessarily comprehensive lists of assets and liabilities. They serve only as examples. Note that where an asset or liability is a future stream of income or expense, discounted present value should be used.

Is the Discounted Present Value of Total Assets minus the Discounted Present Value of Total Liabilities a positive value?  
*This question cannot be answered until a comprehensive risk assessment and economic analysis has been conducted.*

Figure 1. A snapshot of one state's net impacts and tradeoffs, formatted as a balance sheet.

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*Features*

**HISTORICAL ANALYSIS OF OIL AND GAS WELL  
PLUGGING IN NEW YORK: IS THE REGULATORY  
SYSTEM WORKING?**

**RONALD E. BISHOP**

**ABSTRACT**

The aim of this work was to evaluate New York State's regulatory program for plugging inactive oil and gas wells. Analysis of reports from the Division of Mineral Resources, Department of Environmental Conservation, reveals that three-fourths of the state's abandoned oil and gas wells were never plugged. Inadequate enforcement efforts have resulted in steady increases of unplugged oil and gas wells abandoned since 1992. Further, no program exists or is proposed to monitor abandoned wells which were plugged. These results strongly suggest that comprehensive reform and increased agency resources would be required to effectively regulate conventional oil and gas development in New York. Industrial expansion into shale oil and gas development should be postponed to avoid adding stress to an already compromised regulatory system.

**Keywords:** oil, gas, plugging, regulatory, New York, fracking

New York's oil and gas industry is just nine years from its bicentennial, since the pilot project, a natural gas well near Fredonia, was drilled in 1821. Now, there is a dedicated and sophisticated Bureau of Oil and Gas Permitting and Management (BOGPM), established as a unit of the Division of Mineral

Resources (DMN) within the state Department of Environmental Conservation (DEC) in 1970. State guidance documents and regulations have undergone multiple updates, including those newly proposed in 2011 to accommodate concerns peculiar to the extraction of oil and gas from unconventional reservoirs such as shale. But before state regulators adopt new rules to permit expansion of the industry into shale oil and gas development, we should evaluate how the regulatory system has managed petroleum development so far. Few aspects of the regulatory system are as cogently diagnostic as New York's record on plugging abandoned oil and gas wells.

## **BACKGROUND**

### **Abandoned Wells Issue**

With great attention paid these days to proper oil and gas well construction, appropriate control of chemicals and wastes, and other production issues, post-production plugging and cleanup has received relatively little notice. But as production from the first oil and gas wells declined, this was recognized as an important issue. New York became the first state to require the plugging of abandoned wells in 1879 [1]. No particular state entity existed to monitor compliance or enforce the plugging law, but an 1882 amendment to it offered half of any fines collected to informants who reported violations [1]. From that time forward, regulating this aspect of the petroleum industry has posed a unique challenge.

### **Scope of the Problem**

The number of abandoned oil and gas wells in New York State is not definitely known. The Historic Well Survey of 1988, included in that year's DMN annual report, established a baseline of 42,322 oil and gas wells of unknown status [2], while the Plugged Wells Estimate of 1993, included in that year's annual report, identified 13,070 wells which were known to have been plugged [3]. For their external review in 1994 by the Interstate Oil and Gas Compact Commission, BOGPM staff estimated that 61,000 wells had been developed historically, but the agency had no records on 30,000 of them [4]. Of the wells on record, 12,857 were active and about 18,000 were known to not be plugged. Therefore, of 48,000 abandoned oil and gas wells total, 13,000 were plugged and approximately 35,000 were not plugged as of 1994 [4]. It should be noted that this report represented an improvement in the BOGPM's accounting for oil and gas wells since the Historic Wells Survey of 1988, reducing the approximate number of "unknown status" wells from 42,000 to 35,000 over that six-year period.

## Well Accounting Issues

Accounting for abandoned oil and gas wells is complicated by the fact that New York's BOGPM maintains more than one system for recording them. For example, the 2005 DMN annual report reported on (a) inactive oil and gas wells, (b) known, unreported wells and (c) "other, known orphan wells" [5], which summed to fewer than 9,000 wells, far short of the 35,000 unplugged, abandoned wells noted above. Annual reports from 2002 onward suggest that the locations of fully half of the state's orphan abandoned oil and gas wells are unknown, and from the 2009 annual report, "Most of the [abandoned] wells date from before New York established a regulatory program" [6]. Thus it appears that state regulators have given up on old wells for which location or operational data are missing; for clarity, I will call them "forgotten." Abandoned oil and gas wells in known locations, but for which the BOGPM lacks current ownership data, dominate the Priority Plugging List [7]. Although some of these wells have been plugged with the use of agency or external funds, most have not. Therefore, I refer to this group as "generally ignored." The primary focus of the BOGPM, then, is on those inactive wells for which all information is actionable; I call them "standing inventory." The boundaries that delimit these groups are not always clear, but the fresh discovery of a "forgotten" well typically results in its transfer to the "generally ignored" category, and the loss of ownership information may move a well from "standing inventory" to "generally ignored." Plugging oil or gas wells results in their removal from the state's accounting, although they are still abandoned structures; one might call them "forsaken."

## Practical Significance

Why would abandoned wells matter to anyone? As if to answer this question, DMN annual reports from 2002 and 2003 presented case studies with photographs of individual abandoned oil and gas wells [8, 9]. One case involved an old gas well that discharged brine at a rate of five gallons per minute into a wetland near Rome, killing over an acre of vegetation [8]. Another involved the entire village of Rush, on the border between Ontario and Schuyler Counties, where two dozen unplugged abandoned wells were responsible for widespread emanation of gas from the soil, so that methane accumulated to explosive levels in some structures [8]. Plugging or excavation of abandoned wells on school properties in Allegany and Wyoming Counties cost those school districts thousands of dollars [8]. Further, abandoned wells have been found leaking oil into creeks and wetlands in Steuben and Allegany Counties, and into residential ponds and lawns in Allegany and Cattaraugus Counties [9]. These case studies provide evidence that many abandoned petroleum wells across New York leak fluids to the ground surface.

This issue is by no means limited to New York. In a 1987 report, the U.S. Environmental Protection Agency (EPA) estimated that, of about 1.2 million abandoned oil and gas wells nationwide, approximately 200,000 (17%) were portals for pollution to reach the surface [10], and in 1989 the U.S. General Accounting Office reported that the number of improperly abandoned wells was increasing [11].

### **Long-Term Instability**

Abandoned wells leak because well casings deteriorate over time, and once-depleted rock formations repressurize with oil, gas, and brines [12–14]. Dusseault and coworkers showed that because temperature, pressure, and salt concentrations all tend to increase with depth, steel pipe and concrete degradation occurs most rapidly in the deepest segments of abandoned wells, where the damage is most difficult to detect. They estimated that essentially all unmaintained well bores lose integrity over a 50-year time frame, and further, that deep rock structures frequently repressurize [12]. One industry study of offshore oil and gas wells determined that half of the well casings studied began to leak in just 15 years [13]. A more recent industry study of oil and gas projects in Alberta, Canada, found leaks in just over 4 percent of the wellbores, including some which were plugged before abandonment [14]. A possible explanation for the lower percentage of leaks found in the onshore wells might be that they were more actively maintained. That is, the Canadian projects were more consistently monitored for sustained casing vent flow and external gas migration, and were more aggressively re-grouted when these problems were discovered [14]. Ongoing maintenance, then, is required to keep old wellbores stable. Therefore, to be effective, the state's oil and gas regulatory program must not only ensure that abandoned wells are properly plugged, but must also periodically inspect and, when necessary, repair the plugged wells.

### **Economic Impact**

The cost of plugging abandoned oil and gas wells varies for different situations, but two contract awards cited in DMN's 2008 annual report provide some context [15]. One contract was for \$190,000 to plug 45 wells in Allegany County, an average cost of \$4,222 per well, and the other was for \$150,000 to plug 25 wells in Cattaraugus County, or \$6,000 per well. At about \$5,000 per abandoned well, plugging the 4,722 wells on the BOGPM's current priority plugging list [7] would cost \$23.6 million. And on this basis, finding and plugging the 35,000 unplugged, abandoned wells which were estimated in 1994 would cost at least \$175 million.

In the agency's defense, the DMN began to amass an "Oil and Gas Fund" in 1981 to pay for the plugging of priority oil and gas wells, but in 1993 the Legislature appropriated \$1 million of that fund for general expenditures, and

changed state law to prevent the use of collected fines for plugging activities [4]. The DMN never accumulated that much money again; the plugging fund balance at the end of 2009 was \$209,000 [6].

### **Difficulty of Enforcement**

What is involved in enforcing compliance with the state's oil and gas plugging laws? This question is nuanced, according to Louis W. Allstadt, a former senior oil and gas company executive [16]:

Very little attention is paid to the end of the life of an oil or gas well. I think you will find that it is rare for the larger companies to plug and abandon their older wells. Rather, at some point, a smaller company with lower overheads and less expensive operating costs will offer to buy the old wells at a price that gives the original company a better return than continued operations. The original company uses the cash to finance new investments. The buying company operates with lower costs because they spend less on maintenance and safety items and they have fewer well-qualified people to pay. The chain may end there or continue through smaller and ever lower cost operators who do no preventive maintenance at all, do the bare minimum of repairs to keep the well going and eventually walk away, maybe after plugging the hole as cheaply as possible and maybe not plugging at all.

In conventional fields these selling/buying cycles might start when the field is 20-30 years old and run for another 20-30 years. By the time these wells are abandoned, the casings have been subjected to corrosive fluids for many years. When it costs too much to repair versus what might be produced, the well is abandoned. Whether it is plugged before it is abandoned depends on the final operator. In tight shale this could all take place over a much shorter time period and the abandoned wells could increase quickly [16].

Hence, inspecting low-production oil and gas projects and tracking well ownership through multiple transfers pose particular challenges to state regulators, and may help to explain how many owners have avoided plugging their abandoned wells. This problem would be exacerbated by shorter-lived projects, and indeed, industry analysts have presented evidence that tight shale gas wells decline much more quickly than oil and gas wells in conventional deposits, with shale gas projects exhibiting half-lives of about eight years [17, 18].

Therefore, with state regulators proposing to permit dramatic expansion of the oil and gas industry into extraction from shale, the principal aim of this study is to answer the question: "How successful has New York's oil and gas regulatory program been, especially since the 1994 review, with respect to post-production plugging?"

## METHODS

### Data Sources

Most data for this investigation came from annual reports by the DEC's Division of Mineral Resources. Reports that were accessible from the DEC's web site included those from 1994 through 2009 [19]. Reports from 1985 through 1993 were obtained by Freedom of Information Law (FOIL) request from the DEC. Other data came from the 1994 New York State Review (STRONGER review) [4] and the New York State priority plugging list [7]. These documents constitute the entire body of publicly available records on this topic in the State of New York.

### Categories of Inactive Wells

As stated in the introduction, the primary focus of the BOGPM appears to be the "standing inventory" of oil and gas wells declining to zero commercial production, for which complete location and owner information is currently available. That subset of inactive wells represents all that are detailed in the DMN annual reports, and forms the main substance of the Results section, below.

### Influence of Shut-in Wells

The results below are expressed in terms of oil and gas wells that had been reported as "inactive," defined as having zero commercial production. An oil or gas well may be considered inactive either because it is depleted or because it is shut in. From 1966 to 1990, no distinction was made in DMN annual reports between depleted and shut-in wells. Since 1991, shut-in wells have been consistently identified as those that may be capable of producing oil or gas, but are not connected to pipelines or for some other reason are temporarily sealed to prevent product loss. Shut-in wells are not required to be plugged, even though they are inactive. Therefore, a summary of shut-in application approvals by year was requested from the BOGPM. The agency claimed to have no responsive records, but informed me that "269 shut-in applications are currently approved" [20]. Hence, the number of inactive oil and gas wells in each year's standing inventory may include some which were not required to be plugged at the time, but no data are available to resolve that question for individual years.

### Influence of "Other" Plugged Wells

In DMN annual reports, data for well plugging included oil, gas, and "other regulated wells." The other regulated wells included salt solution and stratigraphic geothermal wells, and their numbers were expressly stated in only seven of the reports, from 2003 through 2009. These "other" plugged wells ranged from 15 to 55 per year, with mean and median averages of 28.3 and 24,



respectively. To maintain consistency of data handling across the entire 39 years reported, the more conservative median average of 24 wells was subtracted from the raw “plugged” data for each year from 1971 through 1992, and the actual number of “other” plugged wells was subtracted from the raw “plugged” data prior to plotting and analysis. This modest correction is supported by data from the salt solution mining section of the DMN 1995 annual report, which indicated that 167 wells were plugged in the seven-year period from 1988 through 1994 (average of 24 wells per year) for a single salt solution project (Tully Valley) [21].

## RESULTS

The yearly data for inactive and plugged wells are summarized in Table 1, and a plot of inactive oil and gas wells and corrected plugged wells by year shows the results of Table 1 graphically (Figure 1).

### Trend Analysis

The results shown in Figure 1 indicate that New York has maintained a significant standing inventory of inactive oil and gas wells, a fraction of which have been plugged each year. Over time, this standing inventory tended to increase, except for the period 1990-1992. That period, when the inventory decreased, coincided with Pennzoil’s closing out of its Chipmunk Field operations in Cattaraugus County; it unilaterally plugged 629 wells in 1990, contributing to a record 937 wells plugged that year [22]. The inventory then increased steadily from 1992 through 2009, approximately doubling over that 17-year period. Hence, for most of their recorded history, New York regulators’ efforts to enforce plugging laws have not kept pace with the number of oil and gas wells that needed to be plugged.

To evaluate what would be required for the BOGPM to prevent an increase in unplugged wells, we need to know how many oil and gas wells become newly inactive each year. When I requested this information, the agency responded that its records are not structured to provide it: one would have to simultaneously monitor every well in the database and observe when each one was first reported to have zero production [20]. Nevertheless, the annual decline of oil and gas wells to zero production can be deduced from the trends shown in Figure 1.

A stable standing inventory would indicate that plugging rates matched the entry of inactive wells into the DMN database. Plugging rates would have to be lower than the entry of inactive wells into the database for the inventory to increase, and conversely, plugging rates would have to exceed the entry of inactive wells into the database for the inventory of unplugged wells to decrease. Average annual values derived from these trend parameters are shown in Table 2.

Table 1. Annual Plugging Data for Abandoned Oil and Gas Wells in New York

Year	Inactive <sup>a</sup>	Number plugged (raw)	Correction	Number plugged (corrected)
1996 <sup>b</sup>	4500	N.A.	N.A.	N.A.
1967	4600	N.A.	N.A.	N.A.
1968	4450	N.A.	N.A.	N.A.
1969	1009	N.A.	N.A.	N.A.
1970	1350	N.A.	N.A.	N.A.
1971 <sup>c</sup>	1567	418	-24	394
1972	1619	573	-24	549
1973	1484	544	-24	520
1974	1862	622	-24	598
1975	1883	553	-24	529
1976 <sup>d</sup>	1825	442	-24	418
1977	1820	455	-24	431
1978	1864	352	-24	328
1979	2020	117	-24	93
1980	1900	119	-24	95
1981	2128	184	-24	160
1982	2304	262	-24	238
1983	2431	90	-24	66
1984	2296	182	-24	158
1985	2519	269	-24	245
1986	2468	471	-24	447
1987	2543	417	-24	393
1988 <sup>e</sup>	2348	322	-24	298
1989	2620	260	-24	236
1990 <sup>f</sup>	2707	961	-24	937
1991 <sup>g</sup>	2069	376	-24	352
1992	1502	244	-24	220
1993 <sup>h</sup>	1642	263	-24	239
1994 <sup>i</sup>	1887	248	-24	224

Table 1. (Cont'd.)

Year	Inactive <sup>a</sup>	Number plugged (raw)	Correction	Number plugged (corrected)
1995	1784	219	-24	195
1996 <sup>j</sup>	2215	233	-24	209
1997 <sup>k</sup>	1974	187	-24	163
1998	2169	169	-24	145
1999 <sup>l</sup>	1748	138	-24	114
2000 <sup>m</sup>	2190	131	-24	107
2001 <sup>n</sup>	2259	79	-24	55
2002 <sup>o</sup>	2272	146	-24	122
2003 <sup>p</sup>	2379	142	-15	127
2004	2526	145	-39	106
2005 <sup>q</sup>	2658	150	-55	95
2006 <sup>r</sup>	2871	213	-22	191
2007 <sup>s</sup>	2460	192	-31	161
2008	3071	221	-12	209
2009 <sup>t</sup>	3043	240	-24	216

<sup>a</sup>Oil and gas wells reported to have zero commercial production.

<sup>b</sup>Earliest official records.

<sup>c</sup>Earliest plugging records.

<sup>d</sup>Earliest reporting of "shut-in" gas wells.

<sup>e</sup>Estimated 42,32 wells of unknown status.

<sup>f</sup>Record high number of wells plugged.

<sup>g</sup>"Shut-in" wells first referred to as "inactive."

<sup>h</sup>Total plugged wells reported as 13,070.

<sup>i</sup>Total unplugged wells estimated at 35,000 [4].

<sup>j</sup>96 newly discovered abandoned wells.

<sup>k</sup>200 newly discovered abandoned wells.

<sup>l</sup>270 newly discovered abandoned wells.

<sup>m</sup>220 newly discovered abandoned wells.

<sup>n</sup>150 newly discovered abandoned wells.

<sup>o</sup>First mention of priority plugging list.

<sup>p</sup>First explicit reporting of "other" plugged wells.

<sup>q</sup>2117 Known wells unreported.

<sup>r</sup>1103 Known wells unreported.

<sup>s</sup>822 Known wells unreported.

<sup>t</sup>Last available annual report.

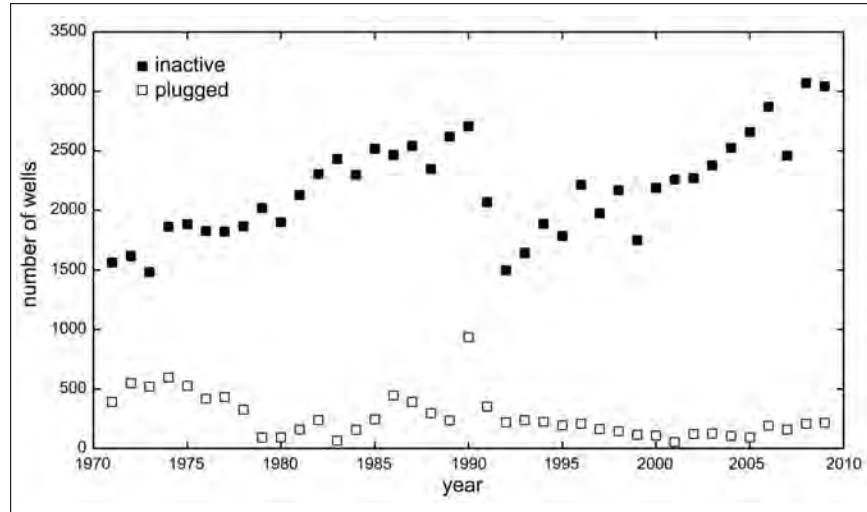


Figure 1. Annual reports of standing inventory of inactive wells (filled squares) and plugged inactive wells (open squares) by year reported, 1971-2009. Data taken from Table 1.

Table 2. Annual Newly Inactive Oil and Gas Wells

Period	Plug rate <sup>a</sup>	Inventory trend	Change <sup>b</sup>	Newly inactive <sup>c</sup>
1973-1978	499/yr	Stable	0	499/yr
1979-1987	151/yr	Increasing	+92/yr	243/yr
1987-1992	444/yr	Decreasing	-208/yr	236/yr
1992-2009	161/yr	Increasing	+91/yr	252/yr

<sup>a</sup>Total oil and gas wells plugged/number of years in period.

<sup>b</sup>Increase or decrease in inventory/number of years in period.

<sup>c</sup>Plug rate column value ± Add/subtract column value.

The results of Table 2 indicate that since 1980, approximately 250 oil and gas wells have become newly inactive annually. Therefore, for plugging to keep pace with ongoing demand, the BOGPM would have to enforce the plugging of at least 250 wells each year. The data in Table 1 show that such an enforcement level has not been achieved since 1991.

### Current Status of Abandoned Oil and Gas Wells

Summary statistics from the DMN annual reports from 2008 and 2009 indicate that 75,000 total oil and gas projects are believed to have been developed in New York, of which about 11,000 remain active [6, 15]. Using these values in conjunction with the results shown in Table 1, it is possible to estimate how many oil and gas wells have been abandoned in the state, both plugged and unplugged. The data for 1994 and 2009 are presented for comparison in Table 3.

The results shown in Table 3 indicate that, while the number of plugged oil and gas wells has grown considerably since 1994, the number of unplugged abandoned oil and gas wells has increased even more. The percentage of plugged wells, out of all the abandoned wells, has slipped from 27 percent in 1994 to 25 percent currently, leaving the state with an estimated 48,000 wells that need to be plugged. At an estimated cost of \$5,000 per well, about a quarter of a billion dollars would be needed to plug all these wells, if they could be found.

### CONCLUSIONS AND RECOMMENDATIONS

Since 1970, New York's Bureau of Oil and Gas Permitting and Management has failed to adequately enforce state laws that require industry operators to plug inactive oil and gas wells. As a result, three-fourths of inactive oil and gas wells remain unplugged, and the number of unplugged abandoned wells in New York continues to increase. In the last year reported, only 216 of an estimated 250 newly inactive oil and gas wells (86%) were plugged. Further, no program to monitor and maintain plugged abandoned wells exists or is proposed, in spite of evidence that plugged wells can disintegrate and leak.

Table 3. Summary of Plugged and Unplugged Abandoned Oil and Gas Wells

Year	1994 <sup>a</sup>	2009 <sup>b</sup>
Total projects	61,000	75,000
Active wells	12,857	10,982
Abandoned wells, plugged	13,070	15,748
Abandoned wells, unplugged	35,000	48,000
Total abandoned wells	48,000	64,000
Percentage plugged	27	25

<sup>a</sup>Data from STRONGER review [4] and Plugged Wells Survey [3].

<sup>b</sup>Data from 2009 DMN annual report [6], Plugged Wells Survey [3], and Table 1.

Therefore, the following actions are recommended:

1. Approval of permits for conventional oil and gas development projects in New York should be reduced by 15 percent immediately until industry compliance with inactive well-plugging requirements can be demonstrated for a minimum of three consecutive years.
2. Oil and gas well transfer requests should be suspended immediately, until the DMN can re-evaluate financial security and bonding levels which will ensure that all declining oil and gas wells are plugged when they reach zero commercial production.
3. The state legislature should appropriate funding for the specific purpose of inspecting and plugging every well in the BOGPM standing inventory and priority plugging list.
4. New York should establish a program to register, inspect, and maintain abandoned oil and gas wells that have been plugged.
5. The New York State Bureau of Oil and Gas Regulation, Division of Mineral Resources, Department of Environmental Conservation should invite the Interstate Oil and Gas Compact Commission to conduct an updated state review.
6. Expansion of the state's petroleum industry into extraction of oil and gas from shale should be postponed until the above actions have been carried out.

Overall, the goal should be to establish a comprehensive plan for regulatory improvement, including progress on the issue of oil and gas well plugging and abandonment in New York.

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*Features*

**ANALYSIS OF RESERVE PIT SLUDGE FROM UNCONVENTIONAL NATURAL GAS HYDRAULIC FRACTURING AND DRILLING OPERATIONS FOR THE PRESENCE OF TECHNOLOGICALLY ENHANCED NATURALLY OCCURRING RADIOACTIVE MATERIAL (TENORM)**

**ALISA L. RICH  
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**ABSTRACT**

Soil and water (sludge) obtained from reserve pits used in unconventional natural gas mining was analyzed for the presence of technologically enhanced naturally occurring radioactive material (TENORM). Samples were analyzed for total gamma, alpha, and beta radiation, and specific radionuclides: beryllium, potassium, scandium, cobalt, cesium, thallium, lead-210 and -214, bismuth-212 and -214, radium-226 and -228, thorium, uranium, and strontium-89 and -90. Laboratory analysis confirmed elevated beta readings recorded at  $1329 \pm 311$  pCi/g. Specific radionuclides present in an active reserve pit and the soil of a leveled, vacated reserve pit included  $^{232}\text{Th}$  thorium decay series ( $^{228}\text{Ra}$ ,  $^{228}\text{Th}$ ,  $^{208}\text{Tl}$ ), and  $^{226}\text{Ra}$  radium decay series ( $^{214}\text{Pb}$ ,  $^{214}\text{Bi}$ ,  $^{210}\text{Pb}$ ) radionuclides. The potential for impact of TENORM to the environment, occupational workers, and the general public is presented with potential health effects of individual radionuclides. Current oversight, exemption of TENORM in federal and state regulations, and complexity in reporting are discussed.

**Keywords:** reserve pit, radiation, Technologically-Enhanced Naturally Occurring Radioactive Materials (TENORM), Naturally Occurring Radioactive Materials (NORM), Barnett Shale, natural gas mining, fracking

Reserve pits are commonly seen throughout areas of unconventional natural gas extraction. The purpose of the reserve pits (commonly referred to as pits, ponds, cellars, tanks, impoundments, etc.) is to hold the large quantities of water and drilling mud required for hydraulic fracturing (“fracking”) operations. These pits also provide a depository for brine water that occurs naturally in natural gas deposits, drilling mud, drilling cuttings and hydraulic fracturing fluids. Hydraulic fracturing fluids can contain chemical additives (acids, bactericides, breakers, corrosion inhibitors, cross-linkers, emulsifiers, flocculants, foaming agents, proppants, scale inhibitors, surfactants) and cuttings (rock, soil and metal shavings excavated by the drill bit) which can contain technologically enhanced naturally occurring radioactive material (TENORM) [1, 2]. Previous research has identified  $^{226}\text{Ra}$ ,  $^{228}\text{Ra}$ , and radon gas ( $^{222}\text{Rn}$ ) as the predominant radionuclides in natural gas wastes from oil and gas drilling. The focus of existing regulation guidelines has been related to  $^{226}\text{Ra}$  and  $^{228}\text{Ra}$ , which have the potential to release radon gas into the atmosphere when these radioactive nuclides are brought to the surface through the oil and gas extraction processes [3]. The long half-lives of these two radium isotopes ( $^{226}\text{Ra}$ , 1,600 years;  $^{228}\text{Ra}$ , 5.8 years) are particularly concerning given that they have been identified as abundant in saline and chloride-rich produced waters [4]. To date, few other radionuclides have been identified as associated with natural gas extraction, and fewer still have had regulatory guidelines developed for occupational or public health exposures.

Naturally occurring radioactive material (NORM) is terrestrial radiation distributed by nature throughout natural geologic formations. It is undisturbed radioactive material that exists in nature as background material, or at its in-situ location, whether at the earth’s surface or subsurface. TENORMs are when naturally occurring radionuclides are transported by anthropogenic activity to where humans are present, thereby increasing exposure potential, which may result in concentrations enhanced above natural background levels [5]. As such, NORM transported or concentrated during exploration and mining of oil and gas is thereby reclassified, according to regulatory definition, as TENORM.

Both NORM and TENORM are clearly defined and distinct from radionuclides that are produced through nuclear reactions, nuclear explosions or nuclear accelerators (commonly referred to as “man-made, artificial, or anthropogenic”). The term NORM is often misused when applied to radioactive material introduced into the human environment by oil and gas exploration and mining processes.

Estimates of water needed for unconventional natural gas extraction are reported to range from one to five million gallons per well for initial well completion [6]. The use of up to 12 million gallons per well completion (one million gallons per stage) has been documented for the 12-stage open-hole completion systems [7]. Disposal of large quantities of chemical- and radionuclide-laden materials in wastewater is a known problem [8]. Reserve pits are commonly

found in agricultural areas where the potential for crop and animal contamination is high. Animals drinking pit water, dust particles blowing onto soil and crops, and berms breaching (thus contaminating adjacent croplands) are all potential exposure pathways. If reserve pits are built with an aerator, aerosolized radioactive material can be further dispersed onto soil, crops, livestock, and humans. Deposition of reserve pit contents in county landfills and municipal water treatment facilities has elicited a public outcry of concern for environmental contamination and potential human exposure to harmful radioisotopes often present in the drilling mud and cuttings, since these facilities do not have the capability to test for or remove radioactive material from the waste stream [9-11]. Incorporation of reserve pit material into the earth's surface either by draining and leveling the reserve pit where it exists, and/or land farming the material into the ground in place or at other locations, may increase the potential for surface and drinking water contamination from percolation or migration of radionuclides into water bodies. A better understanding is needed to assess the potential effects that radionuclides may have on the health of cattle, on cattle productivity, and on agricultural products. The potential exposure to humans is from reserve pit contents via wind, and by consumption of crops and animal products that have taken up radioactivity, has not been established [12-17].

The purpose of this article is to present laboratory analysis of water and soil (sludge) analyzed for the presence of TENORM, obtained from two unrelated reserve pits located on agricultural land in the Barnett Shale (located in Texas) and used as holding ponds for unconventional natural gas mining and extraction processes. This study originated as part of a field study conducted as a preliminary exploratory investigation (Phase II) during a property transaction to ascertain if, in fact, any regulatory impact existed (such as the presence of radioactive materials in the reserve pits). Comparison of study findings to state and federal guidelines for TENORM material identifies the complexity in regulatory reporting and guidelines, and current voids in regulatory oversight.

## EXPERIMENTAL METHODS

### Field Sampling

Soil and water matrices from reserve pits in the core area of the Barnett Shale East Newark Field were obtained and analyzed for the presence of radionuclides (TENORM). Soil and water was collected from two separate site locations: 1) farmland that was once a reserve pit, which had been drained and leveled to the surrounding elevation; and 2) a reserve pit that, at the time of sampling, held drilling mud, water for hydraulic fracturing, processed water and/or cuttings. For the purpose of this report the drained reserve pit has been identified as Reserve Pit #1 (RP1) and the pit with fluid has been identified as Reserve Pit #2 (RP2). In total, four separate samples of water and soil were obtained, two from

each sampling location, and identified by the laboratory as sludge due to high water content. Water was collected in clear plastic 500-ml containers with no preservative. Two sample points were selected for each pit based on each pit's use and the most likely impact resulting from surrounding exploration and extraction activities.

Samples in RP1 were obtained at a soil depth of 6 inches from the soil surface, since the RP1 pit had been drained and appeared to have the greatest potential to be relatively homogeneous from initial field investigation. This reserve pit was originally constructed with above-ground berms without any surface discharge outlet. Water could be pumped into the pit from an adjacent water well and could flow out of the pit only via its natural down-gradient seepage. Two samples were obtained along a line following the direction of the pit's down-gradient groundwater flow, which ultimately intersected with a flowing creek located near to and down-gradient from the pit.

RP2 is a typical triangular ranch pond with the triangle base side perpendicular to the downgradient flow line of the pond. A surface flow outlet is located at the center of the downgradient side. The samples were taken inside of the pond. Since cuttings and drilling mud settle to the bottom of ponds, efforts were made to obtain sludge/sediment samples from the pit bottom of RP2 along with water. Impact to or from the pit appeared to occur at either end of this down-gradient side (i.e., at the corners). Flow gradients dictated exploration and production impact would occur at the corners and then would flow from these corners down-gradient to the outfall. A sample was taken at one corner and a second sample was taken at the upstream pond side of the outfall. RP2 samples were collected from the pond's floor on the down-gradient side of the pit.

Initial observations indicated that impact from well mining extraction and injection materials appeared to be located on the upgradient side of each pond's downhill side. This observed material in the pit was considered likely to be from the geologic formations mined and materials injected. All samples were shipped to a certified radiological laboratory (American Radiation Services, Inc., Port Allen, LA) for analysis of radioactive isotopes by EPA method 901.1M (ARS-007/EPA901.1M). Radioisotope concentrations were reported in picocuries/gram (pCi/g). Reserve pit contents were analyzed for the radionuclides beryllium ( $^7\text{Be}$ ), potassium ( $^{40}\text{K}$ ), scandium ( $^{46}\text{Sc}$ ), cobalt ( $^{60}\text{Co}$ ), cesium ( $^{137}\text{Cs}$ ), thallium ( $^{208}\text{Tl}$ ), lead ( $^{210}\text{Pb}$  and  $^{214}\text{Pb}$ ), bismuth ( $^{212}\text{Bi}$  and  $^{214}\text{Bi}$ ), radium ( $^{226}\text{Ra}$  and  $^{228}\text{Ra}$ ), thorium ( $^{228}\text{Th}$ ), uranium ( $^{235}\text{U}$ ), strontium ( $^{89}\text{Sr}$  and  $^{90}\text{Sr}$ ), and total gamma, total alpha, and total beta radiation.

This study was designed to be an initial investigative field study performed for an industrial land transaction decision. Samples were not randomized, but selected to represent the most likely worst-case down-gradient impact point. Analysis of a control sample was not performed or authorized. Soil sample results were compared to findings of previous studies and to regulatory limits. However, inconsistencies in collection and analysis of specific radioisotopes in

previous studies made comparison difficult and it was not easy to ascertain in many cases whether the samples exceeded expected baseline concentrations.

### **Reserve Pit #1 (RP1)**

The location identified as Reserve Pit #1 (RP1) had originally been part of a reserve pond, but at the time of sampling had been drained and leveled to the original ground surface grade. The original reserve pit was a manmade pond of approximately 2.9 acres, whose depth was increased with berms to a height of six to seven feet above ground level. Soil in the drained and leveled area sampled (RP1 location) appeared to have been undisturbed and the pond material allowed to drain and settle naturally, incorporating back into the existing soil rather than being removed and disposed of offsite. The RP1 sampling sites chosen were at one time the reserve pit bottom material. The remaining reserve pit was still present at the time of sampling and was still in use as a water reservoir for mining operations. Soil and water samples taken at this location were identified as RP1.1-West and RP1.2-East. The RP1.1-West sample was obtained approximately 15 feet from the edge of the existing pit berm, and the RP1.2-East sample was obtained approximately 75 feet from the edge of the existing pit berm. The purpose of obtaining soil from this location was to examine if any radioactivity in the soil existed after the reserve pit had been drained and the land left fallow. The adjacent land was used as agricultural land, which at the time of sampling was growing livestock feed. Field notes taken at RP1 locations identified the soil to be homogeneous black clay with very little organic matter and high water content, believed to be related to a precipitation event a few days prior to sampling. The U.S. Department of Agriculture Natural Resource Conservation Service defines black clay as having slow infiltration rates, high runoff potential when wet, and high shrink swell potential [18].

### **Reserve Pit #2 (RP2)**

At the time of sampling, Reserve Pit #2 was being used as a water reservoir for natural gas extraction and mining operations and was believed to have been used to hold drilling mud, processed water, water for hydraulic fracturing operations, and drill cuttings. RP2 encompassed approximately 11.3 acres. This pit was originally a manmade pond at ground level. The water level was high due to recent precipitation events with an area overflowing the banks of the pit into a neighboring stream. The overflow area led to a creek and had been graded and cemented to provide a controlled exit for overflow water to minimize water breaching the pit berm at various locations. Two separate samples were obtained at RP2: one was obtained inside the pit along the east edge at the overflow location (identified as RP2.1-North), inside the pit along the northeast edge; the second sample was obtained on the south end of the pit closest to the well pad site inside the pit (identified as RP2.2-South). The samples taken in

the reserve pit consisted of both water, obtained from approximately 6 inches below the surface, and soil, obtained approximately 3 feet from the berm edge at the bottom of the pit.

The soil matrix at RP2 location was varied, with the presence of dark grey sticky clay soil, commonly referred to as black clay soils on the exterior of the pit and a light yellowish brown clay soil mixed with high very fine sand (<1 mm diameter) interior to the pit [20].

Field notes taken at the RP2 location identified a noticeable lack of any insects, fish, turtles, snakes or birds present in the or around the pit. The pit contained water grasses and reeds which are optimum breeding and cover areas for fish, snake and bird activity but no activity or signs of any feeding, nesting, or breeding activity were apparent.

## RESULTS

Results of laboratory analysis of the four samples are presented in Table 1. The level of radioactivity is presented as pCi/g, and the minimum detection concentration (MDC) is the lowest concentration reliably detected by the laboratory equipment. The Analysis of Error is a numerical factor that represents error in the laboratory detection technique. This error factor is specific to each radionuclide and specific to each test. A zero is entered in the table if the radioactivity detected is below the MDC.

In general, specific radioisotopes detected included  $^{40}\text{K}$ , elements of the  $^{228}\text{Th}$  decay series ( $^{228}\text{Th}$ ,  $^{228}\text{Ra}$ , and  $^{208}\text{Tl}$ ), elements of the  $^{226}\text{Ra}$  decay series ( $^{226}\text{Ra}$ ,  $^{214}\text{Bi}$ ,  $^{214}\text{Pb}$ ,  $^{210}\text{Pb}$ ), and  $^{90}\text{Sr}$ . With the exception of total alpha radiation for RP2-North, varying levels of total alpha, beta, and gamma radiation were detected in all samples. Interestingly, different portions of the same pit showed some differences in the radioactivity present.

It is important to note that not all radioisotopes present in sample RP1.1-West were also present in sample RP1.2-East, despite their close proximity and presumed homogeneous material. At the time of sampling, both locations had a high water content in the soil due to a recent precipitation event that may have been a contributing factor to variability in radioisotope concentrations. Sample RP1.2-East had a greater variety of isotopes recorded above laboratory minimum detection. Some of the isotopes present in this study are known to have very short half-lives ( $^{214}\text{Bi}$ , 20 minutes;  $^{214}\text{Pb}$ , 27 minutes), and their presence is not easily captured. Their presence is likely to be due to the fact that they are part of a decay series and are continuously being generated. Other isotopes have longer half-lives and are more easily identified. In comparing results of the two RP1 locations, similar concentrations were noted for  $^{40}\text{K}$ ,  $^{208}\text{Tl}$ ,  $^{214}\text{Pb}$ ,  $^{228}\text{Ra}$ ,  $^{228}\text{Th}$ . Notably,  $^{210}\text{Pb}$  and  $^{90}\text{Sr}$  were found in the RP1.1-West sample but not in the RP1.2-East sample, while  $^{226}\text{Ra}$  was detected in the RP1.2-East sample but not the RP1.1-West sample. The gross gamma radiation (22.8 and 21.4 pCi/g),

Table 1. TENORMs Found in Reserve Pits

Isotope	RP1.1-west	RP1.2-east	RP2.1-north	RP2.2-soth
Beryllium ( <sup>7</sup> Be)	0 (0.45)	0 (0.48)	0 (0.45)	0 (0.53)
Potassium ( <sup>40</sup> K)	5.3 ± 1.3 (0.82)	5.5 ± 1.0 (0.41)	4.9 ± 1.1 (0.68)	3.6 ± 1.0 (0.67)
Scandium ( <sup>46</sup> Sc)	0 (0.076)	0 (0.078)	0 (0.064)	0 (0.58)
Cobalt ( <sup>60</sup> Co)	0 (0.090)	0 (0.064)	0 (0.10)	0 (0.69)
Cesium ( <sup>137</sup> Cs)	0 (0.086)	0 (0.062)	0 (0.72)	0 (0.62)
Thallium ( <sup>208</sup> Tl)	0.20 ± 0.07 (0.060)	0.27 ± 0.06 (0.041)	0.18 ± 0.06 (0.076)	0.19 ± 0.05 (0.04)
Lead ( <sup>210</sup> Pb)	1.7 ± 1.2 (1.4)	0 (0.94)	0 (1.1)	0.99 ± 0.65 (0.94)
Bismuth ( <sup>212</sup> Bi)	0 (0.56)	0 (0.46)	0 (0.56)	0 (0.54)
Bismuth ( <sup>214</sup> Bi)	0.45 ± 0.15 (0.17)	0.35 ± 0.30 (0.15)	0.36 ± 0.12 (0.15)	0.25 ± 0.12 (0.18)
Lead ( <sup>214</sup> Pb)	0.68 ± 0.63 (0.14)	0.70 ± 0.15 (0.14)	0.44 ± 0.12 (0.15)	0.40 ± 0.11 (0.13)
Radium ( <sup>226</sup> Ra)	0 (1.3)	2.4 ± 1.0 (1.2)	0 (1.5)	0 (1.1)
Radium ( <sup>228</sup> Ra)	0.66 ± 0.21 (0.26)	0.71 ± 0.13 (0.19)	0.51 ± 0.15 (0.25)	0 (0.24)
Thorium ( <sup>228</sup> Th)	0.72 ± 0.11 (0.087)	0.67 ± 0.11 (0.093)	0.64 ± 0.13 (0.12)	0.36 ± 0.10 (0.10)
Uranium ( <sup>89</sup> Sr)	0 (0.34)	0 (0.27)	0 (0.42)	0 (0.32)
Strontium ( <sup>89</sup> Sr)	0 (0.24)	0 (0.24)	0 (0.36)	0 (0.26)
Strontium ( <sup>90</sup> Sr)	0.30 ± 0.17 (0.24)	0 (0.24)	0.59 ± 0.26 (0.36)	0.29 ± 0.18 (0.26)
Total gamma	22.8	21.4	10.8	8.22
Total alpha	10.8 ± 3.3 (2.6)	16.4 ± 4.6 (3.1)	0 (3.6)	9.1 ± 3.4 (3.9)
Total beta	9.1 ± 2.5 (1.8)	5.7 ± 2.0 (2.3)	1329 ± 311 (5.0)	5.8 ± 1.8 (1.7)

<sup>a</sup>The level of radioactivity is given in pCi/g and is shown with the analysis error. The numbers in parentheses are the Minimum Detection Concentrations (MDCs). In cases where the radioactivity measured was less than the MDC, a value of 0 is entered.

gross alpha radiation ( $10.8 \pm 3.3$  and  $16.4 \pm 4.6$ ), and gross beta radiation ( $9.1 \pm 2.5$  and  $5.7 \pm 2.0$ ) were not significantly different in the two RP1 samples.

Similar results were seen in individual radioisotopes in the second reserve pit RP2.1-North and RP2.2-South samples.  $^{228}\text{Ra}$  was detected in RP2.1-North but not RP2.2-South, whereas  $^{210}\text{Pb}$  was observed in RP2.2-South but not RP2.1-North. Total gamma radiation was similar in the two samples, but gross alpha radiation was observed only in RP2.2-South.

The most unexpected result of this study was the difference identified in gross beta radiation within the same pond. Gross beta radiation in the RP2.1-North sample was considerably higher than in the South sample ( $1329 \pm 310$  vs.  $5.8 \pm 1.8$  pCi/g). The highest beta radiation levels were recorded near the spillway in pond RP2. Radionuclides are unstable isotopes of elements that undergo radioactive decay continually. Accumulation of sediment near the spillway may have accounted for the variability in beta radiation levels. Despite the close proximity of the soil samples within the pond, it is difficult to determine if the variability in concentrations reflects initial concentration in the soil, amount of material deposited in the pond, or lack of uniformity of soil chemistry. The fact that such variability can exist provides a complexity to single sample testing and may indicate that numerous samples within a single reserve pond are needed for accurate identification and quantification of TENORM, and proper representation of potential exposure to radioactive material.

## DISCUSSION

Routine field study analysis of reserve pit contents from unconventional natural gas mining confirmed the presence of alpha, beta, and gamma radiation in the soil and water in reserve pits located on agricultural land. The specific gamma-emitting radionuclides identified included  $^{40}\text{K}$ ,  $^{208}\text{Tl}$ ,  $^{210}\text{Pb}$  and  $^{214}\text{Pb}$ ,  $^{214}\text{Bi}$ ,  $^{226}\text{Ra}$  and  $^{228}\text{Ra}$ ,  $^{228}\text{Th}$ , and  $^{90}\text{Sr}$ . Total beta radiation of 1329 pCi/g found in this study exceeded regulatory guideline values by more than 800 percent. Data from this limited field study showed elevated levels of alpha, beta, and gamma radiation to be present in reserve pit water/sludge material and also in the soil of a vacated reserve pit after draining and grading to original topographic levels. Based on the use of the pit, the presence of radioactive materials was not anticipated. Agricultural land adjacent to the drained reserve pit may have an increased potential for radioactive material taken up in livestock feed crops growing on the land due to wind transport, runoff, and migration of soil onto adjacent land. Deposition of radioactive material on land has been shown to have the potential to raise the radiation levels in soils above natural background levels increasing the potential for contamination of groundwater, soil, animals (domestic and migratory), and humans (through occupational and residential exposures). Historically, background levels of naturally occurring radiation prior to land use have not been measured, and little information on true



background radiation actually exists. Texas has a long history of oil and gas exploration, which has involved the practice of land farming and surface deposition of mining material. Further, for decades, unrefined oil has been deposited on roadways for dust control. Assessment of true background radiation levels may not be possible given this historical misuse of the land. Total radiation was found to be elevated above known background levels for radiation, but information is limited and exposure pathways poorly understood. Regulatory guidance documents currently do not address many of the radionuclides found in this study and provide few directives and little guidance in determining the potential synergistic or additive effects of exposure to several radionuclides simultaneously, or the potential for an increased incidence of disease in animals or humans due to simultaneous multiple exposures. Expansion of urban drilling and the practice of siting reserve pits within residential communities will increase the potential for radiation exposure to the general public. Health complaints related to low-level radiation sickness, common to occupational workers, may be overlooked by medical professionals who do not anticipate an industrial-type exposure to patients living within these communities. Stricter guidelines may be warranted in order to protect the general public from increased levels of radiation in soil, water, and air.

### **Radionuclide Decay**

Radioactive decay releases three types of radiation: alpha ( $\alpha$ ), beta ( $\beta$ ) and gamma ( $\gamma$ ) emissions. All three types of radiation are known to present health hazards. The radionuclides in TENORM that present the most concern in the human environment due to potential health impacts are isotopes of radium, thorium, and uranium and their decay products.  $^{238}\text{U}$  decays by alpha emission into  $^{234}\text{Th}$ , and  $^{234}\text{Th}$  decays by beta emission to protactinium and then  $^{234}\text{U}$ .  $^{226}\text{Ra}$ ,  $^{214}\text{Bi}$ , and  $^{210}\text{Pb}$  are all daughter isotopes of  $^{238}\text{U}$ .  $^{234}\text{U}$  decays by alpha emission into  $^{230}\text{Th}$ , which decays by alpha emission into  $^{226}\text{Ra}$ , ultimately decaying by beta emission into products seen in this study:  $^{214}\text{Pb}$ ,  $^{214}\text{Bi}$ , and  $^{210}\text{Pb}$ .

### **Environmental and Health Impact of Exposure to TENORM**

There are numerous potential pathways of exposure to radioactive material from wastes extracted by natural gas exploration and mining. This study attempts to investigate only one form of waste, reserve pit contents. However, there are several potential pathways of exposure from this one waste form alone. The potential exposures to humans directly, whether occupational or residential, include: ground-water contamination, soil contamination, windborne particulates and aerosolized material, and fugitive air emissions from industrial processes. Another secondary potential exposure pathway exists in the ingestion of agricultural products (vegetables, dairy, and meat products) that may

contain these radionuclides. This is an area that has received little attention or investigation.

The complexity in examining potential exposure is in quantifying how much radiation one has been exposed to, and the dose absorbed due to the exposure, and in accurately assessing the potential health impacts from multiple pathways. In order to properly assess exposure, exposures to all forms of radiation (alpha, beta, gamma) as well as to specific radioisotopes must be quantified and a thorough human health risk assessment performed. This is rarely done unless concentrations of a single radionuclide, for which regulatory guidelines have been established, greatly exceed those guideline levels; and for many radionuclides, no regulatory guideline levels have been established. Since many radionuclides have not been identified to be present in reserve pit wastes until recently, regulatory guidelines have not been established for non-occupational exposure limits.

The radionuclides discussed below were found in the samples taken in this study. Evaluating the potential health impacts of each radionuclide individually is important, in addition to evaluating the total decay (alpha, beta, and gamma) radiation, as the target organs and sites of damage can differ.

#### *Health Effects of Potassium ( $^{40}\text{K}$ )*

Potassium can be taken into the body through ingestion (food or water) or inhalation.  $^{40}\text{K}$  is a naturally occurring radioisotope of potassium and widely distributed in nature (although normally at very low levels—0.015% in soil). It has a very long half-life of 1.3 billion years and decays primarily to  $^{40}\text{Ca}$  by beta emission. External exposure to  $^{40}\text{K}$  is generally to gamma radiation as  $^{40}\text{K}$  decays to  $^{40}\text{Ar}$ . Internal exposure to  $^{40}\text{K}$  can pose a health hazard from ionizing beta and gamma emissions as it decays, with the potential to cause cell damage [19].

#### *Health Effects of Radium ( $^{226}\text{Ra}$ , $^{228}\text{Ra}$ )*

According to a U.S. Geological Survey (USGS) study (2009), little data exists on natural background concentrations of radium in the environment. Levels have been documented to increase as a result of human activity [20]. Radium levels in drinking water can become elevated in areas of mining. Exposure to radium may result in a variety of health effects such as tooth fractures, anemia, and cataracts. Chronic exposure to radium is known to increase the incidence of cancer in humans [21, 22]. Gamma radiation from radium is able to travel long distances through air before expending its energy, thus increasing exposure to the general population [23]. Radium is the radionuclide on which most of the drinking water and air regulations are set. It is the primary radionuclide identified in the past as a potential source of exposure to radon, a decay product of radium and a known lung carcinogen.

*Health Effects of Strontium (<sup>90</sup>Sr)*

<sup>90</sup>Strontium is a manmade isotope of strontium. <sup>90</sup>Sr is used as a subsurface radioactive tracer in mining processes and has a half-life of 29.1 years [24]. It is also present at low levels in surface soil due to fallout from previous atmospheric nuclear tests. It is hydrophilic, easily moving into and through the environment, adding to its ability to contaminate aquifers and drinking water sources [25]. It is known to be dangerous to the health of animals and humans. Exposure to <sup>90</sup>Sr can occur by inhalation of dust, eating food, or drinking water contaminated with the radionuclide. Grains, leafy vegetables, and dairy products can contain significantly high levels of <sup>90</sup>Sr [26]. The primary target organ for <sup>90</sup>Sr is bone. Strontium competes with calcium taken up in bone and can damage bone marrow, causing anemia. It can also cause cancer as a result of damage to cellular genetic material [27].

*Health Effects of Thallium (<sup>208</sup>Tl)*

Thallium is absorbed by the human body through inhalation of dust particles and through ingestion of food and water. The nervous system is the primary target organ for thallium, which is known to cause trembling, nerve pains, paralysis, and behavioral impacts. Tiredness, depression, lack of appetite, and hair loss are all symptoms of chronic low-level Tl exposure. Thallium exposure to the fetus has been known to cause congenital disorders [28].

*Health Effects of Thorium (<sup>228</sup>Th)*

Inhalation of thorium can adversely impact the respiratory system, causing damage that can eventually culminate as lung cancer. Exposure to thorium is known to cause pancreatic cancer, and thorium can be stored in bone, leading to bone cancer years after the initial exposure. People living in industrial areas near hazardous waste sites and near waste materials may be exposed to higher concentrations of thorium from wind-blown dust and consumption of food contaminated by the radionuclide [29].

*Potential for Plant and Animal Exposure to TENORM*

Contamination of soil and water from TENORM can expose workers and the general public to increased levels of radiation above normal background levels. Other important aspects of environmental contamination are through radiation taken up by the soil-plant system and exposure to animals through feedstock. Radionuclides in the soil can be directly intercepted by crops, which are then used as livestock feed, further increasing the potential for human exposure to increased levels of radiation through ingestion of milk and meat products.

In 2009, the U.S. Fish and Wildlife Service identified the importance of protecting migratory birds from exposure to reserve pit contents which can

contain diesel, glycols, and heavy metals, but failed to recognize the potential for bird populations to be exposed to radioactive material deposited in reserve pits [30]. Some states with oil and gas regulations recommend netting or screening of pits or open tanks to prevent contamination of birds and wildlife. For example, Texas Administrative Code, Title 16, Part 1, Chapter 3, Rule §3.22(b) Protection of Birds requires that an operator “screen, net, cover or otherwise render harmless to birds” specific tanks and pits with “frequent surface film or accumulation of oil,” but does not address the potential exposure of birds or cattle to radioactive materials. Proper reserve pit management techniques include fencing cattle out of areas to prevent livestock from drinking reserve pit contents. Consumption of reserve pit fluids by livestock has been documented to cause poisoning, abortions, birth defects, weight loss, contaminated milk, and death [31, 32].

Proper public health protection may involve stringent quality controls upon agricultural and farm practices, to prevent exposure to reserve pit waste materials, and controls on harvest and food movement to prevent exposures to workers and the public. The presence of radioactive materials in agricultural soils and food products can create financial hardship and a significant psychological impact for communities whose economic base consists of agricultural and food products. Many of the radionuclides have long half-lives, which can result in contamination of the soil for decades. This ultimately could affect the marketability of both the land and any products produced from the land for decades.

### **Federal Regulatory Oversight**

Neither the U.S. Environmental Protection Agency (EPA) nor the U.S. Nuclear Regulatory Commission (NRC) has established federal regulations that directly govern NORM waste from the oil and gas industry. In fact, wastes containing NORM are generally not regulated by federal agencies with one exception, transportation. NORM-containing wastes with a specific activity greater than 2,000 pCi/g (70 Bq/g) are subject to U.S. Department of Transportation (DOT) regulations governing transport of radioactive materials [33]. The Occupational Safety and Health Administration (OSHA) has promulgated rules specific to occupational exposure to ionizing radiation [34], which may be applicable to petroleum industry NORM management activities.

By definition, oil and gas industry NORM that does not exceed 0.05 percent uranium or thorium by weight or any combination, is not subject to regulatory control under the Atomic Energy Act of 1954 due to the fact it is not a source material, special nuclear material, or by-product material [35].

The Low-Level Radioactive Waste Policy Act as amended in 1986 provides guidance to states on disposal of low-level radioactivity material, like the waste material generated from oil and gas activities, but does not include oil

and gas NORM waste. NORM wastes generated during the exploration, development, and production of crude oil, natural gas, and geothermal energy have been categorized by the EPA as “special wastes” and are currently exempt from federal hazardous waste regulations under Subtitle C of the Resource Conservation and Recovery Act (RCRA) by the Beville Amendment and are not considered a listed or characteristic waste. The Superfund Amendments and Reauthorization Act listed none of the constituents of NORM as “extremely hazardous substances.” The Comprehensive Environmental Response, Compensation and Liability Act (CERCLA) lists radionuclides as hazardous substances because the CAA (Clean Air Act) lists them as hazardous air pollutants. Oil and gas waste streams that may contain NORM are exempt under RCRA and therefore considered not hazardous substances under CERCLA, although individual radioisotopes might be. Reportable Quantities (RQs) are one pound of radionuclides (cumulative), or concentrations expressed in curies for individual radionuclide, whichever is less (40 CFR 302.4).

In 1989 EPA issued a final regulation covering RQs for radionuclides. EPA used 1, 10, 100, 1000, and 5000 pounds as RQs for non-radionuclides and 0.001, 0.01, 0.1, 1, 10, 100, and 1,000 Curies (Ci) as RQs for radionuclides. Release values for approximately 760 radionuclides were calculated for each of four human health intake pathways. The lowest pathway release value for each radionuclide was selected and then rounded down to the nearest decade to set the RQ for each radionuclide. Radionuclides not having published intake limits were assigned an RQ of 1 Ci, based on the observation that 91 percent of the radionuclides being studied were below the 1 Ci level [36]. These RQ are not applicable to oil and gas exploration as a result of the RCRA Beville Amendment and its relationship to CERCLA.

The EPA under the CAA developed National Emission Standards for Hazardous Air Pollutants (NESHAPs) specific to radionuclide emissions for several sources, but not for industrial activities that include NORM generated by the oil and gas industry.

The EPA under the provisions of the Safe Drinking Water Act (SDWA) regulates the following radionuclides in drinking water: (adjusted) gross alpha emitters, beta particle and photon (gamma) radioactivity,  $^{226}\text{Ra}$  and  $^{228}\text{Ra}$  (combined), and uranium. The EPA established drinking water standards for several types of radioactive contaminants:  $^{226/228}\text{Ra}$  (5 pCi/L); beta emitters (4 mrem); gross alpha standard (15 pCi/L); and uranium (30  $\mu\text{g/L}$ ).

### State Regulatory Oversight

NORM is subject primarily to individual state radiation control measures and varies across the nation. “Section 651(e) of the Energy Policy Act of 2005 gives NRC jurisdiction over discrete sources of NORM by redefining the definition of source material” [37]. For example, the State of Texas has three

agencies are responsible for regulating different aspects of NORM. In Texas, NORM is regulated under the Texas Radiation Control Act (TRCA) as follows:

- The Texas Department of State Health Services (TDSHS), Radiation Control, has jurisdiction over the receipt, possession, use, treatment and storage of NORM (TDSHS NORM Licensing).
- “The Railroad Commission of Texas (RRC) has jurisdiction of handling and disposal of NORM wastes produced during the exploration and production of oil and gas (RRC rules for NORM)” [37], and disposal by the owner through on-site land farming and/or injection well. “The Texas Commission on Environmental Quality (TCEQ) has jurisdiction over the disposal of other NORM wastes” [37].

Under such a system, the Texas Administrative Code (TAC) defines exemptions for persons (parties/agencies) who receive, possess, use, process, transfer, transport, store, and commercially distribute NORM; that is, an exemption does not need to be licensed or is not regulated since NORMs are not hazardous waste streams. Often these exemptions are based on the NORM concentration of the waste stream being below a certain activity level (pCi/g) or radiation level (microRoentgens per hour  $\mu\text{R/hr}$ ). Radium radionuclides are generally the measured standard for multiple radionuclide waste streams, while a higher exemption threshold is used for an individual radionuclide. This system requires the determination of nuclide concentration or emission only when a disposal permit is sought. Ponds used to store and receive waters from drilling, well rework, and hydraulic fracturing operations can be filled without determining radionuclide release or impact since they are not technically considered hazardous waste and no disposal permit is required.

The environmental management of lands contaminated with naturally occurring radioactive materials will require threshold guidance levels to be established to indicate when action is required. Successful management will need federal and state authority to enforce such threshold guidance levels. Unless regulatory loopholes are closed, testing, monitoring, and reporting of radionuclide release to the environment above existing background will continue, resulting in more human and environmental exposure. Guidelines for NORM/TENORM should correspond to levels of naturally occurring radionuclides in the environment at which it is practical to distinguish the radionuclides resulting from human activities from those in the undisturbed natural background. In 2008, the National Council on Radiation Protection and Measurements summarized the issue of radiation exposure and public health in the following statement: “There is a need to address public health concerns and to provide guidance on the cleanup and potential reuse of lands contaminated with NORM or technologically-enhanced NORM (TENORM). Although there are environmental cleanup standards in place for manmade radioactive contamination, there are no consistent federal or state regulatory controls or environmental

management policies for NORM or TENORM contamination resulting from industrial practices associated with processing natural metal and mineral resources” [35].

### Recommendations

Historically,  $^{226}\text{Ra}$  and  $^{228}\text{Ra}$  have been tested for in water and guidance levels set with the intention of protecting people from exposure to radon gas. The findings of this study raise the question of whether radium, a single radionuclide, is the proper indicator for assessing radiation exposure levels to the general public, given the potential for the vast amount of radioactive waste, and number of radionuclides, produced from oil and natural gas exploration and mining that may be present in reserve pits. Current regulations require that  $^{226}\text{Ra}$  and  $^{228}\text{Ra}$  combined exposure levels not exceed 5 pCi/g, averaged over 100 m<sup>2</sup>, identifying radon as the primary emission of concern [39]. The Texas RRC Commission can issue a permit for the burial of oil and gas NORM waste “if, prior to burial, the oil and gas NORM waste has been treated or processed so that the radioactivity concentration does not exceed 30 pCi/g  $^{226}\text{Ra}$  and  $^{228}\text{Ra}$  or 150 pCi/g of any other NORM nuclide” [40]. These limits were not established with the support of public health/medical professionals nor based on potential human health impacts of cumulative exposures to multiple radionuclides. The total beta radiation found in one sample (RP2.1-North) of this study of 1329 pCi/g exceeds regulatory guideline values by more than 800 percent. However, individual radionuclides did not exceed existing regulatory guidelines. Data from this limited field study showed that elevated levels of alpha, beta, and gamma radiation were present in reserve pit water/sludge material and also in the soil of a decommissioned reserve pit. Evaluating the single radionuclide radium as regulatory exposure guidelines indicate, rather than considering all radionuclides, may indeed underestimate the potential for radiation exposure to workers, the general public, and the environment.

Limitations to this study include the small sample size and limited analysis of reserve pit contents. The study does not make the assumption that all reserve pits contain radioactive materials. The study does not imply that all reserve pit contents are disposed of by land farming (either onsite or offsite) or postulate the extent to which contaminated material is incorporated back into the earth. Comparison of radionuclide levels found in this study to existing regulatory levels was difficult since regulatory guidelines have been established for only a few radionuclides. Furthermore, TENORM waste has been excluded from many regulatory guidelines and from regulatory oversight. Future studies are needed to evaluate what percentage of reserve pits are actually used for deposition of radioactive materials. Further studies are needed to understand how radioactive materials transfer to vegetation and animal products and the uptake mechanisms of those materials through the food chain. The long half-lives that

are intrinsic to many radionuclides are a major concern for future generations. Further research needs to be done to understand what exposure levels can be anticipated given the complex interactions within the physical and chemical components of soil and the lack of uniformity of soil chemistry.

As the United States goes forward with the expansion of drilling natural gas reservoirs (especially drilling in shale, which requires hydraulic fracturing with millions of gallons of water and producing nearly equal amounts of flowback), it is imperative that we obtain better knowledge of the quantity of radioactive material and the specific radioisotopes being brought to the earth's surface from these mining processes. Proper regulation of surface deposits and disposal of wastes can prevent elevation of natural levels of radiation and increased exposure of animals and humans to potentially harmful levels of radioactivity. It is essential that the public health community be consulted when establishing future regulatory guidelines. Materials classified as exempt under current regulations should be reviewed given the potential for adverse health effects from radiation exposure to the general public and with continued growth of urban drilling.

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*Features*

**COMMUNITY-BASED RISK ASSESSMENT OF  
WATER CONTAMINATION FROM HIGH-VOLUME  
HORIZONTAL HYDRAULIC FRACTURING**

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**ABSTRACT**

The risk of contaminating surface and groundwater as a result of shale gas extraction using high-volume horizontal hydraulic fracturing (fracking) has not been assessed using conventional risk assessment methodologies. Baseline (pre-fracking) data on relevant water quality indicators, needed for meaningful risk assessment, are largely lacking. To fill this gap, the nonprofit Community Science Institute (CSI) partners with community volunteers who perform regular sampling of more than 50 streams in the Marcellus and Utica Shale regions of upstate New York; samples are analyzed for parameters associated with HVHFF. Similar baseline data on regional groundwater comes from CSI's testing of private drinking water wells. Analytic results for groundwater (with permission) and surface water are made publicly available in an interactive, searchable database. Baseline concentrations of potential contaminants from shale gas operations are found to be low, suggesting that early community-based monitoring is an effective foundation for assessing later contamination due to fracking.

**Keywords:** high-volume horizontal hydraulic fracturing, groundwater contamination, certified baseline testing, volunteer stream monitoring partnerships, fracking

The risk of contaminating surface water and groundwater as a result of shale gas extraction activities utilizing high-volume horizontal hydraulic fracturing (HVHMF) technology has not yet been assessed [1]. An abundance of evidence suggests that contamination can and does occur, including academic studies [2, 3], agency reports [4], accidents [5,6], regulatory violations [7, 8], interviews with sick homeowners near gas well pads [9, 10], and out-of-court settlements with confidentiality agreements between homeowners and gas companies [11]. There is also evidence to suggest that contamination may occur along natural subsurface pathways and not necessarily as a consequence of HVHMF [12]; however, probability bounds analysis points to disposal of HVHMF waste as the greatest risk to water [13]. Despite abundant indications of adverse effects on human health and the environment, conventional risk assessment methodologies have not yet been applied to the shale gas industry, and this has resulted in a void in public health protection on the part of the state and federal governments [14]. Here we explore one possible reason for this void: a lack of government data on water quality. We describe how rural homeowners and communities in New York's Southern Tier region are attempting to fill data gaps and create baselines for risk assessment purposes before HVHMF is approved in New York.

The nonprofit Community Science Institute (CSI) was founded in 2000 and has operated a state-certified water quality testing laboratory in Ithaca, New York, since 2003 (New York State Department of Health–Environmental Laboratory Approval Program (NYSDOH-ELAP) ID# 11790). With financial support from local governments in Tompkins County, CSI partners with seven groups of volunteers who perform synoptic sampling of Cayuga Lake tributary streams— that is, volunteers collect samples at specified locations within a few hours of one another, allowing comparison of water quality values throughout the area sampled. These volunteers collect approximately 350 samples a year and transport them to the CSI lab, where they are analyzed for bacteria, phosphorus and nitrogen nutrients, suspended sediment, minerals, and other parameters. Results are made publicly available in an interactive, searchable data archive at [www.communityscience.org/database](http://www.communityscience.org/database), which currently contains over 30,000 certified water quality data items. We have been recruiting, training, and providing technical support for community groups to conduct long-term baseline stream monitoring in New York's gas-rich Southern Tier region since 2010. Further, with the prospect of HVHMF in New York, CSI began offering pre-drilling baseline testing of private drinking water wells in 2009. The existence of pre-drilling data should make it possible to detect whether groundwater and surface water are impacted by HVHMF and to begin the essential task of conducting formal risk assessments using methodologies that are widely accepted in the public and private sectors [15-17].

## METHODS

For the Cayuga Lake watershed, surface water samples (from Six Mile Creek and its tributaries) were analyzed for parameters including a set of gas well “signature chemicals.” For the Upper Susquehanna River Basin, samples from Catatonk Creek and Cayuta Creek were analyzed for “red flag” indicators of water quality. Finally, samples of untreated groundwater, collected by CSI from private wells across the Utica and Marcellus Shale regions within New York, were analyzed for gas well “signature chemicals.”

### Streams in Cayuga Lake Watershed

Trained groups of volunteers perform synoptic sampling of Cayuga Lake tributary streams independently of each other up to five times per year under base-flow and stormwater conditions ( Figure 1). Data collection began between 2002 and 2009, depending on when a monitoring group was established for a tributary of Cayuga Lake. Each group collects grab samples at four to 23 fixed locations, depending on the size of the watershed. Volunteer teams deliver samples to the CSI lab in Ithaca with chain-of-custody documentation. Certified analyses are performed within prescribed holding times and using methods approved by NYSDOH-ELAP. Certified results are posted in CSI’s online searchable data archive at [www.communityscience.org/database](http://www.communityscience.org/database). While focused primarily on impacts from agriculture and residential development, such as nutrients and pathogenic bacteria, Cayuga Lake watershed monitoring also includes a number of parameters that overlap with gas well “signature chemicals”: pH, alkalinity, total hardness, turbidity, total suspended solids, chloride, and specific conductance. Monitoring of Cayuga Lake tributaries is guided by a Quality Assurance Project Plan (approved by the New York State Department of Environmental Conservation (NYSDEC)).

Expanded monitoring of gas well “signature chemicals” in the Cayuga Lake watershed began in 2012, with financial support from the Tompkins County Legislature. Volunteer teams collect additional samples once a year at a subset of their regular synoptic monitoring locations for certified laboratory analyses of barium, strontium, gross alpha and gross beta radioactivity, total dissolved solids, chemical oxygen demand, sulfate, and methylene blue active substances (MBAS) (anionic surfactants). The list of “signature chemicals” recommended by CSI to screen for gas well impacts on surface water quality is similar to that for groundwater quality (as listed in Table 7 below) and is based on general knowledge of HVHFF technology and on analyses reported in the NYSDEC’s 2011 draft Supplemental Generic Environmental Impact Statement of the frequencies and concentrations of chemicals in flowback from gas wells in Pennsylvania and West Virginia [18]. A moderate degree of redundancy is included, such that screening for several of the major characteristics of flowback

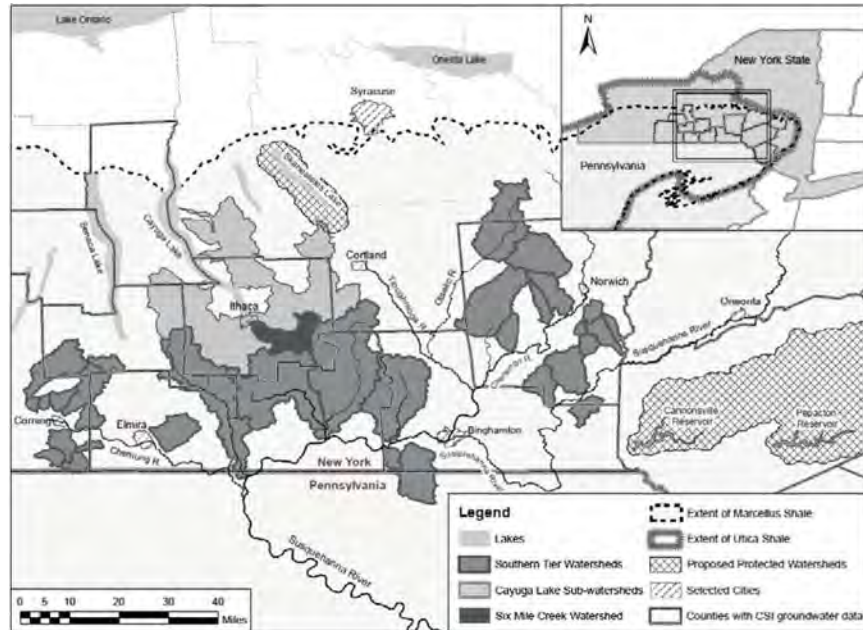


Figure 1. Map showing CSI-volunteer baseline water quality monitoring activities in the Marcellus and Utica Shale regions. Shaded areas are watersheds where volunteers monitor streams in the Finger Lakes and Upper Susquehanna River regions. The 13 counties where CSI has collected groundwater data from private drinking water wells and where clients have given permission to incorporate their results into CSI's regional groundwater baseline are shown in outline. The crosshatched areas—so-called Proposed Protected Watersheds—are areas feeding unfiltered drinking water systems in Syracuse and New York City where the New York State Department of Environmental Conservation proposes to exclude high-volume hydraulic fracturing per Section 6.1.5.4 in its 2011 draft Supplemental Generic Environmental Impact Statement, which states that “high volume hydraulic fracturing operations within the NYC and Syracuse watersheds pose the risk of causing significant adverse impacts to water resources” [18].

is based on two or more related tests. Streams are not tested for methane and volatile organic compounds (VOCs) as concentrations are expected to be low and difficult to detect due to volatilization.

### Streams in Upper Susquehanna River Basin

CSI initiated a “red flag” volunteer stream monitoring program in 2010, training and partnering with groups of volunteers in several Southern Tier counties where HVHFF is most likely to take place if approved in New York

(Figure 1). Groups of 15 to 30 of these volunteers monitor local streams that together drain 250 to 400 square miles. Each group is organized in teams of two to six, and each team takes responsibility for monitoring a specific set of stream locations once a month for five red-flag indicators of water quality: temperature, pH, dissolved oxygen, specific conductance, and total hardness. Teams are required to calibrate their portable test kits and meters prior to each monitoring event, using standards provided by the CSI lab, and to perform at least one set of duplicate tests for each red-flag indicator. Teams submit original field data sheets to CSI in hard copy. Results that meet data quality criteria for accuracy and precision (Table 1) are entered in the open searchable data archive on the CSI website. For added quality control, red-flag groups are asked to split all samples with CSI's certified lab during the first two months of their monitoring program, and one sample per team per quarter thereafter. Groups are encouraged to seek funding from local sources and to contract with CSI or a local certified lab to conduct expanded baseline testing of gas well "signature chemicals" at as many stream locations as possible at least once a year, similar to the expanded baseline testing in the Cayuga Lake watershed made possible by the Tompkins County Legislature.

Stream water quality data presented for comparison with CSI data (see Tables 2, 3, and 4) were extracted from the U.S. Geological Survey's (USGS's) National Water Information System (NWIS) and the U.S. Environmental Protection Agency's (EPA's) STORET (STORage and RETrieval) Data Warehouse. All data were filtered to extract only base flow sampling events. The NWIS data available for Six Mile Creek were from three sites on the main stem and two sites on tributaries. STORET data were for four sites in the Catatonk Creek watershed and five sites in the Cayuta Creek watershed.

### **Groundwater in the Marcellus and Utica Shale Regions**

CSI's certified lab offers fee-for-service baseline testing of private residential wells for gas well "signature chemicals" in groundwater. Baseline testing provides a form of insurance for homeowners in the event their water supply is contaminated and the contamination can reasonably be traced to nearby shale gas extraction activities. Clients are advised that the recommended baseline is designed as a broad screen that attempts to balance cost against the probability of identifying a "chemical signature" of gas well contamination, and that more extensive testing for specific carcinogenic, neurotoxic, teratogenic, endocrine-disrupting, and radioactive chemicals is indicated if post-drilling changes in results for some, but not necessarily all, "signature chemicals" provide reasonable evidence that contamination has occurred. Residential groundwater well samples are collected by CSI staff onsite, at a point that precedes any treatment system, such as a filter or a water softener, with chain-of-custody documentation to the CSI lab and subcontract labs.



Table 1. CSI Acceptance Criteria<sup>a</sup> for “Red-Flag” Stream Monitoring Results Reported by Volunteer Teams on Hard-Copy Field Data Sheets

	Temperature (°C)	pH <sup>b</sup>	Dissolved oxygen <sup>c</sup> (mg/L)	Specific conductance <sup>d</sup> (μS/cm)	Total hardness <sup>e</sup> (mg CaCO <sub>3</sub> /L)
Precision— acceptance of reported duplicates	± 1°C	± 0.5 pH Units	Greater of ± 20% or 0.4 mg/L <sup>c</sup>	± 10%	Greater of ± 20% or 8 mg/L <sup>e</sup>
Accuracy— acceptance of reported standards	Calibration <sup>f</sup>	± 0.5 pH Units	No calibration necessary <sup>c</sup>	± 1%	± 20% <sup>e</sup>
Splits—comparison with certified lab	N/A	N/A <sup>b</sup>	N/A <sup>c</sup>	± 20% <sup>d</sup>	± 20% <sup>e</sup>

<sup>a</sup>Red-flag teams of two to five volunteers typically monitor five or fewer stream locations once a month. For quality control, teams are required to perform one standard and/or one duplicate, depending on the analyte. Quality controls are performed once per monitoring event. Red-flag teams are required to split samples with CSI at the rate of one location per quarter, or four splits per year, for certified analyses of specific conductance and total hardness. In the first months of a new red-flag monitoring program, volunteer teams are required to split one sample from every location in order to establish baselines for specific conductance and total hardness and to facilitate trouble-shooting by CSI staff if the team is having difficulty performing the tests.

<sup>b</sup>pH is measured streamside using a wide range pH test kit accurate to 0.5 pH units over the pH range 3.0 to 10.5, LaMotte code 5858, or a hand-held meter, Hanna Instruments model HI98103. The CSI lab provides volunteer teams with an unlimited supply of pH 7.0 standard. Split samples are analyzed if requested by volunteers and if split is received by lab for analysis within 48 hours of sample collection as the frequency of spontaneous changes in pH is observed to increase after 48 hours.

<sup>c</sup>Dissolved oxygen is measured using test kit, LaMotte code 5860-01, based on the modified Winkler method approved by EPA. Test is accurate if performed correctly. Measurement range for titrator is 0.2-10.0 mg/L and is readily extended to higher concentrations by continuing to add titrant until the endpoint is reached. Limit of quantitation (sensitivity) is 0.4 mg/L or two times the smallest unit of measurement on the titrator. Results are considered reportable to the limit of quantitation, assuming quality control criteria are met, consistent with certified lab protocol. At low concentrations, precision is acceptable if duplicates agree within the limit of quantitation, 0.4 mg/L. Split samples are analyzed if requested by volunteers and if split is fixed streamside and received by lab within 8 hours of sample collection, as per EPA protocol.

<sup>d</sup>Specific conductance is measured using Hanna Instruments hand-held meter model HI 98303, range 1 to 1,999 μS/cm. CSI lab provides volunteer teams with an unlimited supply of 353 NTU specific conductance standard. Volunteer teams may hold stream samples at 4°C and perform the specific conductance test up to 28 days after sample collection, as per certified lab holding time.

<sup>e</sup>Total Hardness is measured using LaMotte kit 4482-DR-LT-01. Measurement range for titrator is 4 to 200 mg/L as calcium carbonate equivalents (CCE) and is readily extended to higher concentrations by continuing to add titrant until the endpoint is reached. Limit of quantitation (sensitivity) is taken to be 8 mg/L CCE, or two times the smallest unit of measurement on the titrator. Results are reportable to the limit of quantitation, assuming quality control criteria are met, consistent with certified lab protocol. At low concentrations, precision is acceptable if duplicates agree within the limit of quantitation, or 8 mg/L CCE. The CSI lab provides teams with an unlimited supply of 100 mg/L CCE or 20 mg/L CCE total hardness standard, depending on sampling sites. Teams may hold samples at 4°C and perform the total hardness test up to 14 days after sample collection, as per certified lab holding time.

<sup>f</sup>Volunteers are instructed to calibrate their thermometers based on the temperature of boiling water equal to 100°C.

While onsite, CSI staff ask clients for voluntary written permission to incorporate their test results in CSI's data pool on groundwater quality in the Marcellus and Utica Shale regions in upstate New York. Approximately 85 percent of clients have granted permission to date. Groundwater data will be incorporated into CSI's online interactive data archive by 2013. Data will be pooled in one-mile grid squares to protect homeowners' privacy. Each grid square will link to 20 separate graphs, one for each "signature chemical" (Figure 2). The grid squares will allow chemical concentrations to be mapped, providing enough information to spot spatial trends in "signature chemicals" relative to nearby gas wells or other potential sources of contamination, while protecting homeowners' privacy. As the map in Figure 2 shows, sample wells tend to occur in loose clusters, probably because private clients often find out about CSI through word of mouth, and because CSI splits travel costs among clients whose wells we sample in the same area on the same day. Other than splitting travel costs, CSI does not offer financial incentives. Clients pay 100 percent of the cost of baseline tests themselves. Therefore, pooled groundwater results comprise a near-random sample of groundwater quality in the Marcellus and Utica Shale regions in rural Southern and Central New York.

Groundwater quality data for New York State were downloaded from NWIS from 1990 to September 2012. ArcGIS [19] was used to select groundwater sampling sites in the area of New York State underlain by the Utica and Marcellus shale gas formations. Within the shale gas formations, a subset of sites was selected that corresponds more closely with the 13 counties in upstate New York where CSI has performed baseline testing on private wells: Otsego, Tompkins, Chenango, Delaware, Steuben, Tioga, Schuyler, Broome, Chemung, Yates, Schoharie, Seneca, and Sullivan. Results were averaged if a well was sampled more than once. A geographic information system (GIS) layer representing urban centers, residential areas, and industrial zones was created as a way to evaluate the distribution of the USGS's groundwater monitoring sites.

### **The CSI Database: A Tool for Community-Based Risk Assessment**

Placing water quality data in the public domain and facilitating its analysis and use by stakeholders is central to the Community Science Institute's nonprofit mission of empowering communities to understand local water resources and manage them sustainably. The CSI data archive at [www.communityscience.org/database](http://www.communityscience.org/database) is an integral feature of community-based risk assessment because it makes it possible for any member of the public, free of charge, to view, search, download, and analyze surface water data developed in collaboration with our volunteer stream monitoring groups as well as groundwater data belonging to our private clients who voluntarily agree to include their test results in CSI's anonymous groundwater data pool. CSI's database structure has evolved from a

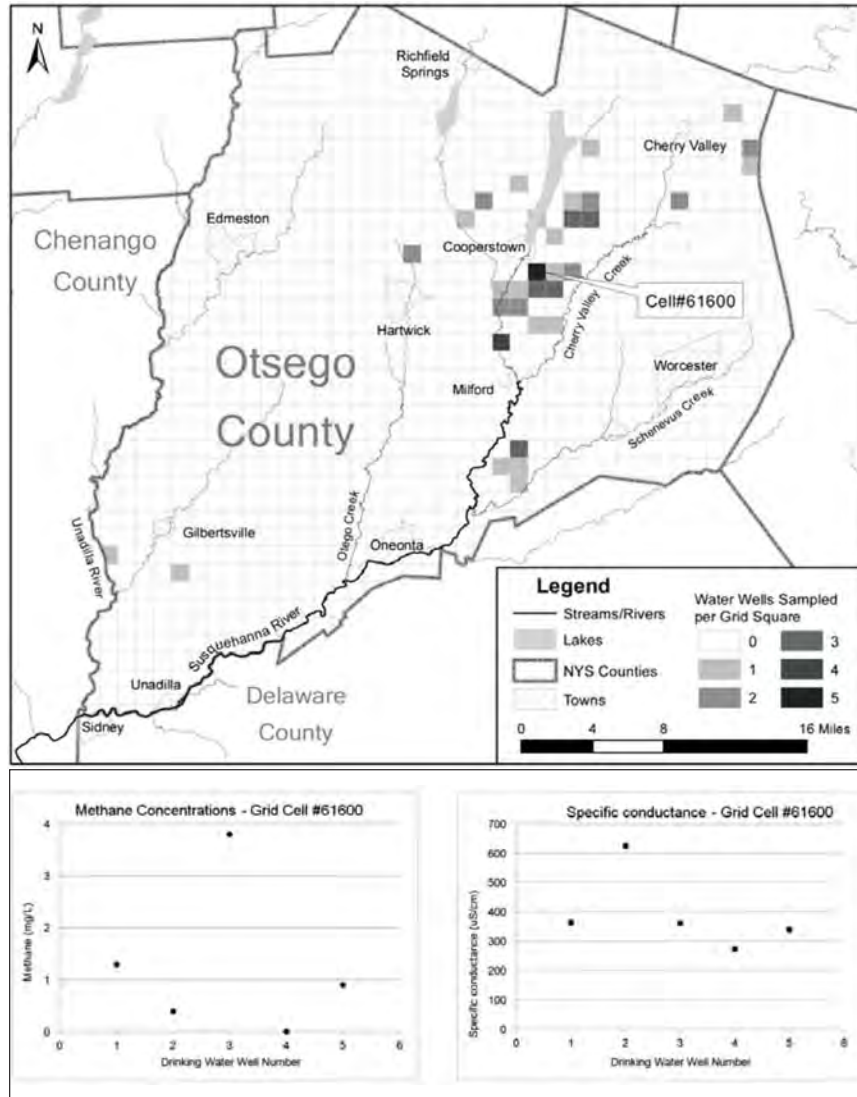


Figure 2. Example map and graphs illustrating presentation of regional groundwater baseline data planned for CSI website in 2013. The drinking water wells sampled by CSI in Otsego County are aggregated by one-mile grid square (total wells = 65). Methane and specific conductance data are grappled for one-mile grid square #61600.

Microsoft Excel-based approach, to a web-based architecture using the PHP scripting language and an SQL database back-end, and finally since 2011 to a Ruby on Rails® platform, chosen for its efficiency in building web applications. Visitors are provided with interactive tools to access over 30,000 data items linked to maps and graphs and to use a powerful querying mechanism to search the archive and export raw data. As a scalable archive, the CSI database is capable of organizing and presenting surface water and groundwater data from geographic areas of any size, including individual monitoring locations, watersheds, regions, countries, and continents. One hundred percent of the raw data produced by volunteer-CSI stream monitoring partnerships is made available to the public on the CSI website. Surface water data is searchable by region, stream, location, date, “signature chemical,” and flow conditions. Pooled groundwater data shared by private clients will be incorporated into the database by 2013. Groundwater data will be searchable by region, county, one-mile grid square and “signature chemical” (see Figure 2).

## RESULTS AND CONCLUSIONS

### Surface Water Monitoring in Partnership with Groups of Trained Volunteers

#### *Streams in Cayuga Lake Watershed*

Baseline stream monitoring for an expanded list of gas well “signature chemicals” is in progress at this writing (October 2012). As noted above, although CSI’s volunteer monitoring partnerships in this watershed since 2002 have focused on impacts from agriculture and residential development, there is some overlap between CSI’s traditional sampling parameters and gas well “signature chemicals.” Beginning in 2012, additional gas well “signature chemicals” are being tested once a year at a subset of Cayuga Lake watershed monitoring locations (see Methods). As a representative dataset for streams in the Cayuga Lake watershed, selected certified test results for Six Mile Creek and tributaries, downloaded through the data query interface for the CSI database at <http://www.communityscience.org/database/entries>, are summarized in Table 2 and compared to available data from the NWIS database. Median values are in good agreement considering CSI volunteers and agency staff sampled different locations on Six Mile Creek. As a preliminary estimate of variability in the CSI data set, the coefficient of variation was calculated for specific conductance under base-flow conditions for each of the 14 monitoring locations on Six Mile Creek, as follows. The data query interface in the CSI database was used to select the time period (2004-2012), monitoring region (Cayuga Lake watershed), monitoring set (Six Mile Creek), analyte (specific conductance), flow conditions (base flow), and test location (lab). The filtered data were

Table 2. Comparison of Selected “Signature Chemical” Indicators of Water Quality Under Base Flow Conditions<sup>a</sup> in Six Mile Creek and Tributary Streams as Measured by CSI’s Certified Lab in Stream Samples Collected Synoptically by Volunteers<sup>b</sup> and by the U.S. Geological Survey (USGS)

Parameters	Data from certified CSI lab analyses of samples collected by Six Mile Creek volunteer group in 23 synoptic sampling events at 15 stream locations <sup>c</sup>			USGS data <sup>d</sup>
	Min	Max	Median (n)	Median (n)
Alkalinity (mg CaCO <sub>3</sub> /L)	10.3	165	92.3 (299)	79 (14)
Barium (mg/L) <sup>e</sup>	0.017	0.056	0.0435 (8)	no data
Calcium hardness (mg CaCO <sub>3</sub> /L)	19	89	71 (13)	no data
Chloride (mg/L)	3.54	57.8	18.6 (312)	19.7 (18)
Gross alpha radioactivity (pCi/L) <sup>e</sup>	0.22	1.55	0.595 (8)	no data
Gross beta radioactivity (pCi/L) <sup>e</sup>	0.97	3.83	1.69 (8)	no data
Total hardness (mg CaCO <sub>3</sub> /L)	10.3	183	108 (312)	120.5 (18)
pH	6.75	8.85	7.5 (312)	8 (17)
Total nitrogen (mg/L) <sup>f</sup>	non-detect (< 0.11)	1.754	0.4 (291)	0.545 (15)
Total suspended solids (mg/L)	non-detect (< 0.625)	85	2.05 (311)	no data
Specific conductance (μS/cm)	58	450	254.5 (312)	297.5 (20)
Strontium (mg/L) <sup>e</sup>	0.045	0.108	0.085 (8)	no data
Sulfate (mg/L)	4.4	17.4	10.25 (139)	11.7 (18)
Total dissolved solids (mg/L) <sup>e</sup>	100	180	161.5 (8)	173 (17)
Turbidity (NTU)	0.38	81.2	4.48 (312)	no data

<sup>a</sup>Base flow is defined as a flow equal to or less than two times the historic median as recorded by the U.S.GS gauging station on Six Mile Creek at Bethel Grove for the day of a synoptic sampling event. The Six Mile Creek volunteer group performs on average three base flow and two stormwater sampling events per year.

<sup>b</sup>A “synoptic sampling event” or “synoptic monitoring event” is defined as one in which a group of volunteers collect samples at specific locations on the same day within a few hours of each other in order to facilitate comparison of water quality values throughout the sampled drainage area. In the CSI database ([www.communityscience.org/database](http://www.communityscience.org/database)), “synoptic monitoring location” refers to a stream location that is always included in synoptic monitoring events for a particular monitoring set (e.g., the Six Mile Creek watershed) year after year. An “investigative monitoring location” is one which is sampled occasionally to track pollution that may be detected at synoptic locations.

<sup>c</sup>Certified lab data from 23 base flow sampling events at 14 synoptic sampling sites plus one investigative site on the Six Mile Creek mainstem and tributary streams from 2004-2012. Results may be viewed at [www.communityscience.org/database/monitoringsets/5](http://www.communityscience.org/database/monitoringsets/5). Raw data may be selected and downloaded at <http://www.communityscience.org/database/entries>.

<sup>d</sup>U.S. Geologic Survey data from 16 sampling events at three sites on the Six Mile Creek main stem and six sites on Six Mile Creek tributaries from 2003-2005 ([waterdata.usgs.gov/](http://waterdata.usgs.gov/)).

<sup>e</sup>Expanded gas well baseline parameters measured one time at seven synoptic sampling sites and one investigative site as part of a base flow synoptic sampling event in 2012.

<sup>f</sup>CSI Total Nitrogen equal to sum of total Kjeldahl nitrogen (TKN) and nitrate- + nitrite-nitrogen. According to Table 5.10 in the 2011 draft Supplemental Generic Environmental Impact Statement (dSGEIS) by the New York State Department of Environmental Conservation (NYSDEC), TKN is elevated approximately 300-fold in flowback compared to typical values in Six Mile Creek, making it a potential contributor to a “chemical signature” of gas well impacts.

downloaded to MS Excel, the mean and standard deviation were calculated, and the coefficient of variation (COV) was calculated as the ratio of the standard deviation to the mean multiplied by 100. The COV was calculated for each of the 14 synoptic sampling locations on Six Mile Creek. COVs for specific conductance at the 14 locations ranged from 13.6 percent to 31.5 percent, the mean COV was 21.4 percent, and the median COV was 20.7 percent. It is noted that the data query interface in the CSI database can be used to select and export other data sets for Six Mile Creek and analyze their variability. For example, COVs for total hardness were calculated for each of the 14 locations, and the mean COV for total hardness was found to be 22 percent. This low variability strengthens the baseline from which to assess possible impacts on specific streams and stream reaches if HVHFF activities take place in the Cayuga Lake watershed.

#### *Streams in Upper Susquehanna River Basin*

Unlike the Cayuga Lake watershed, where volunteer groups collect grab samples two to five times a year for certified analyses by the CSI lab, volunteers in the Upper Susquehanna River Basin perform monthly measurements of five red-flag parameters in the field and report their results to CSI. At this writing (October 2012), 77 red-flag volunteers are monitoring 125 locations draining 1,233 square miles in sub-watersheds of the Upper Susquehanna River basin (Figure 1). Volunteers are added continuously as word spreads and citizens contact CSI for training and technical support. Volunteer results that meet data acceptance criteria (provided in Table 1) are entered in the CSI database by CSI staff and may be searched and downloaded via the data query interface at <http://www.communityscience.org/database/entries>. Results obtained by CSI's first red-flag group, the Cayuta-Catatonk Water Watch, in the first year of their monthly monitoring program from February 2011 to February 2012, are summarized in Tables 3 and 4 and compared to data reported by state and federal agencies. Median values for pH, specific conductance and total hardness are lower than values reported by the NYSDEC and the Susquehanna River Basin Commission (SRBC). A possible explanation is that most of the agency data are collected from a single monitoring site located near the mouths of Catatonk Creek (Table 3) and Cayuta Creek (Table 4), while volunteers collected red-flag data throughout both watersheds including headwater streams. Coefficients of variation for specific conductance at 26 red-flag monitoring locations under base-flow conditions in Catatonk and Cayuta Creeks ranged from 9.8 percent to 74.6 percent with a mean COV for all locations of 33 percent and a median COV of 32.9 percent. The generally higher COVs at red-flag monitoring locations compared to Six Mile Creek locations may be due to the smaller data set, the lower accuracy of field measurements (Tables 3 and 4) compared to certified lab results (Table 2), greater temporal variation in specific conductance in Cayuta

and Catatonk Creeks compared to Six Mile Creek, or a combination of these and other factors. Nevertheless, field measurements at fixed stream locations by volunteers (Tables 3 and 4) are sufficiently consistent over time to serve as effective baselines for detecting possible HVHMF impacts on streams. Baselines established by volunteers are important in view of the paucity of agency data on streams in recent years. A search of the federal STORET database indicated that stream data had been collected at 270 agency monitoring sites between 1990 and October of 2012 in the 13 counties in upstate New York where CSI is focusing its baseline monitoring programs ( Figure 1). At least three of four red-flag parameters (pH, dissolved oxygen, specific conductance, total hardness) were measured at 85 percent of STORET sites. However, the median number of sampling events per site over the 22-year period from 1990-2012 was only four. Of the 270 STORET sites in the 13-county region, only 39 have been sampled since January 1, 2010.

### Groundwater in the Marcellus and Utica Shale Regions

The NWIS database was searched for gas well “signature chemicals” that might be used in a regional baseline to assess HVHMF impacts on groundwater quality. Search results indicated that only a small fraction of wells in New

Table 3. Comparison of “Red-Flag” Indicators of Water Quality Measured by Cayuta-Catatonk Water Watch (CCWW) Volunteers with Agency Data under Base Flow Conditions in Catatonk Creek

“Red-flag” indicators	Catatonk Creek—CCWW data <sup>a</sup>			Catatonk Creek—NYSDES data <sup>b</sup>		
	Median (n)	Min	Max	Median (n)	Min	Max
pH	7.25 (48)	6.39	8.14	7.76 (46)	6.49	8.42
Dissolved oxygen (mg/L)	9.25 (58)	5.8	13.4	10.25 (22)	7.85	13.48
Specific conductance (μS/cm)	154.5 (56)	36	431	211 (46)	49	395
Total hardness (mg/L)	68 (44)	16	160	98.5 (10)	70.4	160

<sup>a</sup>Data collected by 4 volunteer teams at 11 sites throughout the Catatonk Creek watershed from Feb. 2011-Feb. 2012 (<http://www.communityscience.org/database/monitoringsets/13>).

<sup>b</sup>Data are primarily from the New York State Department of Environmental Conservation (NYSDEC), Rotating Integrated Basin Studies (RIBS), site #06032102, Apr.-Nov. 2004 ([http://www.epa.gov/storet/dw\\_home.html](http://www.epa.gov/storet/dw_home.html)), with additional data from two Susquehanna River Basin Commission sites and one NYDEC site.

Table 4. Comparison of “Red-Flag” Indicators of Water Quality Measured by Cayuta-Catatonk Water Watch (CCWW) Volunteers and Agency Data under Base Flow Conditions in Cayuta Creek

“Red-flag” indicators	Catatonk Creek—CCWW data <sup>a</sup>			Catatonk Creek—SRBC data <sup>b</sup>		
	Median (n)	Min	Max	Median (n)	Min	Max
pH	7 (118)	6	8.71	7.8 (186)	6.1	9
Dissolved oxygen (mg/L)	9.4 (135)	5.8	13.9	9.8 (164)	4.95	15.2
Specific conductance (μS/cm)	118 (134)	22	351	282 (190)	71	1165
Total hardness (mg/L)	53 (128)	12	152	120 (3)	106	148

<sup>a</sup>Data collected by 4 volunteer teams at 15 sites throughout the Cayuta Creek watershed from Feb. 2011-Feb. 2012 (<http://www.communityscience.org/database/monitoringsets/12>).

<sup>b</sup>Data are primarily from the Data are primarily from the Susquehanna River Basin Commission (SRBC), Interstate Stream Water Quality Network, Apr.-1990)-Oct. 2010 ([http://www.epa.gov/storet/dw\\_home.html](http://www.epa.gov/storet/dw_home.html)). The station providing the majority of data is CAYT001.7-4176 near the mouth of Cayuta Creek. Additional data are from three SRB stations and one NYSDEC station within the Cayuta Creek watershed.

York have been characterized with respect to potential HVHFF contamination. A total of 1,995 wells in New York have been analyzed for at least one chemical in at least one of eleven “signature chemical” categories since 1990 (Table 5). However, only 208 wells have been analyzed for at least one chemical in each of eight “signature chemical” categories, and of these, only 16 are located in rural areas of the Southern Tier (Table 5). Thus, the geographic distribution of agency data on groundwater quality is skewed away from the rural areas that are most at risk of impacts from HVHFF in New York.

Available agency data were filtered and tabulated in Table 6 to facilitate comparison with CSI groundwater data on “signature chemicals” in Table 7. Median values in CSI’s regional groundwater database reported in Table 7 were generally similar to median values extracted from the USGS’s NWIS database and tabulated in Table 6. Chloride, total dissolved solids, total hardness and specific conductance values were somewhat higher in the USGS data set. These differences could be explained by random variability. Groundwater quality is known to change over short horizontal and vertical distances as a result of differences in aquifer characteristics, geochemical conditions, and residence time [20]. Indeed, we observed substantial variability among private drinking water wells, including wells in the same 1-mile grid square (Figure 2). Another possible



Table 5. Certified Measurements of CSI "Signature Chemicals" in Groundwater Wells in Urban and Rural Areas of New York State Performed by the Community Science Institute and the U.S. Geological Survey

Geographic area	Number of groundwater wells where certified measurements of gas well "signature chemicals" (SC) have been performed in New York									
	CSI					USGS				
	8 <sup>a</sup> of 11 SC categories <sup>b</sup>	11 <sup>a</sup> of 11 SC categories <sup>b</sup>	1 <sup>a</sup> of 11 SC categories <sup>b</sup>	5 <sup>a</sup> of 11 SC categories <sup>b</sup>	7 <sup>a</sup> of 11 SC categories <sup>b</sup>	8 <sup>a</sup> of 11 SC categories <sup>b</sup>				
New York total	121	110	1,995	1,260	580	208				
New York shale region	121	110	709	458	109	80				
Shale region—rural <sup>c</sup>	121	110	415	274	62	46				
Shale region—urban/contaminated <sup>c</sup>	0	0	294	184	47	34				
Outside of shale region	0	0	1,286	802	471	128				
13-county area	121	110	245	162	48	27				
13-county area <sup>d</sup> —rural <sup>c</sup>	121	110	178	110	28	16				
13-county area <sup>d</sup> —urban/contaminated <sup>c</sup>	0	0	67	52	20	11				

<sup>a</sup>Number of "signature chemical" categories for which certified measurements were performed on groundwater wells.

<sup>b</sup>CSI's recommended list of 19 gas well "signature chemicals" and 52 volatile organic compounds (VOCs) were organized into eleven (11) categories of chemical characteristics with the goal of searching the NWIS database of the U.S. Geological Survey for existing groundwater quality data related to "hydrofracking." Each of the eleven "signature chemical" ("SC") categories contains one or more certified tests recommended by CSI as part of a pre-HVHFH baseline designed for use in screening groundwater for possible contamination due to gas well waste. The eleven (11) CSI "signature chemical" categories used to search the NWIS database are: (1) Methane; (2) Chemical oxygen demand; (3) Methylene blue active substances (anionic surfactants); (4) Total hardness, calcium; (5) Barium, strontium; (6) Iron, manganese, arsenic; (7) Turbidity, total suspended solids; (8) Gross alpha radioactivity, gross beta radioactivity; (9) Benzene, ethylbenzene, toluene, xylene; (10) pH, alkalinity; and (11) Chloride, specific conductance, total dissolved solids. While these eleven (11) categories are considered to be broadly representative of the chemical characteristics most likely to change as a result of contamination from shale gas wells, it is recognized that they are not completely inclusive, and that there are other groundwater characteristics in the NWIS database that might be impacted by "fracking."

<sup>c</sup>Urban/contaminated areas are defined as the union of four GIS layers: (1) U.S. Census Bureau 2010 populated places, (2) U.S. Census Bureau 2010 urban areas, (3) One-mile corridors around EPA facilities and sites subject to environmental regulation and (4) One-mile corridors around the NYDEC remediation sites. This final GIS layer represents a rough measure of areas that have intensive residential, commercial, and industrial land use and can be distinguished from areas that are primarily rural in character.

<sup>d</sup>The 13-county area in upstate New York is defined as those counties where CSI has performed baseline testing on private groundwater wells: Otsego, Tompkins, Chenango, Delaware, Steuben, Tioga, Schuyler, Broome, Chemung, Yates, Schoharie, Seneca, and Sullivan.

Table 6. Levels of Gas Well "Signature Chemicals" in USGS Groundwater Monitoring Wells, 1990-2012

Gas well signature chemical (units)	USGS results for Marcellus and Utica Shale regions			USGS results for 13-county area in rural Southern Tier <sup>a</sup>		
	Wells tested (wells with detects) <sup>b</sup>	Min-max values for all wells <sup>c</sup>	Median values for all wells <sup>d</sup>	Wells tested (wells with detects) <sup>b</sup>	Min-max values for all wells <sup>c</sup>	Median values for all wells <sup>d</sup>
Calcium (mg Ca/L)	16 (16)	11.13-309.2	85	0 (0)	—	—
Alkalinity (mg CaCO <sub>3</sub> /L)	0 (0)	—	—	0 (0)	—	—
Total hardness (mg CaCO <sub>3</sub> /L)	590 (590)	0.28-87,600	219	119 (119)	1.47-1,700	137
Total dissolved solids (mg/L)	459 (459)	33-193,000	294	119 (119)	33-7,130	205
Total suspended solids (mg/L)	0 (0)	—	—	0 (0)	—	—
Turbidity (NTU)	17 (17)	0.2-230.06	15.9	0 (0)	—	—
pH (pH units)	566 (566)	5.8-12.4	7.6	114 (114)	5.9-9.1	8
Chloride (mg/L)	574 (574)	0.4-126,000	32.4	119 (119)	0.4-3,380	13
Specific conductance (μS.cm)	555 (555)	45-129,333	535	119 (119)	47-11,300	356
Chemical oxygen demand (mg/L)	4 (0)	non-detect (< 10)	non-detect (< 10)	4 (0)	non-detect (< 10)	non-detect (< 10)
Gross alpha radioactivity (pCi/L) <sup>e</sup>	98 (90)	-4-10.7	0.7	24 (16)	-0.4-10.7	1.05
Gross beta radioactivity (pCi/L) <sup>e</sup>	98 (87)	-0.9-19.1	1.6	24 (13)	-0.5-19.1	1.05
Methane (mg/L)	172 (153)	non-detect (< 0.001)-45.4	0.003	37 (18)	non-detect (< 0.001)-38.3	non-detect (< 0.001)

Methylene blue active substances (MBAS) (mg/L)	0 (0)	—	—	0 (0)	—	—
Barium, unfiltered (mg/L)	276 (276)	0.00109-10.4	0.1155	73 (73)	0.00488-10.4	0.110
Iron, unfiltered (mg/L)	275 (272)	non-detect (< 0.0046)-29.171	0.138	69 (66)	non-detect (< 0.0046)-3.47	0.138
Manganese, unfiltered (mg/L)	273 (271)	non-detect (< 0.00016)-1.6	0.0351	70 (68)	non-detect (< 0.00016)-0.594	0.03265
Arsenic, unfiltered (mg/L)	219 (209)	non-detect (< 0.00006-0.148)	0.00084	50 (40)	non-detect (< 0.00006)-0.027	0.00079
Strontium, unfiltered (mg/L)	276 (276)	0.0104-53.8	0.227	73 (73)	0.0104-31.1	0.247
Benzene (mg/L)	338 (5)	non-detect (< 0.00002)-0.0561	non-detect (< 0.00002)	85 (1)	non-detect (< 0.00002)-0.0003	non-detect (< 0.00002)
Ethylbenzene (mg/L)	335 (4)	non-detect (< 0.00003)-0.0076	non-detect (< 0.00003)	85 (1)	non-detect (< 0.00003)-0.0001	non-detect (< 0.00003)
Toluene (mg/L)	340 (30)	non-detect (< 0.00002)-0.023	non-detect (< 0.00002)	85 (8)	non-detect (< 0.00002)-0.001	non-detect (< 0.00002)
Xylene (mg/L)	27 (2)	non-detect (< 0.0002)-0.00475	non-detect (< 0.0002)	0 (0)	—	—

<sup>a</sup>Counties included in this analysis: Otsego, Tompkins, Chenango, Broome, Steuben, Sullivan, Delaware, Schuyler, Tioga, Chemung, Schoharie, Seneca, Yates. Rural areas are defined as not urban/industrial areas. Urban/industrial areas are defined as U.S. Census Bureau 2010 populated places and urban areas; these GIS layers were merged with a layer comprised of 1-mile corridors around EPA facilities and sites subject to environmental regulation as well as NYSDEC remediation sites.

<sup>b</sup>Number of wells with concentrations above the laboratory's limit of quantitation (similar to detection).

<sup>c</sup>Minimum values that are below the laboratory's limit of quantitation (LOQ) are reported as "non-detect" with the LOQ in parenthesis.

<sup>d</sup>If the laboratory reported a non-detect, the value is less than the laboratory's limit of quantitation (similar to detection). If a well was sampled more than once, the value is taken to equal the average of all samples collected from that well. The quantitation limit is indicated by "<"; for example, a chloride value of < 2 means that the measurement was less than a limit of quantitation of 2 mg/L.

<sup>e</sup>USGS non-detects defined as "Radiochemistry non-detect, result below sample specific critical level."

Table 7. Levels of Shale Gas Well "Signature Chemicals" in Private Groundwater Wells Measured by the Community Science Institute, 2009-2012

Gas well "signature chemical" (units)	USGS results for rural Southern Tier <sup>a</sup>			Drinking water regulations/guidelines	
	Number of wells tested (number of wells with detects) <sup>b</sup>	Min-max values for all wells <sup>c</sup>	Median values for all wells <sup>d</sup>	Federal MCL value <sup>e</sup> (number of CSI wells over)	NY State MCL value <sup>f</sup> (number of CSI wells over)
Calcium (mg Ca/L)	121 (120)	< 1.2-156	32.6	none	none
Alkalinity (mg CaCO <sub>3</sub> /L)	122 (122)	8.13-450	140.5	none	none
Total hardness (mg CaCO <sub>3</sub> /L)	121 (121)	8.8-635	107	none	none
Total dissolved solids (mg/L)	120 (114)	< 50-1090	180	none	500g (3)
Total suspended solids (mg/L)	121 (5)	< 4.0-91.6	< 4.0	none	none
Turbidity (NTU)	121 (120)	< 0.01-91.8	0.83	5 (14)	5 (14)
pH (pH units)	122 (122)	5.9-8.65	7.535	none	6.5-8.5 <sup>g</sup>
Chloride (mg/L)	121 (82)	0.46-281.5	4.18	none	250 <sup>g</sup> (2)
Specific conductance (µS.cm)	122 (122)	40.4-1682	298.5	none	none
Chemical oxygen demand (mg/L)	121 (31)	non-detect (< 10)-26.9	non-detect (< 10)	none	none
Gross alpha radioactivity (pCi/L)	121 (121)	-0.45-4.97	0.655	15 (0)	15 (0)
Gross beta radioactivity (pCi/L)	121 (121)	-0.59-40.83	1.08	15-50 <sup>i</sup> (0)	15-50 <sup>i</sup> (0)
Methane (mg/L)	122 (51)	non-detect <sup>h</sup> -14	non-detect <sup>h</sup>	none	10 <sup>i</sup> (2)

Methylene blue active substances (MBAS) (mg/L)	122 (13)	non-detect (<0.04)-0.054	non-detect (<0.04)	none	0.5 <sup>g</sup> (0)
Barium, unfiltered (mg/L)	122 (122)	0.0019-0.895	0.0657	2 (0)	2 (0)
Iron, unfiltered (mg/L)	122 (110)	non-detect (<0.005)-11.3	0.0885	none	0.3 <sup>g</sup> (26)
Manganese, unfiltered (mg/L)	122 (101)	non-detect (<0.002)-1.52	0.045	none	0.3 <sup>g</sup> (2)
Arsenic, unfiltered (mg/L)	122 (44)	non-detect (<0.0005)-0.0248	non-detect (<0.0005)	0.01 (2)	0.01 (2)
Strontium, unfiltered (mg/L)	108 (108)	0.0006-2.07	0.217	none	none
Benzene (mg/L) <sup>k</sup>	114 (0)	non-detect (<0.0005)	non-detect (<0.0005)	0.005 (0)	POC <sup>l</sup>
Ethylbenzene (mg/L) <sup>k</sup>	114 (0)	non-detect (<0.0005)	non-detect (<0.0005)	0.7 (0)	POC <sup>l</sup>
Toluene (mg/L) <sup>k</sup>	114 (3)	non-detect (<0.0005)-1.3	non-detect (<0.0005)	1 (1)	PCO <sup>l</sup>
Xylene (mg/L) <sup>k</sup>	114 (0)	non-detect (<0.0005)	non-detect (<0.0005)	10 (0)	POC <sup>l</sup>

<sup>a</sup>Counties (number of wells included in baseline): Osego (59), Tompkins (13), Chenango (13), Broome (10), Steuben (7), Sullivan (5), Delaware (4), Schuyler (4), Tioga (3), Chemung (2), Schoharie (1), Seneca (1), Yates (1). Private clients must give written permission for their results to be included in the regional baseline.

<sup>b</sup>Number of wells with concentrations above the laboratory's limit of quantitation (similar to detection).

<sup>c</sup>Minimum values that are below the laboratory's limit of quantitation (LOQ) are reported as "non-detect" with the LOQ in parenthesis.

<sup>d</sup>If the laboratory reported a non-detect, the value is less than the laboratory's limit of quantitation (similar to detection). The quantitation limit is indicated by "<"; for example, a chloride value of < 2 means that the measurement was less than a limit of quantitation of 2 mg/L. If a well was sampled more than once, the value is taken to equal the average of all samples collected from that well with one exception: Exceedances of federal and state standards are noted regardless of the number of times a well is sampled.

Table 7. (Cont'd.)

<p><sup>e</sup>The MCL refers to the Maximum Contaminant Level, a health-based, enforceable standard under the federal Safe Drinking Water Act (SDWA). MCLs are based on human health risk assessments and are listed on the EPA website at: <a href="http://water.epa.gov/drink/contaminants/index.cfm#List">http://water.epa.gov/drink/contaminants/index.cfm#List</a>. MCLs are distinct from National Secondary Drinking Water Standards (NSDWS), which are not health-based and not enforceable by EPA.</p>	<p><sup>f</sup>State standards refer to levels of chemicals in drinking water that are enforced by New York State under the federal Safe Drinking Water Act (SDWA) and are listed at <a href="http://www.health.ny.gov/regulations/nycrr/title_10/part_5/subpart_5-1_tables.htm">http://www.health.ny.gov/regulations/nycrr/title_10/part_5/subpart_5-1_tables.htm</a>. An enforceable state standard must be equally or more stringent than a federal standard. A state is not required to base its enforceable standards on human health risk assessments; however, a state may refer to its standards as MCLs. In general, state MCLs are a mixture of federal health-based MCLs and federal non-health-based National Secondary Drinking Water Standards (NSDWS). For example, New York bases several enforceable standards on NSDWS, available at <a href="http://water.epa.gov/drink/contaminants/index.cfm#SecondaryList">http://water.epa.gov/drink/contaminants/index.cfm#SecondaryList</a>. NSDWS are not enforceable at the federal level because they are directed at cosmetic properties of drinking water such as taste and odor, not at risks to human health.</p>
<p><sup>g</sup>Based on a National Secondary Drinking Water Standard (NSDWS) that is not health-based and is not enforceable by the federal government (see <a href="http://water.epa.gov/drink/contaminants/index.cfm#SecondaryList">http://water.epa.gov/drink/contaminants/index.cfm#SecondaryList</a>).</p>	<p><sup>h</sup>The limit of quantitation (LOQ) for methane depends on the subcontract lab used. The lab used from 8/2009 to 6/2010 had an LOQ of 0.01 mg/L; the lab used since 6/2010 has an LOQ of 0.001 mg/L.</p>
<p><sup>i</sup>A guidance value, not a standard. The U.S. Department of the Interior recommends that wells containing greater than 10 mg/L of dissolved methane be vented to minimize the explosion hazard that could result from methane volatilizing (escaping) from water and building up inside a home.</p>	<p><sup>j</sup>Standard is based on an exposure limit of 4 mrem/year. This level of exposure corresponds to a concentration of 15 pCi/L to 50 pCi/L, depending on various factors. It is possible that the one well that exceeded 15 pCi/L may have resulted in an exposure greater than the federal MCL of 4 mrem/year.</p>
<p><sup>k</sup>Results for so-called BTEX chemicals are reported here. Additional 48 volatile organic compounds (VOCs) analyzed by EPA Method 524.2 are omitted from this table but will be included in CSI's online groundwater database.</p>	<p><sup>l</sup>POCs (principal organic contaminants) have an automatic New York State MCL of 0.005 mg/L: <a href="http://www.health.ny.gov/regulations/nycrr/title_10/part_5/subpart_5-1_tables.htm">http://www.health.ny.gov/regulations/nycrr/title_10/part_5/subpart_5-1_tables.htm</a></p>

explanation is that more USGS samples may have been collected in areas or regions with higher mineral content than CSI samples. Minimum values were similar in the CSI and USGS data sets, while maximum values were significantly higher in the USGS data set (compare Tables 6 and 7). The most likely explanation for the maximum values for chloride (126,000 mg/L), total dissolved solids (193,000 mg/L) and specific conductance (129,333  $\mu\text{S}/\text{cm}$ ) is groundwater brine resulting from salt deposits in the Syracuse area [21].

CSI's growing database indicates that groundwater quality in rural areas of New York's Southern Tier region is generally excellent with respect to gas well "signature chemicals." Results from 122 private wells with an aggregate total of 8,224 certified test results including 2,296 tests for 19 parameters related to brine, acid, metals, suspended solids, surfactants, bulk organic compounds, radioactivity, and methane, and 5,928 tests for 52 VOCs included in EPA Method 524.2, are summarized in Table 7. Twelve wells exceeded the federal standard for turbidity, one well exceeded the federal standard for arsenic and one exceeded the federal standards for both turbidity and arsenic. A fifteenth well exceeded the federal standards for turbidity and toluene; however, this was a newly drilled well, and no exceedances were observed in follow-up sampling. The remaining 107 wells showed no exceedances of federal standards for any of the 19 "signature chemicals" and 52 VOCs. Stated as a fraction of the total number of "signature chemical" results summarized in Table 7, exceedances of federal standards comprised 17 of 8,224 test results or 0.2 percent. Methane was detected in 51 of 122 wells (detection limit 0.001 or 0.01 mg/L, depending on subcontract lab); two wells had levels greater than 10 mg/L, the federal guideline for explosion hazard (Table 7). Methane concentrations may have been underestimated because containers were open during the approximately 20 seconds required to collect a sample, providing an opportunity for methane, a gas, to volatilize. Ethane, which was routinely analyzed along with methane, was not detected in any wells (detection limit 0.019 mg/L, data not shown).

It is important to note that state drinking water standards differ substantially from federal standards. In particular, New York enforces several federal National Secondary Drinking Water Standards (NSDWS), which address cosmetic, smell, and taste characteristics as MCLs, including state MCLs for iron, manganese, total dissolved solids, and methylene blue active substances (MBAS) (anionic surfactants). While the state has valid reasons for these regulations, they result in MCLs that are not based strictly on human health risk assessments. For example, the Institute of Medicine of the National Academy of Sciences has set an upper intake level (UL) for iron for adults of 45 mg/day [22], and thus an adult would have to ingest 150 liters or about 37 gallons of water per day to incur adverse health effects when the iron concentration is 0.3 mg/L, the MCL for New York State. A number of VOCs are regulated by New York as Principal Organic Contaminants (POCs) with obligatory MCLs of 0.005 mg/L even though health-based toxicity thresholds may be higher or



unknown (Table 7). For these reasons, the number of MCL exceedances under New York State regulations exceeded the number of MCL exceedances under federal regulations (Table 7).

## DISCUSSION

High-volume horizontal hydraulic fracturing or HVHHF, commonly known as fracking, is a new technology that is widely believed to present substantial risks to human health and the environment. Weak regulation of fracking by federal and state governments has resulted in a dearth of data on exposure to the hazardous chemicals employed by the shale gas industry and the effects of exposure on humans and other species.

### The Value of Risk Assessment

Many if not most large-scale industrial activities entail the use of hazardous chemicals and the generation of hazardous chemical waste. The role of government is to encourage entrepreneurship, innovation, and productivity while ensuring that public health and environmental resources required for diverse economic activities are protected [23]. Risk assessment, properly conducted, provides an effective tool with which to evaluate industrial activities and decide the extent to which benefits to society justify inherent risks to human health and environmental resources. Even rudimentary risk assessments offer effective decision-making tools by helping to situate risks and benefits within the broader context of economic activity and quality-of-life goals for a place or a region.

The principles of risk assessment are well known to policymakers in government agencies and, one presumes, to lawmakers and their staffs in state legislatures and Congress. Nevertheless, the authors are not aware of a single systematic risk assessment anywhere in the United States that follows protocols developed by the National Academy of Sciences and the U.S. Environmental Protection Agency [15-17, 24] and widely accepted throughout the risk assessment community to marshal available evidence and examine the risks and benefits of HVHHF-based shale gas extraction. To the contrary, the industry has been exempted from key provisions of federal environmental laws [25], and its hazardous byproducts have been arbitrarily classified as non-toxic “industrial wastewater” in New York [26], effectively privileging the industry’s growth and deflecting attention from the risks its growth entails. Risk assessment is the only available tool to evaluate the industry’s impacts within the broader context of the diverse human and environmental communities in which it operates. In the absence of action by government, it is up to citizens to gather evidence on risk. The goal of CSI-volunteer monitoring partnerships is to target data gaps at the local level where government agency data is scarce or non-existent.

### Surface Water Monitoring by Citizen Volunteers

Through its partnerships with groups of volunteers from rural communities in Upstate New York, the Community Science Institute collects scientifically credible water quality data in an effort to evaluate risks to local streams and lakes from land uses such as agriculture, residential development and, most recently, from the burgeoning HVHFF-based shale gas industry. Results are disseminated to the general public through CSI's unique online data archive, providing factual information that can be accessed by citizens and municipal and county governments to help understand and manage water resources in their jurisdictions.

There is a growing scientific literature that seeks to understand the degree to which data collected by volunteers are valid, the purposes for which these data can or should be used, how volunteer data might be disseminated, and how to create a nexus between volunteers, planners, and regulators so that the data are put to use [27-31]. We report here on monitoring partnerships between trained groups of volunteers and CSI's certified lab that represent a workable compromise between a formal structured program with integrated quality control and a more autonomous organizational structure that promotes volunteer empowerment. Key elements of CSI-volunteer monitoring partnerships are:

- Recruitment of volunteers in groups of 15-30 people loosely defined by region.
- A series of three free training workshops spaced at least two weeks apart to give group members an opportunity to reflect on what they are learning and to foster group identity and commitment.
- Stream-side demonstrations of test kits and meters by CSI staff and hands-on practice with test kits by volunteers.
- Organization of each group into teams of two to five volunteers.
- A clear quality assurance protocol that volunteer teams can implement on their own.
- Selection of sampling sites by teams with guidance and mapping support from CSI.
- Management of the online data repository by CSI, with CSI staff entering only data that satisfy acceptance criteria (Table 1).
- Capacity for dynamic mapping and graphing of data in CSI's public database, including capacity for visitors to the CSI website to select and export raw data free of charge.

The results presented here provide evidence that surface water monitoring partnerships between groups of public-spirited citizens and CSI's certified lab are capable of generating and publicizing data for use in understanding, protecting, and managing water resources in New York State's shale gas region. Median values obtained by CSI-volunteer monitoring partnerships agreed well

with available agency data on surface water quality in the same general region, taking into account CSI's intentional focus on sampling sites located upstream and on small tributary streams as opposed to agencies' greater reliance on sampling sites located near stream mouths and agencies' inclusion of areas where contamination is suspected. Generally low coefficients of variation of data collected by volunteers at individual monitoring locations suggest that potential contamination events as well as long-term trends can be detected. The quality of volunteer data reported here is consistent with reports by other authors [29, 31].

### **Regional Groundwater Initiative**

Groundwater monitoring is structured differently from surface water monitoring. While surface water monitoring is structured around active partnerships between CSI and volunteer groups, groundwater monitoring is based on private clients who contract with CSI's certified lab to collect and test drinking water samples from their home, then grant permission to aggregate their test results for anonymous dissemination on the CSI website. CSI's groundwater database continues to grow as more private clients request baseline tests and grant permission to pool their results. The groundwater data in CSI's archive of aggregated private client results were found to be representative of New York's shale gas region as indicated by the similarity of median values for gas well "signature chemicals" (Table 7) to groundwater data in the NWIS database (Table 6). Higher median and maximum values in the NWIS data set (Table 6) were probably due to the inclusion of groundwater data from areas with salt deposits and industrial and contaminated sites. The quality of groundwater in rural households with respect to gas well "signature chemicals" can only be described as excellent (Table 7). The most prevalent water quality issue by far was turbidity, which exceeded the federal standard of 5 NTU in 14 out of 122 private groundwater wells tested and which accounted for 14 out of 17 documented exceedances of federal health-based standards (Table 7). Methane was present in nearly half of private wells, in line with agency data [32, Table 6]. Methane concentrations ranged from barely detectable up to 14 mg/L, and the median value was 0.005 mg/L. The principal hazard associated with methane is explosion when concentrations reach 5.5 percent by volume in air, or about 55,000 ppm, and similar concentrations of methane can cause asphyxiation [33]. The U.S. Department of the Interior recommends venting wells containing methane concentrations greater than 10 ppm by weight or 0.001 percent in water in order to avoid gradual methane accumulation in air in enclosed living spaces. Methane is classified as toxicologically inert as long as oxygen is available, and animals are not affected by concentrations up to 10,000 ppm by volume in air [33, 34]; however, at concentrations greater than 50 percent or about 500,000 ppm by volume in air, nonspecific toxic effects secondary to oxygen deprivation have been noted [33]. The prevalence of methane in groundwater does not negate the

value of methane as a “signature chemical,” because concentrations would be expected to increase dramatically in the event of contamination resulting from leaks in well casings or from methane migration through subsurface fractures [12]. Ethane was not detected in any groundwater wells.

Aggregated private client groundwater results are being incorporated into CSI’s electronic database ([www.communityscience.org/database](http://www.communityscience.org/database)) and will be made available to the general public online by 2013. Online groundwater data will be organized by region, county and 1-mile grid square (Figure 2) in contrast to surface water results, which are organized by region, “monitoring set” (e.g., the watershed of a stream such as Six Mile Creek or Catatank Creek), and monitoring location. One-mile grid squares should provide sufficient spatial information to investigate increases in post-drilling concentrations of “signature chemicals” in private drinking water wells.

### **Documenting HVHFF Impacts on Water**

A post-fracking increase in the concentration of one or more “signature chemicals” can, in principle, be interpreted as evidence that water has been contaminated by nearby shale gas operations. The greater the number of “signature chemicals” and the higher their concentrations compared to pre-fracking baseline levels, the stronger the evidence of contamination. This application of “signature chemical” baselines should be valid both for an individual groundwater well and for a specific stream reach where pre-fracking baseline data is available. While it should be easier to detect contamination of a groundwater well that has been characterized on the basis of over 70 certified lab tests than a stream location that has been characterized on the basis of five red-flag tests performed by volunteers in the field, the guiding principle is the same: A significant change in the “chemical signature” of water quality that can be reasonably attributed to waste from the shale gas industry. Clearly the terms “significant” and “reasonable” are subject to interpretation. We anticipate that regulatory agencies and the courts will make decisions on a case-by-case basis, and that they will use a weight-of-evidence approach and take into account other factors in addition to changes in water quality, for example, proximity to a drill pad and visual evidence of a spill. Nevertheless, an increase over pre-fracking levels of “signature chemicals” is likely to constitute a strong, if not the strongest, piece of evidence that HVHFF-related contamination has occurred.

Detecting contamination by extrapolating “signature chemical” levels to groundwater wells and stream locations that lack pre-fracking data is decidedly less robust conceptually than comparing pre- and post-fracking data for the same drinking water well or the same stream location. Nevertheless, regional baselines should prove useful to agencies as part of a weight-of-evidence approach to identifying HVHFF impacts. Agencies will have to decide whether post-fracking levels of “signature chemicals” exceed regional values for groundwater, in the

case of a private well, or regional values for surface water, in the case of a stream or a stream reach, sufficiently to support a determination that the well or the stream has been degraded as a result of shale gas extraction activities.

It seems possible that despite the heterogeneity of groundwater sources in the regional baseline, some “signature chemicals” might be distributed in statistically recognizable patterns, the simplest example being a normal distribution, or bell curve. The regional baseline for a normally distributed “signature chemical” in groundwater might be used to estimate the probability that its post-fracking concentration in a private well is due to chance (that is to say, it falls within the normal distribution of the pre-fracking data set); a low probability would strengthen the case for contamination. Similarly, statistical patterns of “signature chemicals” in regional stream baselines, if present, might be used to estimate the probability that post-fracking concentrations signify contamination of a stream for which no baseline data exists. Regional surface water baselines also include a temporal component, because red-flag data are collected monthly. Temporal patterns such as seasonal variation, which can be readily analyzed by filtering and downloading red-flag data from the CSI database (<http://www.communityscience.org/database/entries>), might strengthen the case for or against HVHFF impacts.

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*Features*

**DISCLOSURE OF HYDRAULIC FRACTURING  
FLUID CHEMICAL ADDITIVES: ANALYSIS OF  
REGULATIONS**

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**ABSTRACT**

Hydraulic fracturing is used to extract natural gas from shale formations. The process involves injecting into the ground fracturing fluids that contain thousands of gallons of chemical additives. Companies are not mandated by federal regulations to disclose the identities or quantities of chemicals used during hydraulic fracturing operations on private or public lands. States have begun to regulate hydraulic fracturing fluids by mandating chemical disclosure. These laws have shortcomings including nondisclosure of proprietary or “trade secret” mixtures, insufficient penalties for reporting inaccurate or incomplete information, and timelines that allow for after-the-fact reporting. These limitations leave lawmakers, regulators, public safety officers, and the public uninformed and ill-prepared to anticipate and respond to possible environmental and human health hazards associated with hydraulic fracturing fluids. We explore hydraulic fracturing exemptions from federal regulations, as well as current and future efforts to mandate chemical disclosure at the federal and state level.

**Keywords:** groundwater, Safe Drinking Water Act, contamination, legislation, fracking

Hydraulic fracturing, also known as fracking, is an increasingly widespread practice used to extract natural gas and oil from shale formations deep below the surface of the earth. Optimization of recovery technologies and lucrative natural gas prices led to a 48 percent increase in U.S. shale gas production from 2006 to 2010 with an estimated 35,000 wells drilled annually [1, 2]. Hydraulic fracturing involves drilling a vertical well approximately 5,000 to 9,000 feet into a shale formation [3]. Horizontal drilling, when appropriate, stems perpendicularly from the base of the vertical well and may extend outwards up to 10,000 feet [4]. Wells are drilled and lined by a steel pipe and cemented into place. After placement, electric currents are sent to a perforating gun located near the base of the well, where a charge shoots small holes through the steel and cement into the shale [3]. This allows the highly pressurized fluid-and-proppant mixture injected into the well to escape the well and create cracks and fractures in the surrounding shale layers [5]. Proppants are size-graded, rounded and nearly spherical white sand, ceramic, or man-made particles which are suspended in pressurized fluid [6]. The resultant fractures allow gas trapped within the shale to escape, along with some fracturing fluid and naturally occurring mineral deposits, and flow back up the well to the surface for capture [3].

### **FRACTURING FLUIDS AND ENVIRONMENTAL HEALTH**

Hydraulic fracturing is controversial. Proponents argue that fracking creates a novel source of cheap, domestic energy and may replace some “dirty” energy sources like coal-fired power plants [5]. They claim that using natural gas as a “clean” energy source will make it easier to meet federal air and water quality standards [7] while also reducing our dependence on foreign oil [4]. The website of Halliburton, one of the major corporate proponents of fracking, states: “fracture stimulation is a safe and environmentally sound practice based on the industry’s decades-long track record, as well as the conclusions of government and industry studies and surveys” [8]. In 2009, industry estimated undeveloped but recoverable shale gas reserves in the lower 48 states amounting to 24 billion barrels: enough to heat U.S. homes for 30 years [9, 10].

#### **Use of Fracturing Fluids**

Opponents of hydraulic fracturing primarily cite concerns related to the environment, human health, and questions about the reality of promised long-term economic benefits in areas that are heavily drilled. The primary threat and controversy surrounding hydraulic fracturing, as it pertains to human health and groundwater contamination, is the use of fracturing fluids. Current estimates place the volume of fracturing fluid pumped into each well between 2 million and 4 million gallons, with the major components being water (90%),

sand or proppants (8-9.5%), and chemicals (0.5-2%) [11]. Chemicals are added to fracturing fluids to increase well productivity by creating fractures in the rock (mostly shale) formation and holding the fractures open for the release of natural gas. Fracturing fluid additives include proppants (particles that keep fractures open), acids, gelling agents (which thicken the fracturing fluid), gel breakers (which allow fracturing fluid and gas to flow easily back to surface), bactericides, biocides, clay stabilizers, corrosion inhibitors, crosslinkers (which help maintain viscosity of fracturing fluid), friction reducers, iron controls, scale inhibitors, and surfactants. The composition of the fluid is determined based on characteristics of the well (e.g., geology of area) and production objectives. Some of the identified chemicals have known human health effects. For example, the surfactant benzene is classified by the U.S.EPA as a known human carcinogen (Group A), and xylene is a central nervous system depressant [12, 13]. Since companies invest time and resources into perfecting their fluid technologies, industry views chemical recipes as proprietary information that should be protected as trade secrets; thus many of the chemicals used remain unknown [5, 14].

The use of chemicals in the natural gas extraction process is not limited to the injection of fracking fluids. During the initial process of drilling the vertical well, chemicals are added to “drilling muds” to reduce friction, ease the drilling process, and shorten drilling time [14]. In addition to concerns regarding contamination of water during the drilling and fracturing process, there are concerns about groundwater contamination from the salts, chemicals, and naturally occurring radioactive material present in flowback, which is usually temporarily pumped into wastewater ponds and then moved off-site, where it is re-injected back into the ground or transferred to wastewater treatment facilities for treatment and disposal. The practice of treating flowback and “produced water” at publicly owned treatment works (POTWs) has largely ended; particularly in Pennsylvania, where less than 1 percent of fracking wastewater is treated in this manner after the state’s Department of Environmental Protection (PaDEP) asked POTWs to voluntarily stop accepting fracking wastewater [15]. Now, the majority of flowback or “produced water” that is not disposed of in injection wells is treated at centralized waste treatment (CWT) facilities that are designed to treat industrial wastewater, and which may then discharge into sewers or surface water bodies. However, a report by the Natural Resources Defense Council (NRDC) found that wastewater discharged from these CWT facilities into surface water bodies still contained high levels of salts, bromides, and other pollutants [15].

Between 2009 and 2011, the EPA investigated potential groundwater contamination due to fracking in Pavilion, WY, and released its draft report in December 2011 [16]. EPA detected high concentrations of benzene, xylenes, and other gasoline and diesel range organics (types of petroleum hydrocarbon compounds), indicating a source of shallow groundwater contamination [16].

This EPA report is one of the few investigations of possible environmental contamination by hydraulic fracturing fluid injection. A single EPA report from 2004 found minimal risk to underground sources of groundwater due to hydraulic fracturing; however, this study was conducted in an area where coalbeds were being fractured, and not shalebeds, where the vast majority of fracturing occurs today [17]. No EPA reports to date have been released regarding the risks to groundwater and air associated with hydraulic fracturing in shalebeds. However, in 2011, Osborn and colleagues at Duke University published a study that showed increased concentrations of methane, ethane, and propane in private drinking-water wells directly attributable to the gas-well drilling in the Marcellus shale formation of Pennsylvania and New York [18]. The same research group did not find evidence of increased salinity or contamination from fracking fluids in a sample of private drinking-water wells [19]. However, these two studies and others acknowledge that hydraulic fracturing increases the permeability of shalebeds, creating new flow paths and enhancing natural flow paths for gas leakage into aquifers; these same pathways create a possible, although unlikely, contamination pathway for fracturing fluids [18-20]. The creation of additional fractures in the shalebeds and the drilling of wastewater disposal injection wells also change the hydrostatic pressure of the shale formation, possibly speeding up the normally extremely slow vertical flow of native and injected fluids closer to aquifers and the surface [20].

### **Voluntary Chemical Disclosure**

With the exception of state-specific laws, disclosure of the chemicals present in fracturing fluid is primarily based on self-regulation: that is, voluntary reporting by the natural gas companies. Starting in January 2011, the Groundwater Protection Council and the Interstate Oil and Gas Compact joined forces to create the website [FracFocus.org](http://FracFocus.org). Natural gas companies can provide well-specific information including the chemical composition of the fracturing fluid used at that particular well [21]. The chemical information may include Chemical Abstract Service (CAS) numbers, the purpose of an additive (e.g., proppant, biocide, gelling agent), and the maximum volume of the additive in hydraulic fracturing fluid [21]. The reporting of hydraulic fracturing chemicals is completely voluntary, and thus the accuracy and completeness of the information reported is unknown. The website does provide guidance stating that any chemical that has a Material Safety Data Sheet (MSDS) and is deemed nonproprietary should be reported [21]. However, chemicals are often reported as classes of chemicals (e.g., carbohydrate polymer, aliphatic alcohol), so that the exact identity of the chemical is unknown. While voluntary reporting is a first step toward increasing disclosure and public knowledge—and industry and some state governments view it as sufficient—the website does not have any government oversight nor does it provide complete information for lawmakers,

regulators, or communities regarding the specific chemicals that are being injected during hydraulic fracturing.

Recently, The Endocrine Disruption Exchange (TEDX)<sup>1</sup> conducted a study to determine chemical mixtures present in fracturing fluids [14]. TEDX created a list of 944 products currently used in natural gas operations as reported by a variety of sources including the U.S. Bureau of Land Management, the U.S. Forest Service, state government departments, and the natural gas industry. Among those products, 632 different chemicals were identified (e.g., methanol, ethylene glycol) [14]. More than 75 percent of the chemicals identified in the TEDX report are known to affect the skin, respiratory system, and/or the gastrointestinal system. Further, approximately 50 percent of the chemicals are known to have effects on the nervous system, immune system, and/or cardiovascular/circulatory system [14].

The chemical additives are undeniably a small fraction of the fluid composition. However, they consist of up to 2 percent of approximately 2 million gallons of fluid used in each operation; which results in nearly 40,000 gallons of undisclosed chemicals used at each well [11]. TEDX was able to identify many chemicals commonly used in fracturing fluid; however, it reports that for 43 percent of the products it investigated, only 1 percent of the total chemical composition of the product was identified [14]. This demonstrates that the precise chemical makeup of most fracturing fluids remains largely unknown. Lawmakers and the public lack information regarding the chemical mixtures used in fracturing fluid because companies are largely not required to release this information to regulators or the public. There is no federal regulation that mandates chemical disclosure, and state regulations exist but are varied. Lack of full chemical disclosure prevents us from understanding possible health and environmental effects associated with hydraulic fracturing and injection of fracturing fluids, as well as preventing proper monitoring of chemical contamination as a result of hydraulic fracturing operations.

### **HYDRAULIC FRACTURING EXEMPTIONS IN FEDERAL REGULATIONS**

Currently there are no federal regulations requiring natural gas companies to disclose information about chemicals used in hydraulic fracturing fluids. As a technology used by the natural gas industry, hydraulic fracturing is often considered a protected practice in laws from which the oil and gas exploration industry as a whole is exempt from regulation, including the Emergency

<sup>1</sup> TEDX ([www.endocrinedisruption.com](http://www.endocrinedisruption.com)) is a nonprofit organization whose mission is to prevent harmful exposures to endocrine-disrupting chemicals by seeking out, selecting, organizing, reviewing, and interpreting scientific research.

Planning and Community Right-to-Know Act of 1986 (EPCRA) [22]. Hydraulic fracturing as an injection process is specifically exempt from the Safe Drinking Water Act (SDWA) [23, 24].

### **Emergency Planning and Community Right-to-Know Act**

Hydraulic fracturing and reporting of the chemicals used in fracturing fluid is exempt from EPCRA [24]. Section 313 of EPCRA created the Toxic Release Inventory (TRI), which requires companies that manufacture and/or use toxic chemicals to report information on chemicals, including identities and quantities that are stored, released, transferred, or “otherwise used” [25, 26]. The reporting requirements for toxic chemical releases include any intentional or unintentional discharge of toxic chemicals into the air, water, and/or soil [25]. Except for chemicals claimed as trade secrets, the information reported to TRI is deemed public knowledge, so that communities remain informed about possible chemical exposures [26]. However, the North American Industry Classification System (NAICS) code for Oil and Gas Extraction is not listed under Section 313 of EPCRA, exempting this industry from reporting information on the release of toxic chemicals [26]. Consequently, quantities of chemicals used in hydraulic fracturing fluid are not subject to TRI reporting guidelines.

### **Safe Drinking Water Act**

Historically, the EPA did not regulate hydraulic fracturing under the Underground Injection Control (UIC) Program of the SDWA because the combined processes (well-drilling, injection of hydraulic fracturing fluids, and natural gas extraction) were considered primarily “extraction” processes rather than “injection” processes [17]. The UIC Program is responsible for regulating the construction, operation, permitting, and closure of injection wells that place fluids underground for storage or disposal [27].

However, a 1997 decision by the 11th Circuit Court of Appeals in a lawsuit brought by the Legal Environmental Assistance Foundation (LEAF) against EPA required the agency to regulate hydraulic fracturing in Alabama as a Class II injection well (injection related to the production of oil and gas) under the UIC Program of the SDWA [28].

LEAF originally petitioned the EPA on behalf of the McMillian family, who claimed that nearby fracking had contaminated their well water [29]. The petition requested that the EPA withdraw Alabama’s primary enforcement responsibility (known as primacy) for the state’s UIC program until the state included regulations for the injection of hydraulic fracturing fluids as part of the program plan [29]. If included under this regulation, injection of fracturing fluid would be subject to a permitting, reporting, and monitoring process [26]. The EPA asserted that the UIC Program under the SDWA does not specifically require

regulation of hydraulic fracturing and maintained that it had no legal requirement to regulate hydraulic fracturing as an injection process [30]. The 11th Circuit Court of Appeals disagreed with the EPA. Following the court's decision, the EPA was required to conduct a study to assess the risk posed to human health by the process of hydraulic fracturing.

While EPA's study was ongoing, in 2003, the agency entered into Memorandum of Agreement (MOA) with three companies which are together responsible for 95 percent of the hydraulic fracturing projects in the United States. As part of the MOA, these companies would not use diesel as part of the fracturing fluid mixture when they are removing natural gas from areas near underground drinking water sources. However, this MOA is not enforceable, and there is no penalty for a company should it wish to terminate the agreement [31].

EPA's court-mandated report, issued in 2004, determined that no further study into the health effects of hydraulic fracturing was necessary. Critics have questioned the legitimacy of this study because it did not involve any data collection, instead depending on existing literature and interviews with industry representatives and state and local government officials. In addition, the study considered effects on drinking water only from drilling in coal beds, but fracking takes place in additional types of substrates [32].

Regardless of the alleged flaws in the EPA report, in August 2005 Congress passed the Energy Policy Act exempting fracking from regulation under the 1974 Safe Drinking Water Act [17]. Specifically, the Energy Policy Act included in Section 322 an amendment to Section 1421(d)(1) of the SDWA exempting hydraulic fracturing as an underground injection process (42 USC 15801 § 322). The amendment states that underground injection "excludes – (i) the underground injection of natural gas for purposes of storage; and (ii) the underground injection of fluids or propping agents (other than diesel fuels) pursuant to hydraulic fracturing operations related to oil, gas, or geothermal production activities" [23].

## **FAILED ATTEMPTS AT FEDERAL REGULATION**

Two acts introduced in the last five years, and one proposed rule by the Obama Administration [33], attempted to amend federal exemptions of hydraulic fracturing and/or introduce provisions mandating the disclosure of the chemical composition of fracturing fluid. All three attempts to regulate chemicals in fracturing fluid at the federal level failed. A third act has proposed to specifically designate this as a responsibility of states.

### **The American Power Act**

In 2010, Senators John Kerry (D-MA) and Joseph Lieberman (I-CT) introduced the American Power Act, which included a section amending Section 324



of the Emergency Planning and Community Right-to-Know Act of 1986 [34]. As mentioned previously, as a practice of the oil and gas extraction industry, hydraulic fracturing is not included in the list of activities/industries required to report toxic chemical releases under EPCRA. Section 4131, Notice of Hydraulic Fracturing Operations, of the proposed American Power Act stipulated that “a hydraulic fracturing service company shall disclose all chemical constituents used in a hydraulic fracturing operation to the public” [35]. The bill would have required information to be distributed to the public via the internet, for the benefit of both private citizens and state and local authorities who are often unaware of the fracturing chemicals being used in their regions [35]. The Act was reportedly opposed for reasons unrelated to the hydraulic fracturing amendment clause and never made it out of committee [34].

### **The Fracturing Responsibility and Awareness Act**

The Fracturing Responsibility and Awareness (FRAC) Act entered House and Senate committees in both the 111th and 112th Congressional Sessions with the sole purpose of regulating hydraulic fracturing at a federal level [36]. The FRAC Act had two major purposes: (1) to amend Section 1421(d)(1) of the SDWA by removing the clause that exempts hydraulic fracturing from regulation under the UIC program; and (2) to mandate the disclosure of fracturing fluid chemical composition by adding regulations to Section 1421(b) of the SDWA, which outlines requirements for State UIC programs [37].

The chemical disclosure requirements in the FRAC Act had four specific objectives. First, operators of a well site must disclose to a designated federal or state regulator a list of chemicals intended for use before the fracturing fluid is injected [36]. When injection and extraction operations are complete, the operator must disclose the list of chemicals that were present in the fracturing fluid that was actually used [36]. Specifically, for every chemical being used (intended and actual), companies must disclose names (including CAS numbers), safety information (MSDS), and specific volumes of each chemical used. Second, the disclosure clause stipulated that information on nonproprietary chemicals be released to the public [36]. Third, if a spill occurs or an emergency situation arises, well operators must disclose the specific identity of all proprietary chemicals so that regulators and emergency personnel can properly address the situation [36]. Finally, the bill allows for proprietary information to be excluded from public disclosure in emergency and non-emergency situations [36]. Only information on nonproprietary chemicals will be released into public domain.

Supporters of the FRAC Act emphasized that the proposed amendment to the SDWA made certain that hydraulic fracturing would be regulated under “a consistent set of federally enforceable regulatory requirements” [38]. Senator Casey (D-PA) released a statement saying, “Disclosure will ensure that if drinking water supplies, surface waters, or human health are compromised,

the public and first responders will know how to respond properly. I view disclosure as a simple matter of citizens having a right to know about all risks in their community” [38].

Opponents of the act included state lawmakers, industry representatives, and even some environmental groups. State lawmakers made arguments against the FRAC Act, asserting that states where hydraulic fracturing is common practice already effectively regulate operators [39]. Furthermore, they argued that each state is best equipped to create laws that address the state’s geologic subtleties, which may necessitate differing operating practices [40]. Despite a specific clause protecting proprietary chemical identity from public release, industry expressed concerns over the disclosure of proprietary chemicals to federal regulators [39]. They feared protection of the information would not be sufficient and release of trade secret information would damage their competitive edge in the natural gas market. Some environmental groups were also critical of the FRAC Act, saying it did not go far enough in regulating hydraulic fracturing. Environmental groups disagreed with the continued protection of proprietary chemical information and cited shortcomings of the information being released about nonproprietary chemicals [36]. Their main concern is the lack of information provided by the MSDS, which often does not include health effects from environmental exposure to chemicals [36]. In addition, MSDS information exists for only a limited number of chemicals; only chemicals deemed hazardous by the Occupational Safety and Health Administration (OSHA) will have an MSDS [26, 41]. The bill was not passed into law; indeed, it did not make it out of committee during either Congressional session.

### **Fracturing Regulations are Effective in State Hands Act**

On March 28, 2012, Senator Inhofe (R-OK) and Senator Murkowski (R-AK) introduced the Fracturing Regulations are Effective in State Hands (FRESH) Act [42]. This act is designed to guarantee that states, not the federal government, have exclusive authority to regulate hydraulic fracturing activities within state boundaries [42]. Justification of sole state regulatory authority is based on a “lack of evidence” that hydraulic fracturing in one state presents a contamination risk to groundwater in another state [42].

## **FRACTURING REGULATIONS AT THE STATE LEVEL**

Arkansas, Colorado, Montana, Ohio, Oklahoma, Pennsylvania, Texas, and Wyoming have enacted fracturing disclosure laws [43, 44]. As of this writing, Ohio’s disclosure law is the most recent to pass, effective August 1, 2012, and reflects some lessons learned from other states [44]. We draw on the examples

of Texas and Pennsylvania, periodically referring to Ohio, to illustrate the issues of contention among environmental health professionals and advocates, regulators, and industry.

### **State of Texas**

Texas is one of the first states to enact a chemical disclosure regulation specific to fracking. The “Hydraulic Fracturing Chemical Disclosure” rules adopted in Texas have become the blueprint for regulation in other states. Many of the technologies responsible for increasing natural gas yields were borrowed from the Texas offshore oil and gas industry. Hence, Barnett Shale natural gas production increased 3000 percent from 1998 to 2007, making Texas the unofficial leader in energy resource recovery through hydraulic fracturing [4]. Texas has fought aggressively to maintain state control over regulations, with some Texans arguing that potential impacts of hydraulic fracturing such as “groundwater contamination, wastewater disposal, impacts to local character, and seismic impacts are essentially local in nature . . . and do not cross state boundaries,” and thus should be regulated at the state instead of at the federal level [45].

The Rail Road Commission (RRC) is the primary agency that regulates Texas’ oil and gas industry. Regulations prior to 2012 primarily identified and established a clear definition of well operators (i.e., owners or managers), confirming the financial security of a well operator, and establishing procedures for public notice of new applications for injection well permits received on or after September 1, 2005 [46]. Areas surrounding aquifers, usually protected from drilling activities, may be used for underground injection wells if the well operator applies for an aquifer exemption [46].

In response to public pressure and possibly as a mechanism of preempting federal oversight, the RRC adopted new rules on December 13, 2011, requiring the disclosure of the intended, nonproprietary chemicals used in hydraulic fracturing fluids [47]. These rules apply to treatments occurring on wells that have been issued an initial drilling permit on or after February 1, 2012, but do not place disclosure requirements on wells with prior permits [46]. This regulation requires the operator of the well to provide general information about the well’s location and dates of drilling activities, volume of water used, and each intended additive—its CAS number, intended use, and its maximum concentration by mass [46]. There is no requirement to report chemical components of hydraulic fracturing fluid before the fracturing activities begin. Instead, no later than 15 days *after* completion of a hydraulic fracturing treatment, the operator is required to file the chemical disclosure report with the RRC, and this information will be uploaded to the FracFocus website and henceforth be considered public information [46]. The RRC is responsible for enforcement, and violations may result in “monetary penalty and/or lead to the revocation of a well’s certificate of compliance” [47].

The chemical disclosure requirements in Texas, as in many of the other states with disclosure rules, have significant loopholes, which provide allowances for incomplete disclosure of the chemicals and quantities used, as well as the disclosure of inaccurate information. First, the rule requires reporting of only “actual or the maximum concentration of each chemical ingredient . . . in percent by mass” [48], instead of the total amount of the chemical used at the site. Second, chemicals that are “unintentionally added” or “occur incidentally” are exempt from disclosure [48]. Another caveat of the disclosure law is that suppliers, service companies, and operators are not held responsible for the reporting of inaccurate information to the RRC [48]. Chemicals entitled to trade secret protection can be entirely exempt from public disclosure, unless disclosure is considered necessary during an emergency situation [47]. In Texas, certain commercial or financial information can be exempted from public disclosure laws if, “based on specific factual evidence, disclosure would cause substantial competitive harm” [49]. The factors that determine if information qualifies for trade secret protection are: the extent to which the information is known by employees within or people outside of the company; the measures taken or amount of money expended by the company in developing and guarding the secrecy of the information; the value of the information to the company; and the ease with which the information could be acquired or duplicated by others [50]. If an emergency situation arises, the presence of additives protected by trade secret must be disclosed to emergency responders or health professionals to allow for proper cleanup and/or medical treatment for exposed individuals [48]. In the case of Texas, first responders must sign a statement of confidentiality, and are allowed to discuss chemical identities only with other first responders or accredited laboratories; they are not permitted to disclose chemical identities to the person(s) receiving medical care [48]. In contrast, Ohio’s recently passed law provides that “Doctors may share even proprietary chemical information with the patient and other medical professionals directly involved in treating a patient” [51]. While these state regulations are intended to establish transparency, they each fall short of full chemical disclosure and provide effective immunity to companies reporting inaccurate data.

### **Commonwealth of Pennsylvania**

It has been known since the 1930s that natural gas existed in the Marcellus Shale formation in Pennsylvania; however, conventional vertical drilling was not successful because the gas occurs in “pockets,” and therefore flows could not be sustained [2, 52]. In 2003, Range Resources–Appalachia began drilling wells, modifying the horizontal drilling techniques utilized in the Barnett Shale; by 2005, Marcellus gas was flowing [52]. Some assessments estimate more than \$500 billion in recoverable natural gas exists in Pennsylvania alone,

bringing on a drilling frenzy and leading to the creation of more than 350,000 active and inactive gas wells in Pennsylvania [7].

In Pennsylvania the Public Utilities Commission and the PaDEP are responsible for policing oil and gas activities. In 2008, a state investigation found 18 methane-contaminated wells after drilling activities began in the Susquehanna County area [53]. PaDEP fined the drilling company \$120,000 and required potable water be brought in until the company installed gas mitigation devices at each residence [53]. In a 2009 incident, gas migrated into a residential water well and exploded, spewing fracturing fluid, brine, unknown chemicals, and gas into a forest about 90 miles outside of Pittsburgh [4]. These and other spill events have intensified public pressure on the pro-drilling Pennsylvania administration to require disclosure of the chemicals used in hydraulic fracturing fluids.

Pennsylvania General Assembly signed a new reform amendment into law on February 14, 2012, providing updates to the 1984 Oil and Gas Act [54]. The new act is designed to update environmental regulations, drilling fees, and local regulations for conventional and unconventional (i.e., hydraulic fracturing) oil and gas operations in the state. Within 60 days of commencement of drilling activities, well operators must complete a chemical disclosure form and post it to the industry-run registry [55]. The chemical disclosure form requirements are essentially identical to those of Texas; for example, they do not require disclosure prior to the start of fracking activities, they include exemptions from disclosure of proprietary information, and they do not hold operators, vendors, or service providers responsible for providing inaccurate data to the registry [55].

## **REGULATORY CHALLENGES AND FUTURE REGULATORY PROSPECTS**

### **Enforcement**

In some states, including Texas, companies have been slow to comply with the disclosure regulations [56, 57]. The NRDC found that state regulators were consistently accepting disclosure reports that were missing information required by Texas's hydraulic fracturing chemical disclosure rules [56]. Further, other investigations have found that almost half of new wells drilled in Texas go completely unreported and disclosure reports are not submitted to FracFocus [57]. These failures to comply indicate that some states are not providing adequate oversight.

In 22 states, the number of new oil and gas wells grew 45 percent between 2004 and 2009, leaving regulators scrambling to keep up. Complaints of understaffing within the responsible departments persist. Common jobs of state regulators include "policing" gas wells, oil wells, waste injection wells, disposal pits, compressor stations, and access roads. In addition, they are responsible for approving new permits, visiting new wells and old ones before they are sealed,

and responding to complaints of all kinds [58]. An example of the insufficiency of state staffing of regulatory agencies can be found in Texas. In 2009, Texas had 273,660 wells and 106 regulators charged with overseeing them. In 2007, the Texas state auditor issued a report on the RRC's enforcement record. The auditor found that between 2001 and 2006, about half of the state's wells had not been inspected. The report also found that 30 percent of all spills were inspected late or not at all. Despite the growing workload, the budget is getting smaller. Between 2005 and 2009 the commission's budget for monitoring and inspections decreased by 10 percent. Even when regulators conduct inspections, there are sometimes flaws in their work [58].

While regulation of chemical disclosure is occurring at the state level, the examples of Texas and Pennsylvania highlight shortcomings and loopholes that result in the provision to the public of inadequate information—or misinformation—regarding the chemical composition of hydraulic fracturing fluids. The above examples also point to a lack of compliance due to failed state oversight. Federal regulation and oversight may be necessary to ensure that sufficient and accurate information is being reported. We suggest that the federal government not preempt state regulation of fracking, but at a minimum require adequate chemical disclosure to federal, state, and local regulators, and to the public.

### **Future Prospects**

In the FY2010 Budget, the U.S. House of Representatives Appropriations Conference Committee included funds for a new EPA study on the effects on drinking water of hydraulic fracturing of shale formations [26]. EPA's first action was to request the chemical composition of drilling muds and fracturing fluids from nine of the largest natural gas and hydraulic fracturing companies [59]. The EPA recognized this as the fundamental first step in completing "a more thorough assessment of the potential impact of hydraulic fracturing," which underscores the importance of chemical disclosure [59]. The EPA study is underway and an initial progress report is expected in late 2012.

In March 2011, President Obama instructed the Secretary of Energy Advisory Board (SEAB) to create a subcommittee focused on exploring options for improving the safety of and public support for shale gas development [40]. From this charge, the Shale Gas Production Subcommittee completed two reports in which disclosure of fracturing fluid composition is a recommendation on the list "for immediate implementation" [40]. The Subcommittee recognized the work done by industry on the FracFocus.org website as a first step and believes that "disclosure should include all chemicals, not just those that appear on MSDS" [40]. They also envision that disclosure of the chemical composition of fracturing fluid will appear on a well-by-well basis and that this information will be made publicly available via a website. While this call for complete disclosure is encouraging, the Subcommittee's implementation plan is lacking.

The Subcommittee recommends relying on the Department of Interior to design and implement a plan for requiring chemical identity disclosure of fracturing fluids on federal lands [40].

The Department of Interior Bureau of Land Management controls all federal and public lands and has historically allowed natural gas extraction, including the use of hydraulic fracturing on public lands. In May 2012 the Bureau of Land Management issued a proposed rule [33] that would have required industry to report fracturing fluid composition prior to drilling on public lands, but the Obama Administration reportedly backed off from this demand, agreeing to allow companies to reveal the contents of drilling fluids after the fact [61].

Efforts also continue to update federal regulations to include hydraulic fracturing under some of the major environmental laws. In August 2011, the environmental group Earthjustice petitioned the EPA on behalf of over 100 community and environmental groups across the country [62] calling for EPA to pursue regulation of hydraulic fracturing (including drilling muds and fracturing fluids) under Section 4 and Section 8 of the Toxic Substances Control Act (TSCA) (15 USC § 2620) in order to protect “public health and the environment from the serious risks posed by chemical substances and mixtures used in oil and gas exploration and production” [62]. The group requested that EPA pursue, under TSCA Section 4, a requirement for manufacturers and users of fracturing fluids to identify all chemicals used and to conduct toxicity testing on those chemicals [62]. The information gained from the disclosure of chemicals and toxicity testing would be used to evaluate impacts on human health and the environment. Under TSCA Section 4, the EPA has “authority to require testing of chemicals which may present a significant risk or which are produced in substantial quantities and result in substantial human or environmental exposure” [26]. Additionally, Earthjustice asked EPA to adopt a rule under TSCA Section 8(a) requiring manufacturers and users of fracturing fluids to maintain, update, and submit records to EPA regarding specific chemical identities, proposed categories of use, potential byproducts, and existing and/or new environmental and health effects data [62]. Under TSCA Section 8 the EPA can implement “recordkeeping and reporting requirements to ensure that the EPA administrator would continually have access to new information on chemical substances” [26].

In November 2011, the EPA Assistant Administrator Stephen Owens responded to the Earthjustice petition in two separate memos [63, 64]. First, the EPA denied the petition’s first request for adoption of a rule under TSCA Section 4 requiring toxicity testing for all chemicals used in fracturing fluid [63]. The EPA stated that the petition “did not set forth facts sufficient to support the required findings under TSCA Section 4(a)(1)(A) or 4(a)(1)(B) for issuance of a test rule” [63]. The EPA response memo suggests Earthjustice did not sufficiently identify a “risk trigger” (TSCA Section 4(a)(1)(A)) or an “exposure trigger” [26]. A *risk trigger* is defined under TSCA as a chemical that the EPA determines presents an “unreasonable risk of injury to human health or the environment”

[26]. An *exposure trigger* is defined under TSCA as chemical that is “produced or released into the environment in substantial quantities” [26].

The burden for EPA of proving that a chemical (or a group of chemicals) is either a risk trigger or exposure trigger is very high. The catch-22 for both of these rules is that often data do not exist that would allow the EPA to conduct a risk determination for a chemical. While the EPA can require testing if it finds that insufficient data exist, often the agency must still prove “unreasonable risk” for the risk trigger and “substantial quantities” for the exposure trigger. In essence: no data, no risk; no risk, no data.

In the EPA’s second memo, it partially granted petitioners’ request for initiating a “rulemaking process” under TSCA Section 8(a) requiring some reporting on chemicals used in fracturing fluids [64]. As a first step, the EPA will convene a “stakeholder process” to determine an approach for reporting that will involve minimal cost and duplication of effort while maximizing information, transparency, and public understanding [64]. States, industry, and public interest groups will be allowed to participate in the dialogue [65].

While there is some movement toward regulating hydraulic fracturing, and mandating chemical disclosure appears to be high on the list of priorities for environmental and community groups as well as some federal legislators, the process of changing federal regulations is slow and will continue to be challenged by industry and some lawmakers.

## CONCLUSIONS

Advancements in natural gas recovery technologies and attractive prices have spurred a modern day “gas rush,” leading to a 48 percent increase in U.S. shale gas production from 2006 to 2010 [1]. Natural gas extraction using hydraulic fracturing does provide benefits, such as a domestic energy source that may be cleaner than coal. However, these benefits should not exempt the industry from federal environmental laws that are put in place to protect public health and the environment. Hydraulic fracturing activities come with a cost—incidents of leaking pipelines, wellhead explosions, lack of wastewater treatment, and toxic air emissions, which can lead to significant cleanup costs and environmental health impacts—so regulation is necessary [4]. To mitigate these environmental and human health costs, all hydraulic fracturing activities should be better regulated. The SEAB recommended regulations to reduce air emissions from hydraulic fracturing practices and also regulations to ensure water management and groundwater safety [40]. We view regulation of hydraulic fracturing fluid chemical disclosure as a first step towards other hydraulic fracturing regulations. To create an enforceable and protective regulatory program, lawmakers should first have knowledge of the chemicals used in these processes and then determine whether the chemicals require regulation to protect public health and safety and the environment.



Shortcomings of state regulations, their variable enforcement, and limitations of the current voluntary reporting mechanism lead us to recommend federal regulations requiring full disclosure of chemical additives in hydraulic fracturing fluids. A federal law that both lifts current federal exemptions for hydraulic fracturing and mandates complete disclosure of chemicals (including proprietary and nonproprietary chemicals, and MSDS and non-MSDS chemicals) is essential. Federal regulations are crucial for setting a baseline of disclosure requirements that all states are required to follow. The foundation for creating federal regulation is a strong scientific base and the consideration and protection of human dignity, equity, and distributional impacts that are not requirements for state regulations or voluntary guidance [66]. Without information on the chemicals of concern, our regulations cannot be informed by scientific information or other knowledge regarding health risks. Oversight at the federal level could ensure that a standard set of regulations will be applied to hydraulic fracturing operations across the country.

Lastly, federal oversight of hydraulic fracturing will standardize and streamline regulatory processes, which can lead to economic benefits. In fact, the U.S. Office of Management and Budget recently reported the estimated cost and benefits associated with federal regulations [66]. The report concluded that, over the course of a decade (FY2001-FY2010), major federal regulations provided an estimated \$132-\$655 billion in net positive benefits while costing taxpayers between \$44 billion and \$62 billion [66]. Federal regulations enforcing the EPA's Clean Water Act, SDWA, and Clean Air Act were among the regulations that produced the highest net benefits compared to costs [66].

The current status of disclosure prevents the public, lawmakers, and scientists from understanding possible health and environmental effects, and also prevents proper monitoring of chemical contamination as a result of hydraulic fracturing operations. We believe federal regulations are essential to ensure that air and water quality will not be compromised, minimum requirements for chemical disclosure will be standardized across all states, and responsible parties will be held accountable if the natural environment or public health is harmed.

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#### **AUTHORS' BIOGRAPHIES**

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*Features*

**MARCELLUS SHALE DRILLING'S IMPACT ON  
THE DAIRY INDUSTRY IN PENNSYLVANIA:  
A DESCRIPTIVE REPORT**

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**ABSTRACT**

Unconventional natural gas drilling in Pennsylvania has accelerated over the past five years, and is unlikely to abate soon. Dairy farming is a large component of Pennsylvania's agricultural economy. This study compares milk production, number of cows, and production per cow in counties with significant unconventional drilling activity to that in neighboring counties with little or no unconventional drilling activity, from 1996 through 2011. Milk production and milk cows decreased in most counties since 1996, with larger decreases occurring from 2007 through 2011 (when unconventional drilling increased substantially) in five counties with the most wells drilled compared to six adjacent counties with fewer than 100 wells drilled. While this descriptive study cannot draw a causal association between well drilling and decline in cows or milk production, given the importance of Pennsylvania's dairy industry and the projected increase in unconventional natural gas drilling, further research to prevent unintended economic and public health consequences is imperative.

QA: Please supply 3-5  
key words

**Keywords:** fracking, dairy industry

The search for clean, efficient, and economic energy sources is a high priority for most nations, industrial and emerging. While oil and coal remain the predominant energy sources worldwide (34% and 30%, respectively), each has its advantages and disadvantages. Natural gas (24% of the world's energy source), hydropower (6%), and nuclear energy (5%) are being promoted as energy options [1]. While there are pros and cons to each of these energy sources, natural gas in particular is abundant around the world and has a "clean" reputation—in that it burns cleaner than coal, for example. It is easy to transport, reasonably economical, requires comparatively quick construction timelines and low capital costs, and has the added advantage of bringing jobs to economically depressed regions where natural gas reserves are plentiful. Because of these benefits, natural gas has emerged as a key energy source around the world.

Most natural gas is currently extracted from conventional deposits, where it has migrated from a source rock and been trapped. However, a significant amount of natural gas is found distributed in relatively impermeable rock formations such as shale. Shale gas, once extracted, is identical to conventional natural gas.

For years, extracting natural gas from vast shale deposits was too costly and technologically challenging. Technical advances, however, have allowed the extraction of fossil fuels that in the past were logistically impossible and/or economically prohibitive (e.g., deep-ocean drilling for gas and oil, extracting oil from tar sands, and deep mining for coal, minerals, and ore). Today, extracting natural gas from vast shale deposits is possible by means of high-volume hydraulic fracturing of shale formations, using slick-water and multiple long, horizontal laterals from clustered, multi-well pads generally referred to in the media as fracking, hydraulic fracturing, or unconventional drilling.

In 2001, shale gas accounted for 2 percent of total natural gas production. As of 2010, it accounted for 23 percent of U.S. natural gas production, and this share is projected to increase to nearly half of the total production by 2035. Ironically, the shale gas boom has positioned the United States to become an overall net exporter of natural gas [2]. Indeed, the natural gas industry now has a glut so vast that import facilities are applying for licenses to export gas to Europe and Asia [3].

Unconventional drilling injects under high pressure huge volumes of fracturing fluid (referred to as slick-water), which is comprised of water, sand, and chemicals, many known to be toxic, several thousand feet underground to create or re-open cracks or fissures in the shale formation to release trapped shale gas. Gas operators in the United States are allowed to protect their proprietary formulas, and they do not have to disclose the chemical compounds used in the drilling process, thus making it difficult if not impossible to assess the full scope of the contents of the fluid that is returned to the surface ("flowback" fluid). Thirty to 70 percent of the fluid will resurface, bringing back with it toxic substances, including heavy metals, naturally occurring radioactive materials (NORMs), and toxic and volatile organic compounds including benzene, a



known carcinogen. Flowback waste fluids, held in open reserve pits or in non-airtight metallic containers, must be disposed of safely because they can potentially contaminate air and soil as well as waterways and watersheds. Despite a recent Environmental Protection Agency (EPA) study of groundwater contamination near the town of Pavillion, Wyoming, that suggests a pathway for exposure [4], no state has adequate regulations on drilling, particularly related to the disposal of the toxic wastewater fluids.

Despite the paucity of studies evaluating the potential impact on human health, unconventional drilling has accelerated at a rapid pace in many areas in the United States. In particular, Pennsylvania, through which the Marcellus Shale extends, has embraced an aggressive policy of unconventional drilling. Almost 6,000 wells have been drilled in a six-year period, and thousands more drilling permits have been issued [5]. In 2011 alone, 2,096 drilling permits were issued in five counties in which there already is substantial ongoing unconventional drilling activity (Bradford, Lycoming, Susquehanna, Tioga, and Washington). Tens of thousands of permits are expected to be issued over the next decade in Pennsylvania.

Agricultural activity in Pennsylvania is important to its economy, and dairy farming is a large component of the state's agricultural economy. The state ranks fifth in milk production in the United States after California, Wisconsin, Idaho, and New York [6]. One of the top milk-producing counties, Bradford, happens to be located within the Marcellus Shale and as of 2011 has the greatest number of unconventional wells drilled of all Pennsylvania counties.

The economic implications of unconventional drilling activity have not been well studied, nor have studies been conducted to assess the impact on the environment or on human and animal health. In the absence of health impact assessments for human health, animal studies can shed light on the potential harmful effects of drilling. Like the canary in the coal mine, cows, horses, poultry, and other wildlife can be used as sentinels to foreshadow impacts to human health. Animals tend to suffer more direct exposure and have shorter life and reproductive cycles, making it easier to document effects.

A recent qualitative study, published in a peer-reviewed journal, focused on the impact of gas drilling on animal health (interviews conducted with animal owners in Colorado, Louisiana, New York, Ohio, Pennsylvania, and Texas), documenting reproductive (irregular cycles, failure to breed, stillbirths), neurological (seizures, incoordination, ataxia), gastrointestinal (vomiting, diarrhea), and dermatological (hair and feather loss, rashes) problems among livestock [7].

Another recently completed study investigating changes in milk production and cow numbers in Pennsylvania counties between 2007 and 2010 found an association between drilling and declining cow numbers, with higher drilling activity associated with larger average declines in cow numbers. Further, counties with 150 or more Marcellus Shale wells on average experienced an 18.5 percent decrease in total milk production compared to an average increase

of 0.9 percent in counties with no Marcellus Shale wells drilled [8]. While the study could not fully explain the findings, the implications for Pennsylvania, with its large dairy industry, need to be more fully investigated.

This descriptive study seeks to lay the basis for observing trends in a longitudinal approach and to raise questions that can be tested in a more analytic manner. We focus on Pennsylvania primarily because there has been an explosive increase in unconventional drilling in this state since 2006 (unlike in neighboring New York, which as of 2012 has a moratorium on drilling in place), and because the implications for its agricultural and dairy industries could be significant.

## METHODS

From 1996 through 2006 there was essentially no unconventional drilling for natural gas in any county in Pennsylvania. From 2007 forward, however, there was a substantial increase in the number of wells drilled in counties that have Marcellus Shale beneath them. We focus on comparing milk production (in thousand of pounds), number of cows, and average milk production per cow in counties with the most unconventional drilling activity to neighboring counties with less unconventional drilling activity (defined as fewer than 100 wells drilled) from 1996 through 2011, with particular focus on the years 2007 through 2011. Five counties with the greatest amount of drilling activity were selected (Bradford, Lycoming, Susquehanna, Tioga, and Washington) and six neighboring counties with fewer than 100 wells drilled were chosen for comparison (Beaver, Clinton, Lackawanna, Potter, Somerset, and Sullivan). Data on milk production per cow, total milk production, and total number of milk cows, by county by year, were obtained from the U.S. Department of Agriculture's National Agricultural Statistics Service (NASS) [9]. The number of drilled wells, measured through spud well data provided by the Pennsylvania Department of Environmental Protection, was obtained for each county by year [10]. In oil and gas parlance, *spud* refers to the actual start of drilling of an unconventional gas well, and this is how Pennsylvania drilling data are compiled.

As noted above, NASS updates statistics on milk production yearly, and Pennsylvania census data on the number of farms become available every five years (the next update is expected in 2014). However, a finer-grained analysis that would relate milk production or herd numbers to distance to active wells is not possible because data are not reported on the level of individual farms.

## FINDINGS

Figure 1 shows the increase in number of wells drilled by county by year for the five counties with the most wells. Of counties with drilling activity, Bradford has the greatest number of wells by far.

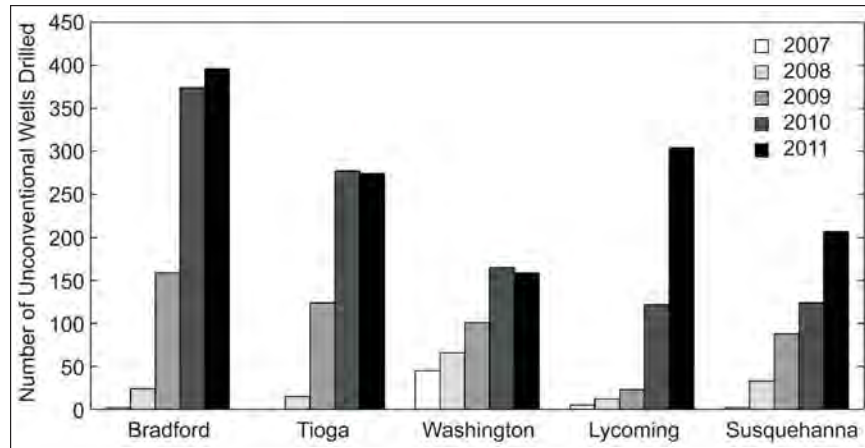


Figure 1. Unconventional wells drilled by county by year.

Table 1 shows, by county, the percent change from 2007 to 2011 in number of milk cows and total milk production (in thousands of pounds), and also the number of wells drilled during these years. The number of milk cows in each of the counties with the most wells drilled declined substantially during this time period, ranging from -18.3 percent in Tioga county to -46.7 percent in Washington county. In the counties with fewer than 100 wells, the percentage change in number of milk cows varied, showing no change in two of the counties, a modest decrease in three of the counties, and an 11.5 percent increase in Potter County. For those counties that showed a decrease in the number of milk cows, there was a corresponding decrease in the total milk production. Similarly, each county in the group with the most drilled wells posted a decrease in total milk production, whereas the change among the adjacent counties with fewer than 100 wells was varied. In this group, the three counties that had a reduction in the number of milk cows also had a reduction in milk production. The two counties with no change in the number of milk cows posted increases in total milk production, and the only county to show an increase in the number of milk cows also showed an increase in total milk production. There does not seem to be a clear relationship between the percentage changes in dairy indicators and the number of wells drilled. For example, Washington County showed the largest decline in the number of milk cows and total milk production, but has far fewer drilled wells than Bradford County. The following tables present the data with more detail.

Tables 2a and 2b show the mean, median, standard deviation, and range in the annual number of milk cows for each county. In all five counties with the most wells drilled, the data show a substantial decrease in the number of milk cows

Table 1. Percent Change in Number of Milk Cows, Total Milk Production, and Number of Wells Drilled by County, 2007-2011

County	Percent change in number of milk cows	Percent change in total milk production (pounds)	Number of wells drilled
Counties with most wells drilled ( <i>N</i> = 5)			
Bradford	-25.6	-20.6	955
Tioga	-18.3	-16.8	690
Washington	-46.7	-28.9	536
Lycoming	-36.0	-26.5	466
Susquehanna	-25.0	-23.9	454
Adjacent counties with fewer than 100 wells drilled ( <i>N</i> = 6)			
Sullivan	-5.3	-2.5	41
Clinton	0	+ 1.4	88
Potter	+ 11.5	+ 8.7	72
Lackawanna	0	+ 10.0	2
Somerset	-12.1	-10.5	19
Beaver	-11.1	-10.1	7

both from 1996 through 2006 (prior to active drilling) and from 2007 through 2011. With the exception of Clinton County, adjacent counties with fewer than 100 wells drilled also showed a decrease in the number of milk cows from 1996 through 2006. From 2007 through 2011, the outcome was more mixed: some of the counties experienced a modest decrease (Sullivan, Somerset, Beaver), some experienced no change (Clinton, Lackawanna), and one experienced a modest increase (Potter). Overall, these findings seem to indicate that drilling did not accelerate a decline in the number of milk cows, as the decline was underway before wells were drilled; however, even though drilling had not commenced prior to 2007, the sale and leasing of land most certainly had.

A decrease in the number of cows could explain a decrease in milk production. Tables 3a and 3b show the mean, median, standard deviation, and range in total milk production (in thousands of pounds) by county by year. Data show that during the years 1996 through 2006 in counties with the most wells drilled, there was a decline in total milk production ranging from -15.7 percent in Bradford county to -53.3 percent in Washington County. Only Lycoming County showed a modest increase (+7.6%). From 2007 through 2011 the trend continued, with every county showing a decline in total milk production. Among adjacent counties with fewer than 100 wells drilled, the picture is more mixed (Table 3b). From 1996 through 2006, some counties posted increases (notably Clinton with

Table 2a. Number of Milk Cows in the Five Counties with Most Wells Drilled, 1996-2011

	Counties				
	Bradford	Tioga	Washington	Lycoming	Susquehanna
Mean	25,843.8	13,387.5	4,640 <sup>a</sup>	6,706.7 <sup>a</sup>	12,481.3
Median	24,850	12,250	4,200	6,800	11,300
SD	3638.9	2555.7	1105.7	859.0	2889.1
Range	19,500-31,500	10,400-18,000	3,000-6,600	5,000-7,900	8,400-16,800
Percent change, 1996 to 2006	-30.7%	-52.5%	-73.7%	-16.2%	-58.5%
Percent change, 2007 to 2011	-25.6%	-18.3%	-46.7%	-36.0%	-25.0%

<sup>a</sup>Missing data for some years.

Table 2b. Number of Milk Cows in Six Adjacent Counties with Fewer than 100 Wells Drilled, 1996-2011

	Counties					
	Sullivan	Clinton	Potter	Lackawanna	Somerset	Beaver
Mean	2,243.8	5,593.3 <sup>a</sup>	5,062.5	1,531.3	18,881.3	2,450
Median	2,100	5,600	5,100	1,500	19,250	2,300
SD	316.2	584.9	239.1	343.9	1098.0	539.1
Range	1,900-2,800	4,700-6,500	4,600-5,400	1,100-2,300	16,500-20,100	1,800-3,300
Percent change, 1996 to 2006	-19.0%	+20.3%	-10.4%	-81.8%	-10.4%	-60.0%
Percent change, 2007 to 2011	-5.3%	0%	+11.5%	0%	-12.1%	-11.1%

<sup>a</sup>Missing data for some years.

Table 3a. Total Milk Production (in Thousand Pounds) by Year in the Five Counties with Most Wells Drilled, 1996-2011

	Counties				
	Bradford	Tioga	Washington	Lycoming	Susquehanna
Mean	471,144.4	229,336.9	69,472 <sup>a</sup>	105,249.3 <sup>a</sup>	204,142.5
Median	463,795	216,110	64,500	114,600	195,950
SD	51,612.1	31,449.8	13,289.6	25,953.1	42,612.8
Range	380,000-539,300	190,000-282,400	52,000-93,800	95,000-122,700	155,000-275,800
Percent change, 1996 to 2006	-15.7%	-27.7%	-53.3%	+ 7.6%	-45.9%
Percent change, 2007 to 2011	-20.6%	-16.8%	-28.9%	-26.5%	-23.9%

<sup>a</sup>Missing data for some years.

Table 3b. Total Milk Production (in Thousand Pounds) for Six Adjacent Counties with &lt; 100 Wells Drilled, 1996-2011

	Counties					
	Sullivan	Clinton	Potter	Lackawanna	Somerset	Beaver
Mean	38,821.9	161,134.7 <sup>a</sup>	92,185	23,540.6	304,555.6	39,385.6
Median	38,200	100,800	94,320	22,250	305,200	37,650
SD	3,604.9	260,086.5	6,057.6	4,552.8	12,569.5	4,709.6
Range	34,400-45,600	69,600-110,050	82,700-102,200	18,000-33,200	285,000-327,000	33,500-46,600
Percent change, 1996 to 2006	-7.9%	+ 32.7%	+ 3.0%	-67.5%	+ 7.8%	-23.1%
Percent change, 2007 to 2011	-2.5%	+ 1.4%	+ 8.7%	+ 10.0%	-10.5%	-10.1%

<sup>a</sup>Missing data for some years.

a 32.7 percent increase during this time period) while other counties showed declines (notably Lackawanna with a 67.5% decrease). From 2007 through 2011, some counties posted modest increases (Clinton, Potter, Lackawanna) while others showed declines ranging from 10.5 and 10.1 percent declines in Somerset and Beaver Counties, respectively, a to 2.5 percent decline in Sullivan county.

To understand better the implications of these findings, data on average milk production per cow were obtained for the years 1996 through 2011. Table 4 compares the five counties with the most drilling to the adjacent counties with fewer than 100 wells drilled. Average annual milk production per cow remained fairly constant from year to year in the five counties with the most wells drilled and the six adjacent counties with fewer than 100 wells drilled. Tables 5a and 5b show the data in greater detail. In all counties with the most wells drilled there were modest increases in average milk production per cow between 1996 through 2006, and this trend continued during the 2007 through 2011 time period. In adjacent counties with fewer than 100 wells drilled, a similar picture emerges for the period 1996 through 2006, when every county posted an increase; however, for the time period 2007 through 2011, the situation is more mixed. Lackawanna county showed a greater increase in average milk production per cow (+10%) than the other counties, which either showed very modest increases or in the case of Potter and Sullivan Counties a slight decrease (-3.3%).

Table 4. Average Milk Production per Cow,  
by Year and County Group, 2007-2011

Year	Average milk production per cow	
	Counties with most wells drilled (N = 5)	Adjacent counties with fewer than 100 wells drilled (N = 6)
2007	17,949.4	17,734.8
2008	18,407.0 <sup>a</sup>	17,868.6 <sup>a</sup>
2009	17,848.2	17,561.5
2010	18,763.7	18,308.5
2011	18,970.3	17,931.2
Average, 2007-2011	18,386.1	17,881.3

<sup>a</sup>Missing data for some counties.

**Note:** *t*-value = 2.33, *p* = 0.05.

Table 5a. Average Annual Milk Production per Cow, for Five Counties with Most Wells Drilled 1996-2011 (N = 5)

	Counties				
	Bradford	Tioga	Washington	Lycoming	Susquehanna
Mean	18,311	17,291	15,181 <sup>a</sup>	16,864 <sup>a</sup>	17,236
Median	18,076	17,100	14,450	16,500	16,750
SD	834.43	996.22	1400	1293	1020.5
Range	17,000-19,744	15,400-18,868	13,881-18,667	15,000-19,400	16,000-18,966
Percent change, 1996 to 2006	+ 11.8%	+ 16.3%	+ 11.8%	+ 15.7%	+ 8.1%
Percent change, 2007 to 2011	+ 4.0%	+ 1.2%	+ 12.1% <sup>a</sup>	+ 7.0%	+ 1.4%

<sup>a</sup>Missing data for some years.

Table 5b. Average Annual Milk Production per Cow for Six Adjacent Counties with Fewer than 100 Wells Drilled, 1996-2011 (N = 6)

	Counties					
	Sullivan	Clinton	Potter	Lackawanna	Somerset	Beaver
Mean	17,345.6	16,959 <sup>a</sup>	18,289.4	15,484.5	16,184.5	16,413.1
Median	17,400	16,900	18,402	15,000	16,050	16,063
SD	941.2	1237.8	1035.1	961.6	1195.0	1724.4
Range	15,700-18,648	14,800-18,750	16,200-19,800	14,400-17,500	14,400-18,155	14,000-18,611
Percent change, 1996 to 2006	+ 15.1%	+ 19.6%	+ 18.2%	+ 7.9%	+ 16.7%	+ 23.1%
Percent change, 2007 to 2011	-3.2%	+ 1.4%	-3.3%	-10.0%	+ 1.5%	+ 0.9%

<sup>a</sup>Missing data for some years.



## DISCUSSION

Data based on U.S. Department of Agriculture statistics show a greater decrease in milk production (in thousands of pounds) and number of milk cows in counties with the most drilling activity compared to neighboring counties with fewer than 100 wells drilled. Similar findings were reported in the Kelsey report [11]. Our study shows that between 1996 and 2006, prior to active well drilling, there was a decrease in the number of cows and in milk production in counties with the most drilling and a more mixed picture in adjacent counties with fewer than 100 wells drilled. Counties with the most wells drilled during 2007 through 2011 uniformly had declines in total milk production ranging from -16.8 percent in Tioga county to -28.9 percent in Washington county. The number of wells drilled did not appear to explain the differences in this decline. Bradford County, for example, had the greatest number of wells drilled yet did not have the highest percent change in either the number of milk cows or total milk production. In fact, Washington County, with fewer wells drilled, posted the highest percentage changes.

This study could not determine whether milk production on farms whose owners had leased or sold land to drilling companies was less than on farms whose owners had not leased or sold part of their land. We do not know either the proportion of farms whose owners have leased or sold land or the proportion on which wells have been drilled. Our data could not explain the extent to which milk production and number of cows on farms in counties with the most drilling decreased compared to the same measures on farms where land had not been leased or sold in adjacent counties with less drilling activity.

Our analysis cannot explain whether dairy farmers downsized their herds, quit dairy farming, or some combination thereof. We also cannot determine how many dairy farmers in counties with the most active well drilling “took the money and ran.” That is, with money earned from selling or leasing their land, what proportion of dairy farmers downsized or left the dairy business entirely? While our data clearly show differences among counties, this descriptive study cannot assume that there is a causal association between well drilling and decline in cow numbers or milk production. Clearly, further investigation should be initiated to better understand what is happening in Pennsylvania counties.

The dairy industry is very important in Pennsylvania, and implications for milk prices could be significant. Many factors probably influence the number of cows, milk production, and even milk prices; yet, the impact a downsized dairy industry would have on the economics of Pennsylvania should be analyzed. Given that the other major milk-producing state in the Northeast, New York, seems poised to begin allowing unconventional gas drilling, the effects on the dairy industry could become a major area of regional, if not national, concern. What is clear is that well drilling in Pennsylvania, based on the number of permits already issued, will continue, if not accelerate, over the next few years. It will be

important for the State of Pennsylvania to monitor changes in milk production over time to see if the downward trend continues, both in counties with more wells drilled and in counties with fewer wells drilled, and to assess the potential effect of this situation on the state's economy.

### **ACKNOWLEDGMENT**

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*Voices*

**INSIGHTS ON UNCONVENTIONAL NATURAL  
GAS DEVELOPMENT FROM SHALE:  
AN INTERVIEW WITH ANTHONY R. INGRAFFEA**

**ADAM LAW  
JAKE HAYS**

**ABSTRACT**

Adam Law, M.D., interviewed Anthony R. Ingraffea, Ph.D., P.E., as part of a series of interviews funded by the Heinz Endowment. Dr. Ingraffea is the Dwight C. Baum Professor of Engineering at Cornell University, and has taught structural mechanics, finite element methods, and fracture mechanics at Cornell for 33 years. He discusses issues related to hydraulic fracturing, including inherent risks, spatial intensity, and the importance of a multi-disciplinary organization in establishing a chain of evidence.

**Keywords:** hydraulic fracturing, fracking, shale gas, spatial intensity, unconventional gas drilling

**LAW: Tony, I wanted to discuss hydraulic fracturing and shale gas development with you since you're an engineer and a long-standing researcher in how objects and faults fracture. Specifically, I am interested in what insights you might have in addition to the information you typically provide regulators, policy makers, and others.**

**INGRAFFEA:** There is one very important aspect of unconventional gas developed from shale that hardly anybody understands, and I'm talking about the general public, policymakers, even regulators. The only entities that get it are the operators and a few individuals like myself who really understand the nexus between geology, geochemistry, engineering, science, and technology. And let me tell you what that issue is. It's called *spatial intensity*.

As you know, people are a bit upset about how things have progressed with shale gas development in a place like Pennsylvania. What people don't understand yet is that we haven't even started. Pennsylvania's been developing shale gas since 2007. And in that period of time there've been roughly 5,500 wells drilled, and people think, well, that's a lot.

But of those 5,500 wells that have been drilled, only about half have been fracked. And that half that's been fracked constitute about 2 percent of the eventual so-called build-out of Pennsylvania. So someone could fly over all of the areas of Pennsylvania right now that have been developed in Marcellus and say, that's not so bad, that's not like mountaintop removal in West Virginia. Well, not yet. Only about 2 percent of the wells that are going to be fracked have been fracked.

Yet, if we look at the consequences already—the number of individual private water wells that have already been contaminated, the number of health incidents that have occurred, the number of spills that have occurred, the number of truck accidents that have occurred—it's pretty simple now to start forecasting and crystal-ball-gazing and say what's it going to be like. If it's like this with 2 percent, what's it going to be like at 10 percent? What's it going to be like at 20 percent? It's going to be hellacious. The industry knows it. The gas is everywhere there's shale. Not in uniform quantities, of course. They still have to drill exploration wells to find their so-called hot spots—a county here, a county there.

But all of the prognoses that I'm reading out of the industry literature are that New York, Pennsylvania, Ohio, West Virginia, Maryland, a little bit of Virginia, are going to be subjected to at least 200,000 Marcellus Shale gas wells. And that's just the Marcellus. Of course they promise us there's also the Utica and a couple of others. So I'm repeating myself, but the single most important aspect that nobody gets is that it hasn't even started yet.

**LAW:** For those of us following up on this who are in the health care area, one of the big concerns has to do with pathways of exposure. In other words, in either the chemicals that we're putting into slick water or into drilling muds, or the flowback-produced waters, or the emissions coming back out as fugitive emissions—is there any way people can be exposed to that?

**INGRAFFEA:** Sure. The pathways are numerous and obvious. I categorize them as: from deep underground, from the surface, and from the air. And this kind

of intense spatial development, number one, as I just said, is going to poke a few hundred holes in the ground that weren't there. Three hundred and thirty million years of sequestration of hydrocarbons, heavy metals, salts, and naturally occurring radioactive material is being de-sequestered. We're taking all that out and putting fresh water down.

Brilliant. What an exchange. What we just spent the last 30 or 40 million years doing, which is sequestering a lot of carbon dioxide, and putting a lot of water, drinkable water on the surface of the earth—we're reversing it. So yeah, poking a couple hundred thousand holes in the Marcellus, every one of those holes has to have a gasket. It's called a cement job. And we know that those gaskets fail at an alarming rate initially because they're really hard to put in place.

And most of them will fail eventually. By "eventually," I mean within a lifetime of a human, which means we're going to have tens of thousands of leaky gaskets. Which means that everything [that] was down there sequestered now has a pathway upwards into an underground source of drinking water or all the way to the surface. So that's pathway number one—poking all those holes and not being able to gasket them while they're operating and then successfully plug them when all these wells go out of operation. So we're postponing a major part of the problem.

At the surface, you have to bring chemicals to a well pad, and then you have to bring those chemicals and all the other waste products away from the well pad. That means transporting and storing. Anytime you transport and store hazardous material, you run the risk of spills. And obviously since it's spatially intense, we're going to have a lot of trucks, we're going to have lots of waste pits, we're going to have lots of pipelines, all of which at some point or another are going to cause some level of problem.

And then finally, air. What comes up out of the well is a gas, not just one gas, but all the other sisters and brothers of methane that want to come along for the ride. And not all of it goes into the pipeline, right? As we know, and as we're learning, a significant amount of it gets into the air in the form of hydrocarbon-based pollutants near the well pads that is capable of influencing people within a few miles, but also on a global scale. Again, spatial intensity. You've got the 200,000 wells in Pennsylvania, New York, West Virginia, Ohio, all those wells and all their ancillary infrastructure—compressor stations, processing stations, pipelines, storage units—they leak.

So we're going to be contributing to climate change in a way and at a time that we can least afford to. And to then say that this is the transition fuel that gets us to a sustainable and clean and climate-friendly future is absurd. It's walking the plank. It's not a bridge. A bridge has a near end and a far end. You want to get to the other end. This is a plank. Here we are, that's where we're going with this.

**LAW:** You're one of the founding board members of Physicians, Scientists, and Engineers for Healthy Energy (PSE), alongside myself. This organization is conceived as a multi-disciplinary group with people from a range of different backgrounds. How would you say this type of collaboration is important in addressing the science and the evidence of this new technology?

**INGRAFFEA:** It's fundamentally the right combination of expertise. As I tell the various aggrieved landowners, sometimes their lawyers who contact me for information, how can we prove the case? No one person has all the expertise.

Case in point, any one of these 200,000 wells that are going to be drilled in the Marcellus over the next  $N$  years can leak initially. Well, somebody has to be able to say, I understand the technology and the engineering of drilling, casing, cementing, and fracking a well. And I understand all the things that can go wrong, I understand why they go wrong, I understand when they go wrong, and I understand where they go wrong.

So if I read a well record, a daily diary that's kept by the operator of every single thing that happens on the well, then I can pinpoint, this is what went wrong, this is why it went wrong, this is where it went wrong, and this is when it went wrong. But that's insufficient. OK. The next thing you have to have is a geohydrologist who can say, well, if that went wrong there, then here are the consequences from the groundwater flow point of view.

If the gas well is upgradient of somebody's water well and I can say what leaked from this well, when it started leaking, and where it started leaking, then the next person in the chain, another kind of engineer, or scientist, geohydrologist, can say: and one, two, three days later, or three weeks later, or one year later, we can expect this concentration of contaminants to arrive in this person's well water. And *that's* not sufficient. OK, so—

**LAW:** What else do we need?

**INGRAFFEA:** Well, we need an engineer to say what went wrong, we need a scientist to say what the consequence was, and somebody down there has to be a professional who says, I can match up the contaminants, the chemistry of those contaminants, the hazardous nature of those contaminants with the health consequences of the people who drank the water or breathed that air. That's called chain of evidence, from my point of view. OK? You got at least those three, engineer, scientist, physician, working together to show causality.

There's a lot of coincidence-making—the industry always says, well, it's just a coincidence. Your well was always contaminated; you just noticed it now because we came into town. And on the other side, the extremist environmentalists, the people who don't think it all through, immediately draw causality conclusions from what might just be coincidence. But you really need an organization like PSE and its constituents, its advisors, its board, its members, who have

all the kinds of technical expertise necessary to observe, determine the cause, and prove effect.

**LAW: And one of the things that PSE is very concerned about as an organization is that the evidence is presented in vetted, peer-reviewed publications. Why is that so important?**

**INGRAFFEA:** It's fundamentally important because in our society, in our civilization, the cornerstone, the wellspring, the gold standard of evidence is anonymous peer review. Without it, we're all bloggers. We're just opinionators. My opinion's as good as yours. My blog has fancier graphics, more people read my blog, therefore I should be believed. I'm sorry, no, that's not the way it works.

I'm very concerned that not only do we have the kinds of pollution that we've all been talking about—water pollution, air pollution, people pollution—we're seeing science pollution. The diminution of the importance of anonymous peer review, as exercised by the very best journals, administered by the best editorial boards. People who have not, are not going to be influenced by financial conflict of interest or by personal aggrandizement.

On average, that's the whole idea. You have enough people working at any journal on the editorial boards in their reviewer suite and in their publisher to know that they have, in that journal, a very grave responsibility for society. It's at least as important as the responsibility that the media have. I would argue it's even more important, because without the ability for—I'm bringing the conversation to an end here—the people, the citizenry, the policymakers, the legislators, the regulators to discern best science from somebody's opinion, it's hopeless.

**LAW: Thanks very much, Tony.**

## AUTHORS' BIOGRAPHIES

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*Movement Solutions*

**NAVIGATING MEDICAL ISSUES IN SHALE TERRITORY**

**POUNÉ SABERI**

**ABSTRACT**

The introduction of natural gas drilling with high-volume hydraulic fracturing to Pennsylvania and neighboring states since 2004 has been accompanied by numerous reports of varied symptoms and illnesses by those living near these operations. Pollutants with established toxic effects in humans may be introduced into the environment at various points during gas extraction and processing. Some community residents, as well as employees of the natural gas industry, believe that their health has deteriorated as a result of these operations and have sought medical care from local practitioners, who may have limited access to immediate toxicological consultations. This article reviews taking an environmental exposure history in the context of natural gas activities, underscoring the importance of thorough and guided history-taking in the discovery of environmental exposure clusters. It also highlights the critical need for funding, research, and peer-reviewed studies to help generate the body of evidence that is needed by practitioners.

**Keywords:** hydraulic fracturing, exposure history, natural gas, health symptoms

Most health care practitioners know what to do when they do not have the answer to a set of symptoms presented by a patient or when they are puzzled about a clinical case. They discuss it with a colleague, look it up in a medical library or online resource, or send the patient to a specialist for a formal consultation.

But what happens when there is no expert or consultant to give advice about the problem the patient is facing? What happens when there is no literature to reference and most colleagues are just as baffled about the problem? That is the situation facing some health care practitioners in Pennsylvania who work in counties where high-volume hydraulic fracturing (also referred to as “fracking” in popular media) for natural gas along with related activities (chemical mixing; silica sand use; waste storage and handling; pipeline drilling, gas processing, compressor stations, and more) is occurring.

These practitioners have patients—both workers and residents—who report symptoms they believe are related to some part of the chain of shale gas operations. The practitioners hear about symptoms such as shortness of breath associated with odors in ambient air occurring after seismic testing; palpitations associated with being in the vicinity of a hydraulic fracturing flow-back waste impoundment; or black particles observed in tap water after a gas well was drilled, followed by an outbreak of a rash when showering. But are these actually related to fracking? The practitioners don’t know, and they don’t know whom to ask. There are no textbooks to consult, no experts to call upon, no adequate body of research to evaluate. They are stumped.

The underlying problem results from several factors. First of all, several of the special techniques essential to unconventional oil and gas extraction are nascent, with less than 10 years of use in Pennsylvania. While data exist on some of the routes of exposure resulting from these techniques, such as the vibration of compressor stations or the noise of truck traffic, the comprehensive environmental monitoring that could lead to informed exposure profiles is lacking. In addition, epidemiological longitudinal studies that would assist in the development of evidence-based clinical recommendations, at this time, have not been funded, conducted or published. Lastly, very few health care providers are trained in how to obtain an occupational history and fewer still are trained in obtaining an environmental exposure history, resulting in a general dearth of experience to guide practitioners in addressing their patients’ symptoms and concerns.

### **TAKING AN ENVIRONMENTAL HISTORY IN SHALE TERRITORY**

This article does not engage in a full discussion of the first two factors. Here, we will attempt to address the third in more detail: how does a health care provider take an environmental history when faced with a health complaint the patient, the provider, or both believe is due to shale gas extraction, processing, or transport infrastructure? Pennsylvania and the Marcellus Shale are chosen as the setting to address the health concerns that have surfaced in recent years. But health practitioners in any region where unconventional extractive techniques are in effect may use the principles outlined as a guide. Natural gas output from

Marcellus has increased tenfold since 2009 [1], and pipeline plans for domestic and global transportation have been expanding daily. I intend to illustrate the point that given the increase in this extractive industry, education about health concerns would be very timely for many clinicians.

To this end, in this article, I will review when and how the health care professional should obtain an environmental history. I hope to demonstrate that obtaining an accurate environmental history is a fundamental step in establishing the epidemiology of specific health issues, and it follows that the step taken by the health professional will be vital in building this foundation. I will end with a brief commentary on the current state of public health research and make the case that all literature related to shale gas, generated in academic and non-academic settings, should be given priority for peer reviewing and analysis to help generate the body of evidence that is needed by practitioners.

A note about terminology is in order. First, while generally “hydraulic fracturing” is used as a catch-all term for the unconventional extraction of methane gas (commonly referred to as “natural gas”) or oil, the more appropriate term would be “natural gas activities” or even more broadly, “unconventional resource extraction.” The message here is that the extraction, production, and transmission of fossil fuels, in this case natural gas, involve many steps during which exposure of residents and workers can occur, and it is important to utilize terminology that includes impacts from the entire life cycle of shale gas production.

Second, while we refer to “chemical” exposure, toxic and hazardous substances, and so forth, it is important for the clinician to realize that despite the attention to the additives in hydraulic fracturing fluid (also referred to as flow-back), an appreciable portion of the mixtures in drilling muds, drill cuttings, flow-back or other waste products are in fact endogenous to the subterranean layer and are therefore considered “naturally occurring.” These substances range from radioactive compounds such as radon, to hydrocarbons such as benzene, heavy metals such as arsenic, or salts (e.g., strontium salts), and can be as hazardous as the additives. The attention given to the additives may be due to the proprietary nature of the mix, but just as many of the chemicals are naturally occurring. What may make them hazardous is that they are mobilized to the surface by the processes involved in the extraction of natural gas [2]. Thus, the practitioner must be alert to all possibilities with regards to the scope of substances and potential migratory pathways. I will expand more on this concept below.

*Vignette:* A health care professional sees a patient who works for the natural gas industry on site. The worker wants a blood test for a certain chemical. The review of physical symptoms is negative. The worker is concerned because he has worked with a mixture of fluids without gloves. He does not know the name of the mixture. What should the health professional do?

The first and most fundamental concept to follow as a guide is the distinction between a hazard and a health risk. For a hazardous substance to pose a health risk it must first be transported through the environment, creating an exposure point where it can be absorbed through inhalation, ingestion, or dermal contact. The range of potential migratory pathways can be demonstrated by the cases that Bamberger and Oswald report [3]: failed well casings, leaking flow-back waste impoundments, dumping of toxic liquids in waterways, and emissions from compressor stations.

The goal is not always to nail down a “smoking gun” chemical to blame for a reported symptom. Insist on performing the routine history and physical exam, because a health problem may very well be uncovered that is unrelated to any environmental exposure. At the same time, incorporate questions about environmental exposures, since the testing should be guided by what the worker was exposed to.

Establishing the chronology of symptoms in the context of external exposures is vital. Precise questions that guide in the determination of the temporal relation between the introduction of an exposure and the appearance of health symptoms will help both the patient and the provider. The patient will recall the events in better detail and the provider is better able to generate possible connections that are biologically valid. Most patients remember that there was a gas well drilled, seismic testing was done, pipelines were dug in their vicinity, etc. They also remember their symptoms, but to fine-tune the temporal relation between these two events is crucial.

On the other hand, some operations are less obvious; for example, people may not be able to tell the approximate date a well is fractured, or be aware that a large out-of-sight waste impoundment is close by. Other examples of less evident connections are those between symptoms that are noticed in daytime but in fact result from exposure to night-time activities such as flaring. Examples of some of the questions are:

- When did you move into your current residence?
- When was the well drilled? When fractured, if known?
- When was the impoundment pit created, the compressor station built, or the wastewater spilled?

The challenge is then to see whether that background information correlates with specific environmental observations, using questions such as these:

- When did you notice your water’s color changing?
- When did you notice the odors in the air?

Clearly medical events that precede the exposure, or illnesses that require a longer lead time than was experienced, will not be related to the exposures under discussion. For example, it is biologically plausible for certain cancers to develop within a given time frame, while for other cancers it is not. A caveat

to the issue of timing deserves mention. The veterinary literature indicates that animal health is a sentinel for human health [3, 4]. Many companion animals may share the same exposures but manifest symptoms more rapidly. While many health care practitioners may not feel comfortable with zoological conditions, simple questions about the health of animals in the household and their behavior can be illuminating. Inquiring after diagnoses given by veterinarians is also helpful in establishing clues.

After obtaining subjective data, obtaining objective data is standard. The physical exam is dictated by the history and review of symptoms. Documenting vital signs as always is essential. For example, some chemicals have cardiotoxic effects that may not be apparent in the short term. But once the trend is reviewed over time it may reveal persistently increasing heart rate and necessitate further workup by electrocardiography. For example, long-term exposure to carbon monoxide, measured in air by well pads and compressor stations [5], worsens symptoms in people with prior cardiovascular disease [6]. Supplemental aids such as obtaining pictures of dermatological rashes can also be helpful.

In assessing the clinical scenario, one of the major pitfalls in interpreting toxicological data is the assumption that the same level of evidence can be applied to these data as to routine laboratory testing. The existing data bank for routine blood work is significantly larger, and therefore the strength of evidence for recommendations on when to order the test, how and when to collect it, and how to interpret it, is similarly much greater. Given the challenges in applying the results of toxicological data to a clinical case, the health care provider must carefully consider the reasons for ordering a test and do so only when sufficient suspicion for an exposure and a potential route of absorption exists. Having a sense of the pre-test probability of a health condition is useful to clinicians in understanding the predictive value of a negative or positive test result.

The health care provider may feel pressured to obtain biomonitoring as promptly as possible, given the time limits of the patient-doctor visit, the time-sensitive nature of the tests, and the desire to alleviate patient concerns. Biomonitoring is the assessment of human exposure to chemicals by measuring the chemicals or their metabolites in human specimens such as blood or urine [7]. It is challenging to balance prompt ordering with unearthing the appropriate tests. Generally in ordering blood and urine tests, obtaining the sample as close as possible to the time of exposure increases the validity of the result. On the one hand, some chemicals have such short half-lives in the body that a negative result obtained long after the exposure will provide false reassurance that the individual was not exposed. On the other hand, some exposures are so ubiquitous in the environment that a positive result obtained long after the exposure of concern may reflect only an unrelated environmental exposure. A key to reaching this balance, and to avoiding missed opportunities by ordering the wrong panel, is establishing a system of fact-finding with a network of medical toxicology

consultants in advance. Governmental labs, such as that of the U.S. Centers for Disease Control and Prevention (CDC) and state labs, as well as private labs, may perform services for specialized biomonitoring tests. For example, National Medical Services performs a significant amount of toxicological testing, and toxicologists at the laboratory can be contacted with clarifying questions to help with appropriate testing ([www.nmslabs.com](http://www.nmslabs.com)). The website lists the phone number for client services, and providers can speak to support staff or request consultation. As with all other consultations, focused questions will receive more useful answers.

The cost of specialized testing may be a barrier for residents who are uninsured. The cost of the testing is variable depending on the type of testing requested, and providers may contact their chosen lab for the exact price. Depending on the test the price may vary from a few hundred to a few thousand dollars no matter which lab performs it. Specialized testing may not be covered by all medical insurances, and many insured residents may find themselves having to pay the expenses out of pocket.

The balancing act by the health care provider extends to recognizing the importance of mental health impacts of the natural gas activities. In the health impact assessment performed by Witter et al. [8] in Colorado in 2007, fear of unknown chemicals was listed as a stressor identified by community members. This illustrates the awareness that the health care provider must have toward appropriate counseling about environmental exposures. The balance lies in not disregarding the concerns raised by the patient and not causing undue alarm at the same time.

### **SOME CONCERNS**

The symptoms, alone and in clusters, that have been repeatedly seen in different parts of the state of Pennsylvania may be cause for concern. The Environmental Health Project has documented dermal, gastrointestinal, and respiratory symptoms as the most commonly occurring complaints [9]. Bamberger and Oswald [3] have reported similar profiles: burning of the nose, throat and eye, headaches, gastrointestinal symptoms such as vomiting and diarrhea, rashes, and nosebleeds.

The following summarizes the problems most commonly reported to me and to other researchers by residents and workers, in order of frequency with the most common problems listed first [10]. As of July 2012, there were about 50 such reports. When evaluated in the context of a possible natural gas operation exposure, these symptoms may be noted as potential “sentinel” symptoms for toxic agents with more serious, but possibly delayed, clinical impacts:

- rashes or skin irritation,
- abdominal pain and cramping,

- shortness of breath,
- recurrent sinusitis, and
- diarrhea.

Looking back at the history of environmental health hazards, a health professional may pause to consider the future implications of toxic exposure from unconventional natural gas operations. For instance, the history of asbestosis shows a lag time between clinical observation (first case of asbestosis documented in the 1920s) and epidemiological proof (asbestosis is shown to cause lung cancer in the 1950s), and regulatory enforcement. Asbestos production plants were shut down in the 1980s after numerous unnecessary deaths from asbestosis and asbestos-related cancers had occurred. Even today, new diagnoses of asbestosis, mesothelioma, and other asbestosis-related cancers are still being made.

A reasonable concern is that in 10 to 80 years, the public will be paying for exposure to both established and new toxic substances, when current symptoms and the lack of public health scrutiny should have been red flags. McKenzie et al. [11], for example, concluded that residents who live closer to gas pads have higher predicted risks of respiratory and neurological conditions in addition to excess lifetime risk of developing cancer. A March 2012 press release issued by the Environmental Protection Agency (EPA) addressed a groundwater investigation in Pavillion, Wyoming, stating [12]: “We believe that collaboration and use of the best available science are critical in meeting the needs of Pavillion area residents and resolving longstanding issues surrounding the safety of drinking water and groundwater.” The collaboration among the EPA, United States Geological Survey (USGS), and the State of Wyoming was an excellent example of using best available science in a speedy manner to identify red flags for the community residents. The EPA report showed benzene concentrations in an aquifer at 50 times the Maximum Contaminant Level (MCL) [13]. What happened subsequently may provide a clue as to the lag time between scientific findings and policy, as seen with the timeline of asbestos regulations. EPA and USGS were made to resample and repeat their findings; their results were questioned, and eventually the oil and gas industry demanded that new tests be done [14].

This story raises several points. One is that when the stakes are so high that the health of residents is dependent on them, red flags should be sufficient to protect the people rather than wait for conclusive evidence. The second point is that conducting health impact studies prior to engaging in operations with potential high-stake outcomes allows dialogue for establishing safeguards ahead of time. Lastly, despite the amount of time spent on hazard assessment, experts remain unable to provide clinicians with guidance for risk communication to patients.

No state to date has attempted a health impact assessment prior to allowing unconventional extraction of shale to begin, nor has any state engaged in creating



a disease or health complaint registry after the process has begun. Unlike the use of asbestos, which exposed workers to a single substance, in unconventional natural gas operations, populations are exposed to a multitude of chemicals that vary both within and between shale gas fields. Time is passing, and there is a strong need for health impact studies in states and areas where natural gas activities have not yet begun, for collaborations to screen for red flags in areas where natural gas activities have begun, and for comprehensive studies that offer both policy recommendations and clinical guidelines.

### **SPECIAL CHALLENGES AND SPECIAL POPULATIONS**

There are special populations with added vulnerability that deserve different considerations by medical professionals [15]. Pregnant women, people whose occupation is working in the industry, and children are examples of such populations. The teratogenicity of many compounds, such as mercury, which occur naturally in the deeper geological formations but are brought up either with natural gas operations or burning of coal, has been firmly established. The adverse embryonic effects of the same chemical may be different depending on the gestational age at exposure. Institutions that are dedicated to such special populations include Pediatric Environmental Health Specialty Units (PEHSU) (<http://aoec.org/pehsu>). A large body of data demonstrates disproportionate impacts on another vulnerable population, the elderly. Ground-level ozone, for example, has been linked to premature death in this cohort [16].

While some special populations, such as pregnant women or children, are rarely unrecognized as such by health care providers, many practitioners may not be aware of regulations surrounding providing care for the workers. The National Institute for Occupational Safety and Health (NIOSH) (<http://www.cdc.gov/niosh>) has an important hazard alert for health care professionals regarding worker exposure to silica during hydraulic fracturing [17]. Medical practitioners should ask patients who are natural gas operation workers if they are involved in dusty drilling operations, and if so, a pulmonary evaluation should be recommended and an onsite inspection made, as explained below.

The Occupational Safety and Health Administration (OSHA) has specific rules and regulations regarding reporting work-related injuries and hazards in the workplace. OSHA requires that most industries keep logs of occupational injuries and illnesses, which must be made available to OSHA during inspections. Injuries that result in fatalities or multiple hospitalizations must be immediately reported to OSHA. The health care practitioner may act as the representative of a worker when faced with the knowledge of a workplace hazard and file a request for onsite work inspections ([www.osha.gov/as/opa/worker/complain.html](http://www.osha.gov/as/opa/worker/complain.html)). For example, an emergency medicine provider may treat several workers for heat stroke and recognize that the recurrent episodes are related to working extended

hours in the heat on a well pad. The physician may then contact the regional office of OSHA, anonymously or otherwise, to report the hazardous working conditions. Studying the logs will help locate areas where possible exposures are occurring with the goal of preventing them.

### SOME RESOURCES

The environmental medicine literature demonstrates the importance of including questions about potential toxic exposure when taking a clinical history. Authors give examples of common symptoms that are found to be due to an environmental exposure [18]. For example, a recurrent headache leads to the discovery of indoor carbon monoxide levels, or a non-resolving rash points to the patient's hobby of working with treated wood. Environmental medicine authorities point out that the key to solving the puzzle is to include the environmental or occupational exposure in the differential diagnosis and ask the relevant questions [19]. If the health care practitioner sees patients in an area where there is natural gas activity, it is reasonable to consider the steps involved in the exposure as a possible etiological factor.

Establishing a connection between an environmental exposure and health symptoms is easier when population-based data are available. At this time in our medical knowledge of the health effects of unconventional shale operations, the relevant questions are far broader than are usually considered in the outpatient setting, and the conclusions not tremendously gratifying. That is why the significance of clinicians participating in the collection of population-based data cannot be understated. A solid investigation at the individual level appreciably contributes to population-level data gathering for such phenomena as cluster investigations or disease registries.

*Vignette:* Two small children are brought in for rashes on their hands. The well nearest to their home has been flared for the last week. The family believes that the rashes are due to flaring, as the symptoms did not exist prior to this event.

This case illustrates the importance of remembering to follow the medical teachings of entertaining all possible differential diagnoses. Childhood viral exanthems (rash) are common, as are other possibilities such as irritant dermatitis in reaction to a new compound in the environment. Some of the resources available are online and include the Case Studies in Environmental Medicine prepared by the federal Agency for Toxic Substances and Disease Registry (ATSDR) (<http://www.atsdr.cdc.gov/csem/csem.html>). They guide the practitioner step by step on how to take an exposure history, and include monographs on a variety of chemicals. ATSDR has also created a summary of key questions to ask, which can either be incorporated into a visit or asked by the ancillary staff. Various environmental organizations also offer questionnaires that may be

helpful. For example, the Southwestern Pennsylvania Environmental Health Project contains some good examples of medical history questions to ask in the context of natural gas operations (<http://www.environmentalhealthproject.org/>). This website also lists resources for environmental monitoring and recommendations for minimizing exposure to many of the sources present in activities associated with the life cycle of hydraulic fracturing. The site also offers helpful brochures explaining how to interpret water test results and other instruction sheets that clinicians can give to their patients (3 Good Things To Do: <http://www.environmentalhealthproject.org/health/steps-you-can-take-now/>). For example, practical advice for the family in the above scenario may be to take steps to purify the indoor air, in order to reduce the load of particulates and other pollutants that have migrated into the home from outside air.

## REGULATIONS

Health care providers are no stranger to the interface of legal matters and medicine. Most education about the medical/legal field achieves the goal of protecting the provider from inadvertently breaking a law. In the context of unconventional natural gas activities, however, it behooves the clinician to become well versed in the intricacies of the legalese that protect both the patient and the patient-doctor relationship. At the time of writing this article, in Pennsylvania, Act 13, the 2012 state law addressing shale gas extraction issues, contains medical provisions addressing disclosure of proprietary chemical mixtures by the industry. If a provider suspects potential exposure to an unknown compound, he or she may request release of data in writing in order to appropriately treat the exposed patient, but must agree not to disclose the information received. Similar regulation is also in effect in other states such as Colorado and is modeled after OSHA's Hazard Communication Standard.

The medical provisions in Act 13 bring up several issues. OSHA regulations have been written to protect workers in their workplace. Historically EPA has been tasked with having a similar role for residents in their living environment. In the context of natural gas exploration and extraction, the bulk of enforcing power has fallen on state government agencies. The federal Energy Policy Act of 2005 has minimized EPA's oversight by exempting the oil and gas companies engaged in hydraulic fracturing from key portions of some fundamental environmental laws. Despite the limitation of jurisdiction, EPA asserts that it has acted when stakeholders have made inquiries.

In Pennsylvania, the application of the medical provision of Act 13 is not well understood, since it has not been effectively tested. Very few providers desire to be the pioneers in applying the complexities of legal procedures such as sharing the data obtained from the company with their patients. Efforts made by medical professionals to understand the scope of action permitted under

the law will improve their capacity to help patients obtain valuable chemical information. The Network for Public Health Law is one resource. While its staff are not able to provide direct advice about the application of the law to a specific circumstance, they can provide technical legal assistance to access and understand the law. They can be contacted via phone at 410-706-5575 or email at [eastern@networkforphl.org](mailto:eastern@networkforphl.org). If a provider has questions about local application of the law, The American Medical Association Litigation Center, (<http://www.ama-assn.org/ama/pub/physician-resources/legal-topics/litigation-center/about-us.page?>) may be able to direct inquiries to lawyers in the state who can provide answers.

### CONCLUSION

In summary, what does a practitioner do when the patient says a health problem is due to unconventional gas drilling operations? The practitioner must be adept at taking a relevant exposure history, and include toxic exposure as a potential cause for the patient's symptoms, while not prematurely arriving at a conclusion of causation. Clinicians may need to think about multiple exposures to chemicals, each of which can create multiple overlapping symptoms, and to deal with the frustration brought on by the uncertainty about which substances are involved. Despite the multiple barriers to obtaining high-quality epidemiological data, every health practitioner who takes a complete case history, including a history of environmental exposure, is providing a tremendous service both for the patient and for public health. The documentation by clinicians has been the foundation of such established and widely used databases as the Surveillance Epidemiology and End Results (SEER) registry. The present-day effort will result in tomorrow's payback of information that will be reliably used in evaluating puzzling environmental clinical scenarios. Health care providers are empowered to see themselves as a vital link in the chain of constructing future epidemiological data banks. The field of public health will ideally be transformed from the perspective of collection of disease counts to one with infrastructure for monitoring and mitigating toxic substances before they have had the chance to cause harm.

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## Impact of Shale Gas Development on Regional Water Quality

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# Impact of Shale Gas Development on Regional Water Quality

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**Background:** Natural gas has recently emerged as a relatively clean energy source that offers the opportunity for a number of regions around the world to reduce their reliance on energy imports. It can also serve as a transition fuel that will allow for the shift from coal to renewable energy resources while helping to reduce the emissions of CO<sub>2</sub>, criteria pollutants, and mercury by the power sector. Horizontal drilling and hydraulic fracturing make the extraction of tightly bound natural gas from shale formations economically feasible. These technologies are not free from environmental risks, however, especially those related to regional water quality, such as gas migration, contaminant transport through induced and natural fractures, wastewater discharge, and accidental spills. The focus of this Review is on the current understanding of these environmental issues.

**Advances:** The most common problem with well construction is a faulty seal that is emplaced to prevent gas migration into shallow groundwater. The incidence rate of seal problems in unconventional gas wells is relatively low (1 to 3%), but there is a substantial controversy whether the methane detected in private groundwater wells in the area where drilling for unconventional gas is ongoing was caused by well drilling or natural processes. It is difficult to resolve this issue because many areas have long had sources of methane unrelated to hydraulic fracturing, and pre-drilling baseline data are often unavailable.

Water management for unconventional shale gas extraction is one of the key issues that will dominate environmental debate surrounding the gas industry. Reuse of produced water for hydraulic fracturing is currently addressing the concerns regarding the vast quantities of contaminants that are brought to the surface. As these well fields mature and the opportunities for wastewater reuse diminish, the need to find alternative management strategies for this wastewater will likely intensify.

**Outlook:** Improved understanding of the fate and transport of contaminants of concern and increased long-term monitoring and data dissemination will help effectively manage water-quality risks associated with unconventional gas industry today and in the future. Confidentiality requirements dictated by legal investigations combined with the expedited rate of development and the limited funding for research are major impediments to peer-reviewed research into environmental impacts. Now is the time to work on these environmental issues to avoid an adverse environmental legacy similar to that from abandoned coal mine discharges in Pennsylvania.



Drilling multiple horizontal wells from a single well pad allows access to as much as 1 square mile of shale that is located more than a mile below. [Image courtesy of Range Resources Appalachia]

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## ARTICLE OUTLINE

Cause of the Shale Gas Development Surge

Methane Migration

How Protective Is the “Well Armor”?

The Source and Fate of Fracturing Fluid

Appropriate Wastewater Management Options

Conclusions

## BACKGROUND READING

General overview that includes geology of major shale plays, description of the extraction process, relevant regulations, and environmental considerations: [www.netl.doe.gov/technologies/oil-gas/publications/EPreports/Shale\\_Gas\\_Primer\\_2009.pdf](http://www.netl.doe.gov/technologies/oil-gas/publications/EPreports/Shale_Gas_Primer_2009.pdf)

Detailed information about individual shale gas wells, including chemical additives used in each hydraulic fracturing treatment: <http://fracfocus.org>

Findings of the U.S. Environmental Protection Agency study on the potential impact of hydraulic fracturing on drinking water resources: [www.epa.gov/hfstudy](http://www.epa.gov/hfstudy)

Comprehensive information from the British Geological Survey about shale gas (including articles and videos): [www.bgs.ac.uk/shalegas](http://www.bgs.ac.uk/shalegas)

Site developed in collaboration with the Geological Society of America promoting the rational debate about energy future: [www.switchenergyproject.com](http://www.switchenergyproject.com)

Latest news and findings about shale gas. [www.shale-gas-information-platform.org](http://www.shale-gas-information-platform.org)

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Unconventional natural gas resources offer an opportunity to access a relatively clean fossil fuel that could potentially lead to energy independence for some countries. Horizontal drilling and hydraulic fracturing make the extraction of tightly bound natural gas from shale formations economically feasible. These technologies are not free from environmental risks, however, especially those related to regional water quality, such as gas migration, contaminant transport through induced and natural fractures, wastewater discharge, and accidental spills. We review the current understanding of environmental issues associated with unconventional gas extraction. Improved understanding of the fate and transport of contaminants of concern and increased long-term monitoring and data dissemination will help manage these water-quality risks today and in the future.

Natural gas has recently emerged as an energy source that offers the opportunity for a number of regions around the world to reduce their reliance on energy imports or strive toward energy independence (1, 2). It may also be a potential transition fuel that will allow for the shift from coal to renewable energy resources while helping to reduce the emissions of CO<sub>2</sub>, criteria pollutants, and mercury by the power sector (3). The driving force behind this shift is that it has become economically feasible to extract unconventional sources of gas that were previously considered inaccessible. Conventional gas is typically extracted from porous sandstone and carbonate formations, where it has generally been trapped under impermeable caprocks after migration from its original source rock. In contrast, unconventional gas is usually recovered from low-permeability reservoirs or the source rocks themselves, including coal seams, tight sand formations, and fine-grained, organic-rich shales. Unconventional gas formations are characterized by low permeabilities that limit the recovery of the gas and require additional techniques to achieve economical flow rates (2).

The archetypical example of rapidly increasing shale gas development is the Marcellus Shale in the eastern United States (Fig. 1). Intensive gas extraction began there in 2005, and it is one of the top five unconventional gas reservoirs in the United States. With a regional extent of 95,000 square miles, the Marcellus is one of the world's largest known shale-gas deposits. It extends from upstate New York, as far south as Virginia, and as far west as Ohio, underlying 70% of the state of Pennsylvania and much of West Virginia. The formation consists of black and dark gray shales, siltstones, and limestones (4). On the basis of a geological study of natural fractures in the for-

mation, Engelder (5) estimated a 50% probability that the Marcellus will ultimately yield 489 trillion cubic feet of natural gas.

Concerns that have been voiced (6) in connection with hydraulic fracturing and the development of unconventional gas resources in the United States include land and habitat fragmentation as well as impacts to air quality, water quantity and quality, and socioeconomic issues (3, 5, 7). Although shale gas development is increasing across several regions of the United States and the world (such as the United Kingdom, Poland, Ukraine, Australia, and Brazil), this review focuses on the potential issues surrounding water quality in the Appalachian region and specifically the Marcellus Shale, where the majority of published studies have been conducted. Our Review focuses on chemical aspects of water quality rather than issues surrounding enhanced sediment inputs into waterways, which have been discussed elsewhere (4, 7, 8).

## Cause of the Shale Gas Development Surge

Recent technological developments in horizontal drilling and hydraulic fracturing have enabled enhanced recovery of unconventional gas in the United States, increasing the contribution of shale gas to total gas production from negligible levels in 1990 to 30% in 2011 (1). Although the first true horizontal oil well was drilled in 1929, this technique only became a standard industry practice in the 1980s (9). Whereas a vertical well allows access to tens or hundreds of meters across a flat-lying formation, a horizontal well can be drilled to conform to the formation and can therefore extract gas from thousands of meters of shale. Horizontal wells reduce surface disturbance by limiting the number of drilling pads and by enabling gas extraction from areas where vertical wells are not feasible. However, horizontal drilling alone would not have enabled exploitation of the unconventional gas resources because the reservoir permeability is not sufficient to achieve economical gas production by natural flow. Hydraulic fracturing—"hydrofracking," or "fracking"—

was developed in the 1940s to fracture and increase permeability of target formations and has since been improved to match the characteristics of specific types of reservoirs, including shales.

Hydraulic fracturing fluids consist of water that is mixed with proppants and chemicals before injection into the well under high pressure (480 to 850 bar) in order to open the existing fractures or initiate new fractures. The proppant (commonly sand) represents generally ~9% of the total weight of the fracturing fluid (10) and is required to keep the fractures open once the pumping has stopped. The number, type, and concentration of chemicals added are governed by the geological characteristics of each site and the chemical characteristics of the water used. The fracturing fluid typically used in the Marcellus Shale is called slickwater, which means that it does not contain viscosity modifiers that are often added to hydrofracture other shales so as to facilitate better proppant transport and placement.

Chemical additives in the fluids used for hydraulic fracturing in the Marcellus Shale include friction reducers, scale inhibitors, and biocides (Table 1 and Box 1). Eight U.S. states currently require that all chemicals that are not considered proprietary must be published online (11), whereas many companies are voluntarily disclosing this information in other states. However, many of the chemicals added for fracturing are not currently regulated by the U.S. Safe Drinking Water Act, raising public concerns about water supply contamination. From 2005 to 2009, about 750 chemicals and other components were used in hydraulic fracturing, ranging from harmless components, including coffee grounds or walnut hulls, to 29 components that may be hazardous if introduced into the water supply (6). An inorganic acid such as hydrochloric acid is often used to clean the wellbore area after perforation and to dissolve soluble minerals in the surrounding formation. Organic polymers or petroleum distillates are added to reduce friction between the fluid and the wellbore, lowering the pumping costs. Antiscalants are added to the fracturing fluid so as to limit the precipitation of salts and metals in the formation and inside the well. Besides scaling, bacterial growth is a major concern for the productivity of a gas well (quantity and quality of produced gas). Glutaraldehyde is the most common antibacterial agent added, but other disinfectants [such as 2,2-dibromo-3-nitropropionamide (DBNPA) or chlorine dioxide] are often considered. Surfactants (alcohols such as methanol or isopropanol) may also be added to reduce the fluid surface tension to aid fluid recovery.

## Methane Migration

As inventoried in 2000, more than 40 million U.S. citizens drink water from private wells (12). In some areas, methane—the main component of natural gas—seeps into these private wells from either natural or anthropogenic sources. Given its low solubility (26 mg/L at 1 atm, 20°C), methane

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that enters wells as a solute is not considered a health hazard with respect to ingestion and is therefore not regulated in the United States. When present, however, methane can be oxidized by bacteria, resulting in oxygen depletion. Low oxygen concentrations can result in the increased solubility of elements such as arsenic or iron. In addition, anaerobic bacteria that proliferate under such conditions may reduce sulfate to sulfide, creating water- and air-quality issues. When methane degasses, it can also create turbidity and, in extreme cases, explode (13, 14). Therefore, the U.S. Department of the Interior recommends a warning if water contains 10 mg/L of CH<sub>4</sub> and immediate action if concentrations reach 28 mg/L (15). Methane concentrations above 10 mg/L indicate that accumulation of gas could result in an explosion (16).

The most common problem with well construction is a faulty seal in the annular space around casings that is emplaced to prevent gas leakage from a well into aquifers (13). The incidence rate of casing and cement problems in unconventional gas wells in Pennsylvania has been reported previously as ~1 to 2% (17). Our count in Pennsylvania from 2008 to March 2013 for well construction problems [such as casing or cementing incidents (18)] cited by the Pennsylvania Department of Environmental Protection (DEP) revealed 219 notices of violation out of 6466 wells (3.4%) (19). Of these, 16 wells in northern Pennsylvania were given notices with respect to the regulation that the “operator shall prevent gas and other fluids from lower formations from entering fresh groundwater” (violation code 78.73A). Most of the time, gas leakage is minor and can be remedied. However, in one case attributed to Marcellus drilling and leaky well casings, stray gas that accumulated in a private water well exploded near the northeastern Pennsylvania town of Dimock. A study of 60 groundwater wells in that area, including across the border in upstate New York (20), showed that both the average and maximum methane concentrations were higher when sampled from wells within 1 km of active Marcellus gas wells as compared with those farther away. Much discussion has since ensued as to whether the methane detected in these wells was caused by drilling or natural processes (21–24) because the area has long had sources of both thermogenic and biogenic methane unrelated to hydraulic fracturing, and no predrilling baseline data are available. The averages reported in that study for sites both near and far from drilling are not dissimilar from values for groundwater from areas of Pennsylvania and West Virginia sampled by the U.S. Geological Survey (USGS) before the recent Marcellus Shale development began, or samples in New York state where high-volume hydrofracturing is currently banned (Fig. 2).

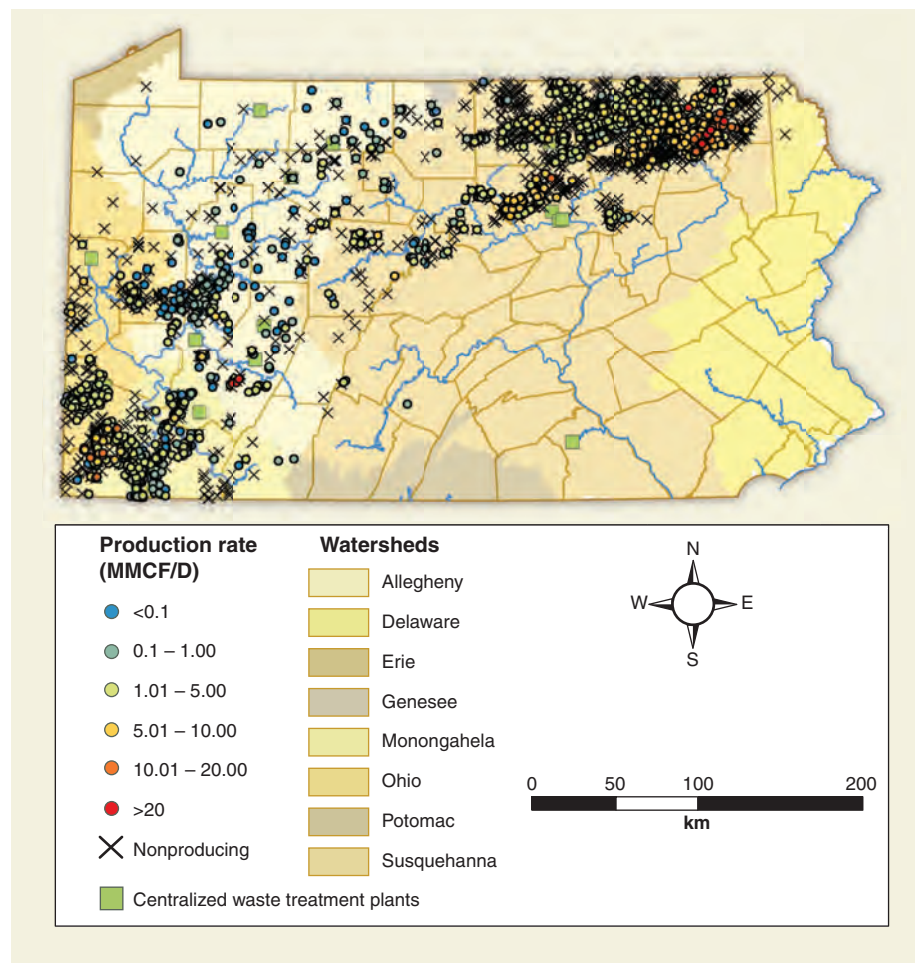
The reason gas is found so often in water wells in some areas is because methane not only forms at depth naturally, owing to high-temperature maturation of organic matter, but also at shallow depths through bacterial processes (25, 26). Both these thermogenic and biogenic gas types can

migrate through faults upward from deep formations or laterally from environments such as swamps (swamp gas) or glacial till (drift gas) (14, 27). In addition, gas can derive from anthropogenic sources such as gas storage fields, coal mines, landfills, gas pipelines, and abandoned gas wells (28). In fact, ~350,000 oil and gas wells have been drilled in Pennsylvania, and the locations of ~100,000 of these are unknown (29). Thus, it is not surprising that gas problems have occurred in Pennsylvania long before the Marcellus development (30). Pennsylvania is not the only state facing this problem because about ~60,000 documented orphaned wells and potentially more than 90,000 undocumented orphaned wells in the United States have not been adequately plugged and could act as vertical conduits for gas (31).

As natural gas moves in the subsurface, it can be partially oxidized, mixed with other gases, or diluted along flow paths. To determine its provenance, a “multiple lines of evidence approach” must be pursued (24). For example, researchers measure the presence of other hydrocarbons as

well as the isotopic signatures of H, O, and C in the water or gas (16, 27, 31). Thermogenic gas in general has more ethane and a higher <sup>13</sup>C/<sup>12</sup>C ratio than that of biogenic gas. Stable isotopes in thermogenic gas may sometimes even yield clues about which shale was the source of the gas (24, 32). In northeastern Pennsylvania, researchers argue whether the isotopic signatures of the methane in drinking-water wells indicate the gas derived from the Marcellus or from shallower formations (20, 24).

Although determining the origin of gas in water wells may lead to solutions for this problem, the source does not affect liability because gas companies are responsible if it can be shown that any gas—not just methane—has moved into a water well because of shale-gas development activity. For example, drilling can open surficial fractures that allow preexisting native gas to leak into water wells (13). This means that pre- and post-drilling gas concentration data are needed to determine culpability. Only one published study compares pre- and post-drilling water chemistry in the Marcellus Shale drilling area. In that study, a



**Fig. 1. Marcellus Shale wells in Pennsylvania.** Rapid development of Marcellus Shale since 2005 resulted in more than 12,000 well permits, with more than 6000 wells drilled and ~3500 producing gas through December 2012 (average daily production ranged from <0.1 to >20 million cubic feet/day (MMCF/D)). Current locations of centralized wastewater treatment facilities (CWTs) are distributed to facilitate treatment and reuse of flowback and produced water for hydraulic fracturing.

sample of 48 water wells in Pennsylvania investigated between 2010 and 2011 within 2500 feet of Marcellus wells showed no statistical differences in dissolved CH<sub>4</sub> concentrations before or shortly after drilling (33). In addition, no statistical differences related to distance from drilling were observed. However, that study reported that the concentration of dissolved methane increased in one well after drilling was completed nearby,

which is possibly consistent with an average rate of casing problems of ~3%.

The rate of detection of methane in water wells in northeast Pennsylvania [80 to 85% (20, 24)] is higher than in the wider region that includes southwestern Pennsylvania [24% (33)], where pre- and post-drilling concentrations were statistically identical. This could be a result of the small sample sizes of the two studies or because the

hydrogeological regime in the northeast is more prone to gas migration (34). Such geological differences also may explain why regions of the Marcellus Shale have been characterized by controversy in regard to methane migration as noted above, whereas other shale gas areas such as the Fayetteville in Arkansas have not reported major issues with respect to methane (35). Reliable models that incorporate geological characteristics are needed to allow prediction of dissolved methane in groundwater. It is also critical to distinguish natural and anthropogenic causes of migration, geological factors that exacerbate such migration, and the likelihood of ancillary problems of water quality related to the depletion of oxygen. Answering some of these questions will require tracking temporal variations in gas and isotopic concentrations in groundwater wells near and far from drilling by using multiple lines of evidence (16, 24). Research should also focus on determining flow paths in areas where high sampling density can be attained.

#### How Protective Is the “Well Armor”?

The protective armor shielding the freshwater zones and the surrounding environment from the contaminants inside the well consist of several layers of casing (hollow steel pipe) and cement (Fig. 3). When the integrity of the wellbore is compromised, gas migration or stray gas can become an issue (14). Gas migration out of a well refers to movement of annular gas either through or around the cement sheath. Stray gas, on the other hand, commonly refers to gas outside of the wellbore. One of the primary causes of gas migration or stray gas is related to the upper portion of the wellbore when it is drilled into a rock formation that contains preexisting high-pressure gas. This high-pressure gas can have deleterious effects on the integrity of the outer cement annulus, such as the creation of microchannels (36). Temperature surveys can be performed shortly after the cementing job is completed in order to ensure that cement is present behind the casing. Acoustic logging tools are also available to evaluate the integrity of the cement annulus in conjunction with pressure testing.

It is well known that to effectively stabilize wellbores with cement in areas with zones of overpressurized gas, proper cement design and proper mud removal are essential (37, 38). If the hydrostatic pressure of the cement column is not higher than the gas-bearing formation pressure, gas can invade the cement before it sets. Conversely, if this pressure is too high, then the formation can fracture, and a loss of cement slurry can occur. Even when the density is correct, the gas from the formation can invade the cement as it transitions from a slurry to a hardened state (39). The slurry must be designed to minimize this transition time and the loss of fluid from the slurry to the formation. Also, if drilling mud is not properly cleaned from the hole before cementing, mud channels may allow gas migration through the central portion of the annulus or along the cement-formation interface. Even if the well is properly cleaned and the cement is placed properly, shrinkage

**Table 1.** Common chemical additives for hydraulic fracturing.

Additive type	Example compounds	Purpose
Acid	Hydrochloric acid	Clean out the wellbore, dissolve minerals, and initiate cracks in rock
Friction reducer	Polyacrylamide, petroleum distillate	Minimize friction between the fluid and the pipe
Corrosion inhibitor	Isopropanol, acetaldehyde	Prevent corrosion of pipe by diluted acid
Iron control	Citric acid, thioglycolic acid	Prevent precipitation of metal oxides
Biocide	Glutaraldehyde, 2,2-dibromo-3-nitropropionamide (DBNPA)	Bacterial control
Gelling agent	Guar/xantham gum or hydroxyethyl cellulose	Thicken water to suspend the sand
Crosslinker	Borate salts	Maximize fluid viscosity at high temperatures
Breaker	Ammonium persulfate, magnesium peroxide	Promote breakdown of gel polymers
Oxygen scavenger	Ammonium bisulfite	Remove oxygen from fluid to reduce pipe corrosion
pH adjustment	Potassium or sodium hydroxide or carbonate	Maintain effectiveness of other compounds (such as crosslinker)
Proppant	Silica quartz sand	Keep fractures open
Scale inhibitor	Ethylene glycol	Reduce deposition on pipes
Surfactant	Ethanol, isopropyl alcohol, 2-butoxyethanol	Decrease surface tension to allow water recovery

#### Box 1. Glossary of Terms

**Casing:** steel pipe that is inserted into a recently drilled section of a borehole to stabilize the hole, prevent contamination of groundwater, and isolate different subsurface zones.

**Cementing:** placing a cement mixture between the casing and a borehole to stabilize the casing and seal off the formation.

**Class II disposal wells:** underground injection wells for disposal of fluids associated with oil and gas production.

**Flowback water:** water that returns to the surface after the hydraulic fracturing process is completed and the pressure is released and before the well is placed in production; flowback water return occurs for several weeks.

**Produced water:** water that returns to the surface with the gas after the well is placed in production; production water return occurs during the life of a well.

**Proppant:** granular material, such as silica sand, ceramic media, or bauxite, that keeps the fractures open so that gas can flow to the wellbore.

**Slickwater fracturing:** fracturing with fluid that contains mostly water along with friction reducers, proppants, and other additives; used for predominantly gas-bearing formations at shallower depths.

**Source rock:** organic-rich sedimentary rocks, such as shale, containing natural gas or oil.

**Stray gas:** gas contained in the geologic formation outside the wellbore that is accidentally mobilized by drilling and/or hydraulic fracturing.

of the cement during hydration or as a result of drying throughout the life of the well can result in crack development within the annulus (40, 41).

Although the primary mechanisms contributing to gas migration and stray gas are understood, it is difficult to predict the risk at individual sites because of varying geological conditions and drilling practices. To successfully protect fresh water and the surrounding environment from the contaminants inside the well, the site-specific risk factors contributing to gas migration and stray gas must be better understood, and improvements in the diagnostics of cement and casing integrity are needed for both new and existing wells. Finding solutions to these problems will provide environmental agencies the knowledge needed to develop sound regulations related to the distances around gas wells that can be affected. It will also provide operators the ability to prevent gas migration and stray gas in a more efficient and economical manner.

### The Source and Fate of Fracturing Fluid

The drilling and hydraulic fracturing of a single horizontal well in the Marcellus Shale may require 2 million to 7 million gallons of water (42). In contrast, only about 1 million gallons are needed for vertical wells because of the smaller formation contact volume. Although the projected water consumption for gas extraction in the Marcellus Shale region is 18.7 million gallons per day in 2013 (39), this constitutes just 0.2% of total annual water withdrawals in Pennsylvania. Water withdrawals in other areas are similarly low, but temporary problems can be experienced at the local level during drought periods (3). Furthermore, water quantity issues are prevalent in the drier shale-gas plays of the southwest and western United States (43). It is likely that water needs will change from these initial projections as the industry continues to improve and implement water reuse. Nevertheless, the understanding of flow variability—especially during drought conditions or in regions with already stressed water supplies—is necessary to develop best management practices for water withdrawal (44). It is also necessary to develop specific policies regarding when and where water withdrawals will be permitted in each region (45).

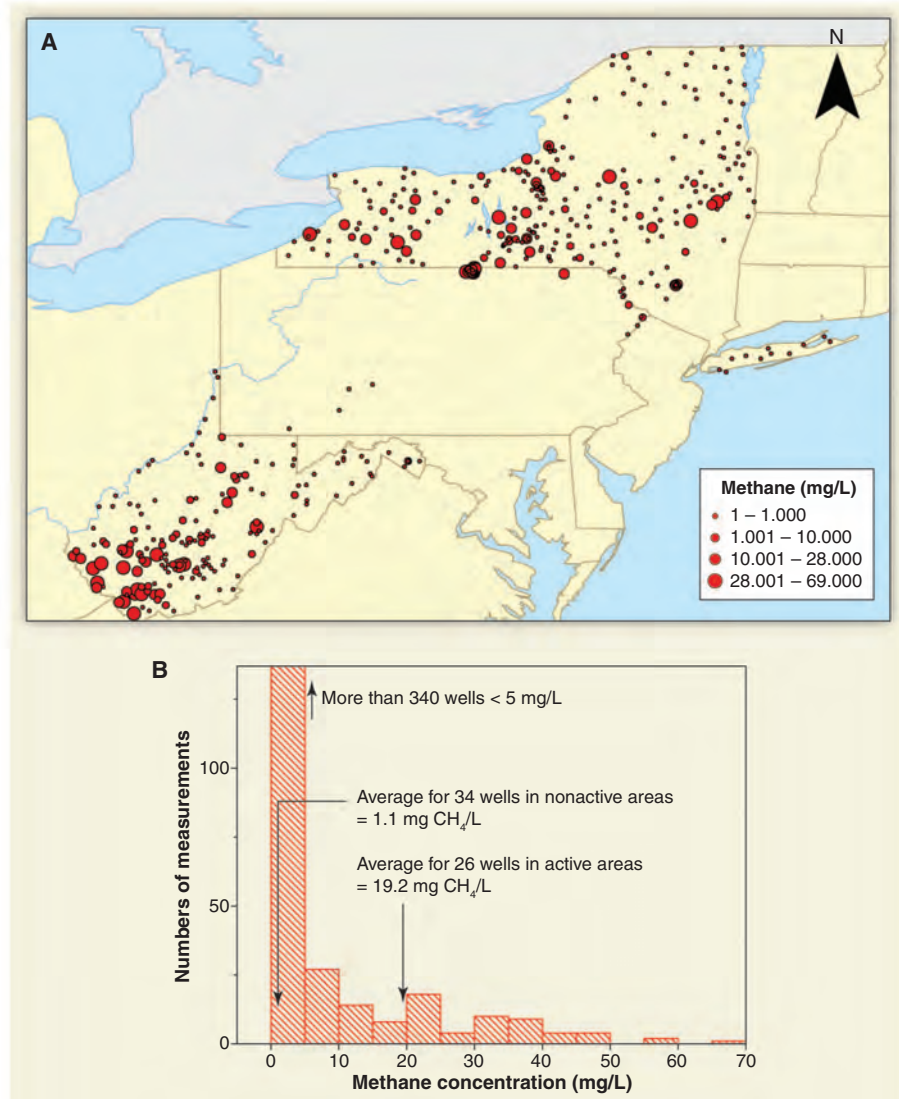
After hydraulic fracturing, the pressure barriers such as frac plugs are removed, the wellhead valve is opened, and “flowback water” is collected at the wellhead. Once the well begins to produce gas, this water is referred to as “produced water” and is recovered throughout the life of the well. Flowback and produced waters are a mixture of injected fluids and water that was originally present in the target or surrounding formations (formation water) (42, 46–50). The fraction of the volume of injected water that is recovered as flowback water from horizontal wells in Pennsylvania ranges from 9 to 53% (9, 41), with an average of 10%. It has been observed that the recovery can be even lower than 10% if the well is shut-in for a period of time (51). The well is shut-in—or maintained closed between fracturing and gas production—so as to allow the gas to

move from the shale matrix into the new fractures. Two of the key unanswered questions is what happens to the fracturing fluid that is not recovered during the flowback period, and whether this fluid could eventually contaminate drinking water aquifers (23, 33, 34, 52–54). The analyses of Marcellus Shale well logs indicate that the low-permeability shale contains very little free water (55, 56), and much of the hydraulic fracturing fluid may imbibe (absorb) into the shale.

Fracturing fluid could migrate along abandoned and improperly plugged oil and gas wells, through an inadequately sealed annulus between the wellbore and casing or through natural or induced fractures outside the target formation. Indeed, out-of-formation fractures have been documented to extend as much as ~460 m above the

top of some hydraulically fractured shales (57), but still ~1.6 km or more below freshwater aquifers. Nonetheless, on the basis of the study of 233 drinking-water wells across the shale-gas region of rural Pennsylvania, Boyer *et al.* (33) reported no major influences from gas well drilling or hydrofracturing on nearby water wells. Compared with the pre-drilling data reported in that study, only one well showed changes in water quality (salt concentration). These changes were noticed within days after a well was hydrofractured less than ~460 m away, but none of the analytes exceeded the standards of the U.S. Safe Drinking Water Act, and nearly all the parameters approached pre-drilling concentrations within 10 months.

In the case of methane contamination in groundwater near Dimock, Pennsylvania, contamination



**Fig. 2. Methane concentrations in groundwater and springs.** (A) Published values for groundwater or spring samples include 239 sites in New York from 1999 to 2011 (84), 40 sites in Pennsylvania in 2005 (27), and 170 sites in West Virginia from 1997 to 2005 (85). Maxima varied from 68.5 mg/L in West Virginia, to 44.8 mg/L in Tioga County, Pennsylvania, where an underground gas storage field was leaking, to a value approaching 45 mg/L in New York. (B) Values shown with down arrows are averages for a set of wells in southeastern New York and northeastern Pennsylvania located <1 km (26 wells) and >1 km (34 wells) from active gas drilling (20).

by saline flowback brines or fracturing fluids was not observed (20). One early U.S. Environmental Protection Agency (EPA) report (54) suggested that a vertically fractured well in Jackson County, West Virginia, may have contaminated a local water well with gel from fracturing fluid. This vertical well was fractured at a depth of just ~1220 m, and four old natural gas wells nearby may have served as conduits for upward contaminant transport. A recent EPA study (53) implicated gas production wells in the contamination of deep groundwater resources near Pavillion, Wyoming. However, resampling of the monitoring wells by the USGS showed that the flowrate was too small to lend confidence to water-quality interpretations of one well, leaving data from only one other well to interpret with respect to contamination, and regulators are still studying the data (58). The Pavillion gas field consists of 169 production wells into a sandstone (not shale) formation and is unusual in that fracturing was completed as shallow as 372 m below ground. In addition, surface casings of gas wells are as shallow

as 110 m below ground, whereas the domestic and stock wells in the area are screened as deep as 244 m below ground. The risk for direct contaminant transport from gas wells to drinking-water wells increases dramatically with a decrease in vertical distance between the gas well and the aquifer.

A recent study applied a groundwater transport model to estimate the risk of groundwater contamination with hydraulic fracturing fluid by using pressure changes reported for gas wells (52). The study concluded that changes induced by hydraulic fracturing could allow advective transport of fracturing fluid to groundwater aquifers in <10 years. The model includes numerous simplifications that compromise its conclusions (59). For example, the model is based on the assumption of hydraulic conductivity that reflects water-filled voids in the geological formations, and yet many of the shale and overburden formations are not water-saturated (60). Hence, the actual hydraulic conductivity in the field could be orders of magnitude lower than that assumed

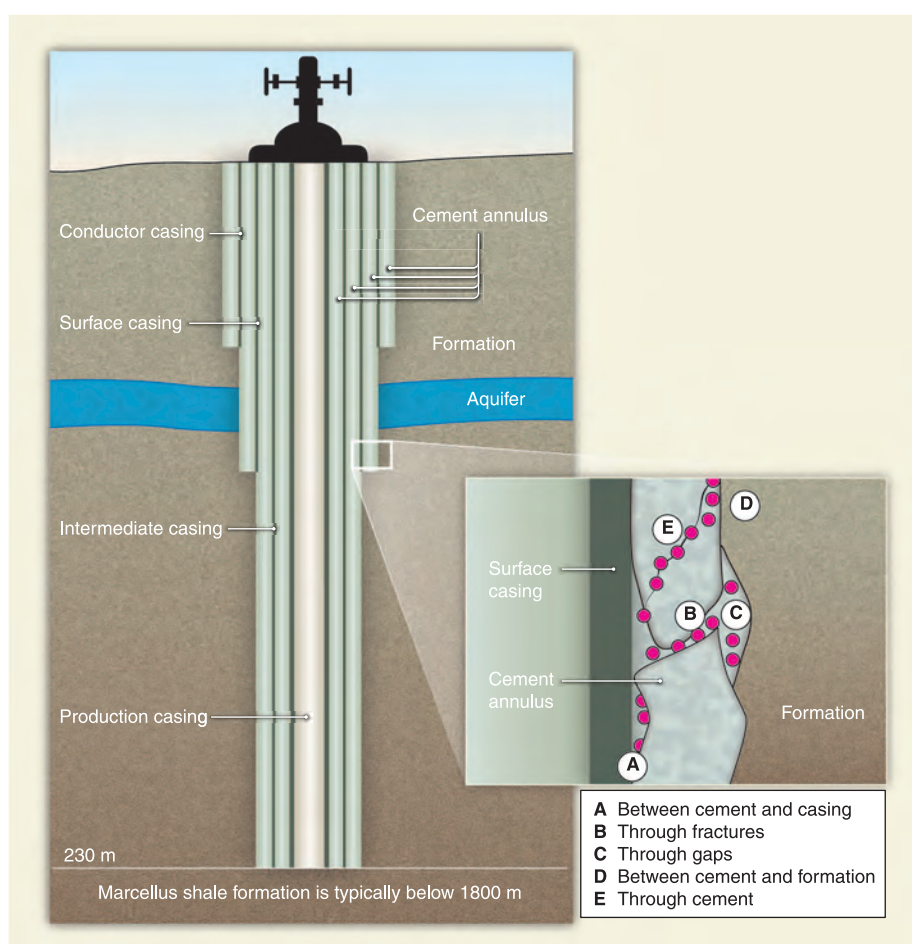
in the study (59). Furthermore, although deep joint sets or fractures exist (14), the assumption of preexisting 1500-m long vertical fractures is hypothetical and not based on geologic exploration. Hence, there is a need to establish realistic flow models that take into account heterogeneity in formations above the Marcellus Shale and realistic hydraulic conductivities and fracturing conditions.

Last, it has long been known (14, 34, 47, 48, 61, 62) that groundwater is salinized where deeper ancient salt formations are present within sedimentary basins, including basins with shale gas. Where these brines are present at relatively shallow depths, such as in much of the northeastern and southwestern United States and Michigan, brines sometimes seep to the surface naturally and are unrelated to hydraulic fracturing. An important research thrust should focus on understanding these natural brine transport pathways to determine whether they could represent potential risk for contamination of aquifers because of hydraulic fracturing.

### Appropriate Wastewater Management Options

The flowback and produced water from the Marcellus Shale is the second saltiest (63) and most radiogenic (50) of all sedimentary basins in the United States where large volume hydraulic fracturing is used. The average amount of natural gas-related wastewater in Pennsylvania during 2008 to 2011 was 26 million barrels per year (a fourfold increase compared with pre-Marcellus period) (64). Compared with conventional shallow wells, Marcellus Shale wells generate one third of the wastewater per unit volume of gas produced (65). However, the wastewater associated with Marcellus development in 2010 and 2011 accounted for 68 and 79%, respectively, of the total oil and gas wastewater requiring management in Pennsylvania. Flowback/produced water is typically impounded at the surface for subsequent disposal, treatment, or reuse. Because of the large water volume, high concentration of dissolved solids, and complex physical-chemical composition of this wastewater, which includes organic and radioactive components, the public is becoming increasingly concerned about management of this water and the potential for human health and environmental impacts associated with the release of untreated or inadequately treated wastewater to the environment (66). In addition, spills from surface impoundments (14) and trucks or infiltration to groundwater through failed liners are potential pathways for surface and groundwater contamination by this wastewater.

Treatment technologies and management strategies for this wastewater are constrained by regulations, economics of implementation, technology performance, geologic setting, and final disposal alternatives (67). The majority of wastewater from oil and gas production in the United States is disposed of effectively by deep underground injection (68). However, the state of Pennsylvania has only five operating Class II disposal wells. Although underground injection disposal wells will likely increase in number in Pennsylvania, shale gas development is currently occurring



**Fig. 3. Typical Marcellus well construction.** (i) The conductor casing string forms the outermost barrier closest to the surface to keep the upper portion of the well from collapsing and it typically extends less than 12 m (40 ft) from the surface; (ii) the surface casing and the cement sheath surrounding it that extend to a minimum of 15 m below the lowest freshwater zone is the first layer of defense in protecting aquifers; (iii) the annulus between the intermediate casing and the surface casing is filled with cement or a brine solution; and (iv) the production string extends down to the production zone (900 to 2800 m), and cement is also placed in the annulus between the intermediate and production casing. Potential flaws in the cement annulus (Inset, "A" to "E") represent key pathways for gas migration from upper gas-bearing formations or from the target formation.

in many areas where Class II disposal wells will not be readily available. Moreover, permissions for and construction of new disposal wells is complex, time-consuming, and costly. Disposal of Pennsylvania brines in Ohio and West Virginia is ongoing but limited by high transportation costs.

The lack of disposal well capacity in Pennsylvania is compounded by rare induced low-magnitude seismic events at disposal wells in other locations (69–71). It is likely that the disposal of wastewater by deep-well injection will not be a sustainable solution across much of Pennsylvania. Nonetheless, between 1982 and 1984, Texas reported at most ~100 cases of confirmed contamination of groundwater from oilfield injection wells, saltwater pits, and abandoned wells, even though at that time the state hosted more than 50,000 injection wells associated with oil and gas (72). Most problems were associated with small, independent operators. The ubiquity of wells and relative lack of problems with respect to brine disposal in Texas is one likely explanation why public pushback against hydraulic fracturing is more limited in Texas as compared with the northeastern United States.

Another reason for public pushback in the northeast may be that in the early stages of Marcellus Shale development, particularly in 2008 to 2009, flowback/produced water was discharged and diluted into publicly owned treatment works (POTWs), or municipal wastewater treatment plants) under permit. This practice was the major pathway for water contamination because these POTWs are not designed to treat total dissolved solids (TDS), and the majority of TDS passed directly into the receiving waterways (6, 73), resulting in increased salt loading in Pennsylvania rivers, especially during low flow (74). In response, the Pennsylvania DEP introduced discharge limits to eliminate disposal of Marcellus Shale wastewater to POTWs (75). In early 2010, there were 17 centralized waste treatment plants (CWTs) in Pennsylvania that were exempted from the TDS discharge limits. However, according to Pennsylvania DEP records none of these CWTs reported to be currently receiving Marcellus wastewater, although they may receive produced water from conventional gas wells. Nevertheless, the TDS load to surface waters from flowback/produced water increased from ~230,000 kg/day in 2006 to 350,000 kg/day in 2011 (64).

It is difficult to determine whether shale gas extraction in the Appalachian region since 2006 has affected water quality regionally, because baseline conditions are often unknown or have already been affected by other activities, such as coal mining. Although high concentrations of Na, Ca, and Cl will be the most likely ions detected if flowback or produced waters leaked into waterways, these salts can also originate from many other sources (76). In contrast, Sr, Ba, and Br are highly specific signatures of flowback and produced waters (34, 47). Ba is of particular interest in Pennsylvania waters in that it can be high in sulfate-poor flowback/produced waters but low in sulfate-containing coal-mine drainage. Likewise,

the ratio of  $^{87}\text{Sr}/^{86}\text{Sr}$  may be an isotopic fingerprint of Marcellus Shale waters (34, 77).

Targeting some of these “fingerprint” contaminants, the Pennsylvania DEP began a new monitoring program in 2011. Samples are collected from pristine watersheds as well as from streams near CWT discharges and shale-gas drilling. The Shale Network is collating these measurements with high-quality data from citizen scientists, the USGS, the EPA, and other entities in order to assess potential water quality impacts in the northeast (78, 79). Before 2003, mean concentrations in Pennsylvania surface waters in counties with unconventional shale-gas development were  $27 \pm 32$ ,  $550 \pm 620$ , and  $72 \pm 81$   $\mu\text{g}/\text{L}$  for Ba, Sr, and Br ( $\pm 1\sigma$ ), respectively (Fig. 4). Most values more than  $3\sigma$  above the mean concentrations since 2003 represent samples from areas of known brine effluents from CWTs. A concern has been raised over bromide levels in the Allegheny River watershed that may derive from active CWTs because of health effects associated with disinfection by-products formed as a result of bromide in drinking water sources (64, 80). Given the current regulatory climate and the fact that the majority of dissolved solids passes through these CWTs, it is expected that these treatment facilities will likely not play a major role in Marcellus Shale wastewater management.

The dominant wastewater management practice in the Marcellus Shale region nowadays is wastewater reuse for hydraulic fracturing [a review of Pennsylvania DEP data for the first 6 months of 2012 indicates 90% reuse rate (81)]. Wastewater is impounded at the surface and used directly, or after dilution or pretreatment. Reuse of wastewater minimizes the volume that must be treated and disposed, thus reducing environmental control costs and risks and enhancing the economic feasibility of shale-gas extraction (67). Currently, operators in the Marcellus region do not fully agree about the quality of wastewater that must be attained for reuse. Major concerns include possible precipitation of  $\text{BaSO}_4$  and, to a lesser extent,  $\text{SrSO}_4$  and  $\text{CaCO}_3$  in the shale formation and the wellbore and the compatibility of wastewater with chemicals that are added to the fracturing fluid (such as friction reducers and viscosity modifiers). Hence, a better understanding of chemical compatibility issues would greatly improve the ability to reuse wastewater and minimize disposal volumes. In addition, radioactive radium that is commonly present in flowback/produced water will likely be incorporated in the solids that form in the wastewater treatment process and could yield a low-concentration radioactive waste that must be handled appropriately and has potential on-site human health implications.

The wastewater reuse program represents a somewhat temporary solution to wastewater management problems in any shale play. This program works only as long as there is net water consumption in a given well field. As the well field matures and the rate of hydraulic fracturing diminishes, the field becomes a net water producer because

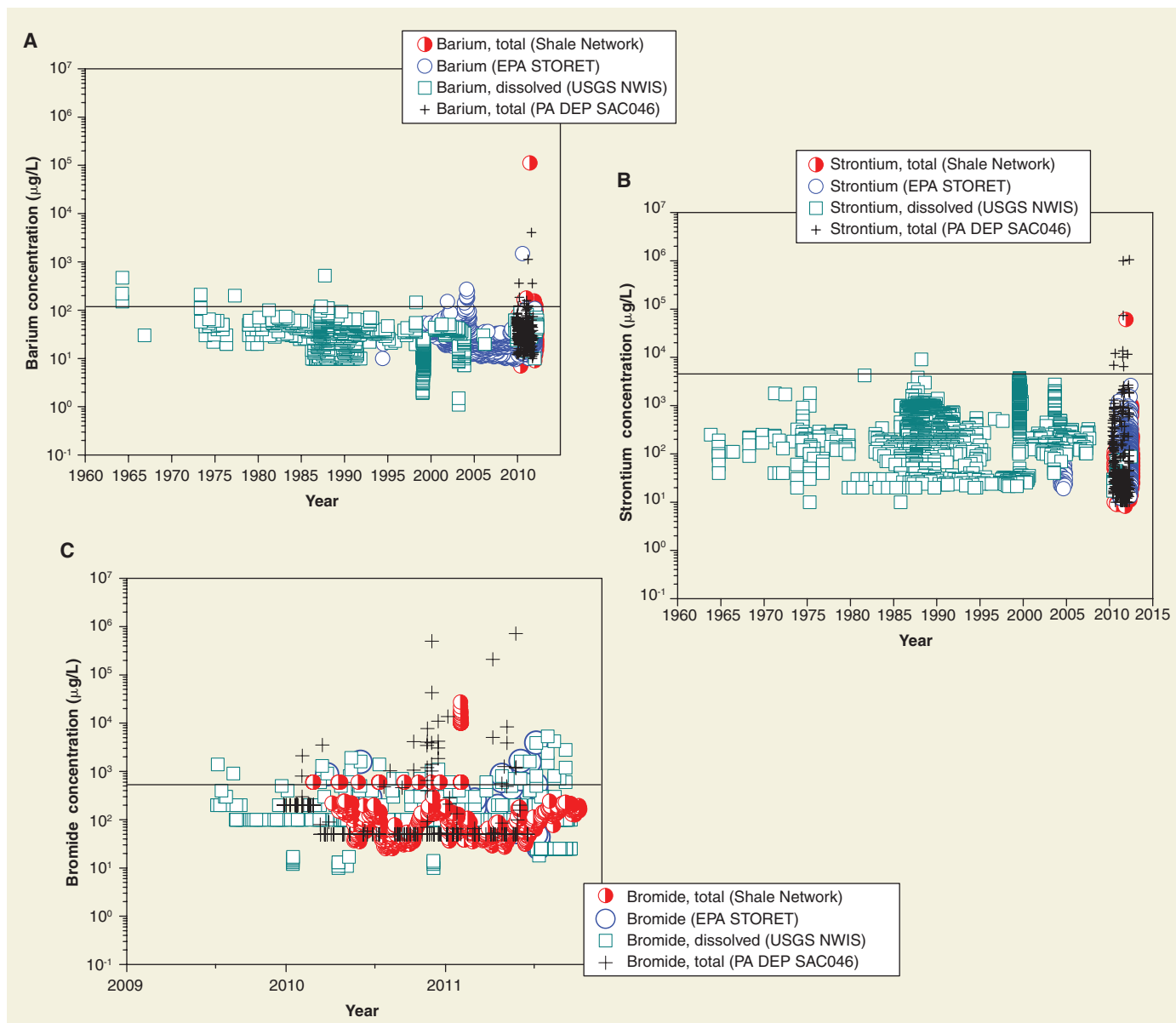
the volume of produced water will exceed the amount of water needed for hydraulic fracturing operations (82, 83). It is not yet clear how long it will take to reach that point in the Marcellus region, but it is clear that there is a need to develop additional technical solutions (such as effective and economical approaches for separation and use of dissolved salts from produced water and treatment for naturally occurring radioactive material) that would allow continued development of this important natural resource in an environmentally responsible manner. Considering very high salinity of many produced waters from shale gas development, this is truly a formidable challenge. Research focused on better understanding of where the salt comes from and how hydrofracturing might be designed to minimize salt return to the land surface would be highly beneficial.

## Conclusions

Since the advent of hydraulic fracturing, more than 1 million hydraulic fracturing treatments have been conducted, with perhaps only one documented case of direct groundwater pollution resulting from injection of hydraulic fracturing chemicals used for shale gas extraction (54). Impacts from casing leakage, well blowouts, and spills of contaminated fluids are more prevalent but have generally been quickly mitigated (17). However, confidentiality requirements dictated by legal investigations, combined with the expedited rate of development and the limited funding for research, are substantial impediments to peer-reviewed research into environmental impacts. Furthermore, gas wells are often spaced closely within small areas and could result in cumulative impacts (5) that develop so slowly that they are hard to measure.

The public and government officials are continuing to raise questions and focus their attention on the issue of the exact composition of the hydrofracturing fluid used in shale formations. In 2010, the U.S. House of Representatives directed the EPA to conduct a study of hydraulic fracturing and its impact on drinking-water resources. This study will add important information to account for the fate of hydraulic fracturing fluid injected into the gas-bearing formation. It is well known that a large portion (as much as 90%) of injected fluid is not recovered during the flowback period, and it is important to document potential transport pathways and ultimate disposition of the injected fluid. The development of predictive methods to accurately account for the entire fluid volume based on detailed geophysical and geochemical characteristics of the formation would allow for the better design of gas wells and hydraulic fracturing technology, which would undoubtedly help alleviate public concerns. Research is also needed to optimize water management strategies for effective gas extraction. In addition, the impact of abandoned oil and gas wells on both fluid and gas migration is a concern that has not yet been adequately addressed.

Gas migration received considerable attention in recent years, especially in certain parts of the Appalachian basin (such as northeast Pennsylvania).



**Fig. 4. Concentrations of three ions in surface waters of Pennsylvania in counties with unconventional shale-gas wells: (A) barium, (B) strontium, and (C) bromide.** Data reported by EPA (STORET data), USGS (NWIS data), Susquehanna River Basin Commission, Appalachian Geological Consulting and ALLARM [from Shale Network database (78, 79)], and from the Pennsylvania DEP (SAC046) include all rivers, streams, ponds, groundwater drains, lysimeter waters, and mine-associated pit, seep, and discharge waters accessed by using HydroDesktop ([www.cuahsi.org](http://www.cuahsi.org)) in the relevant counties (data before 2009 for bromide are not shown). Lines indicate  $3\sigma$  above the mean of data from 1960 to 2003 for the longest duration dataset (USGS). Most values above the lines

since 2003 represent targeted sampling in areas of known brine effluents from conventional oil and gas wells (such as Blacklick Creek receiving brine effluent from a CWT). The highest plotted Ba concentration was measured in Salt Springs in northern Pennsylvania. Three of the four samples with highest Sr and Br are from Blacklick Creek; next highest is from Salt Springs. Original values reported beneath the detection limit are plotted at that limit (10 to 100  $\mu\text{g}$  Sr/L; 10  $\mu\text{g}$  Ba/L; and 10 to 200  $\mu\text{g}$ /L Br). The EPA maximum contaminant level (MCL) for Ba is 2000  $\mu\text{g}$ /L. EPA reports no MCL for Sr or Br. Lifetime and 1-day health advisory levels for Sr are 4000 and 25000  $\mu\text{g}$ /L, respectively, and a level under consideration for Br is 6000  $\mu\text{g}$ /L.

It has been known for a long time that methane migrates from the subsurface (such as coal seams, glacial till, and black shales), and the ability to ignite methane in groundwater from private wells was reported long before the recent development of the Marcellus Shale (14). However, in the absence of reliable baseline information, it is easy to blame any such incidents on gas extraction activities. It is therefore critical to establish baseline conditions before drilling and to use multiple

lines of evidence to better understand gas migration. It is also important to improve drilling and cementing practices, especially through gas-bearing formations, in order to eliminate this potential pathway for methane migration.

Water management for unconventional shale gas extraction is one of the key issues that will dominate environmental debate surrounding the gas industry. Reuse of flowback and produced water for hydraulic fracturing is currently address-

ing the concerns regarding the vast salt quantities that are brought to the surface (each Marcellus well generates as much as 200 tons of salt during the flowback period). However, there is a need for comprehensive risk assessment and regulatory oversight for spills and other accidental discharges of wastewater to the environment. As these well fields mature and the opportunities for wastewater reuse diminish, the need to find alternative management strategies for this wastewater

will likely intensify. Now is the time to work on these issues in order to avoid an adverse environmental legacy similar to that from abandoned coal mine discharges in Pennsylvania.

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