Production and Disposal of Waste Materials from Gas and Oil Extraction from the Marcellus Shale Play in Pennsylvania

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The increasing world demand for energy has led to an increase in the exploration and extraction of natural gas, condensate, and oil from unconventional organic-rich shale plays. However, little is known about the quantity, transport, and disposal method of wastes produced during the extraction process. We examined the quantity of waste produced by gas extraction activities from the Marcellus Shale play in Pennsylvania for 2011. The main types of wastes included drilling cuttings and fluids from vertical and horizontal drilling and fluids generated from hydraulic fracturing [i.e., flowback and brine (formation) water]. Most reported drill cuttings (98.4%) were disposed of in landfills, and there was a high amount of interstate (49.2%) and interbasin (36.7%) transport. Drilling fluids were largely reused (70.7%), with little interstate (8.5%) and interbasin (5.8%) transport. Reported flowback water was mostly reused (89.8%) or disposed of in brine or industrial waste treatment plants (8.0%) and largely remained within Pennsylvania (interstate transport was 3.1%) with little interbasin transport (2.9%). Brine water was most often reused (55.7%), followed by disposal in injection wells (26.6%), and then disposed of in brine or industrial waste treatment plants (13.8%). Of the major types of fluid waste, brine water was most often transported to other states (28.2%) and to other basins (9.8%). In 2011, 71.5% of the reported brine water, drilling fluids, and flowback was recycled: 73.1% in the first half and 69.7% in the second half of 2011. Disposal of waste to municipal sewage treatment plants decreased nearly 100% from the first half to second half of 2011. When standardized against the total amount of gas produced, all reported wastes, except flowback sands, were less in the second half than the first half of 2011. Disposal of wastes into injection disposal wells increased 129.2% from the first half to the second half of 2011; other disposal methods decreased. Some issues with data were uncovered during the analytical process (e.g., correct geospatial location of disposal sites and the proper reporting of end use of waste) that obfuscated the analyses; correcting these issues will help future analyses.

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The increasing world demand for energy has led to increased exploration and extraction of unconventional hydrocarbon (oil and natural gas) resources. One such resource is the natural gas, condensate, and oil from unconventional organic-rich shale plays. Shale is a fine-grained, low-permeability, sedimentary rock, and therefore requires stimulation techniques to increase production [United States Department of Energy (USDOE), 2009]. A key need is a cumulative assessment of the quantity of waste produced during the gas extraction process, as well as a cumulative assessment of the location and method of waste disposal. Here, we examine waste production and the treatment of these waste materials from gas extraction activities associated with the Marcellus Shale play in Pennsylvania.

Two technological advancements, horizontal drilling and hydraulic fracturing, are being used to increase hydrocarbon productivity of wells installed in these shales. Horizontal drilling is a process that enables a well to be drilled vertically and then gradually turned until landing horizon-

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tally in the target shale formation. The horizontal section of the well is then advanced 1–2 km or more through the shale, resulting in increased contact area of the reservoir conjointly with reduced disturbance of the surface landscape. *Hydraulic fracturing* (often referred to as *fracking*) is the process that incorporates stimulation of the gas and oil reserves in the shale by expanding fractures in the shale via injection of *fracking fluid* (a combination of water, proppants such as sand, and other chemicals) under high pressure (USDOE, 2009). The exact makeup of the fracking fluid varies, but, in general, each hydraulic fracturing of a well requires 3–7 million gallons of fluids consisting of 90%–95% water, 5%–10% sand proppant, and 0.1%–1% of chemical additives, such as friction reducers, biocides, acids, and gelling agents (FracFocus, 2012). Following the hydraulic fracturing process, the well enters the production stage where, due to the enhanced fracture network, natural gas, condensate, and oil, when present, return to the surface through the well's production casing. The gas is then treated, compressed, and sent to distribution.

The extraction of gas and other fuels from unconventional shale plays has been increasing significantly over the last decade, especially in North America. Potential environmental and health impacts from shale development have received much attention from media and regulators, which has led to increased research on topics such as impacts to land surface (forest fragmentation), air quality, water quality, and human health [Drohan et al., 2012; Kargbo, Wilhelm, and Campbell, 2010; Entrekin et al., 2011; New York Department of Environmental Conservation (NYSDEC), 2011; US Environmental Protection Agency, 2011]. However, no comprehensive study has assessed the amount and distribution of waste material created during the extraction process.

Waste materials are generated during each phase of the extraction process. During the drilling, well cuttings and fluids are produced. Cuttings, although low in naturally occurring radioactive materials (NORMs) (Kargbo, Wilhelm, and Campbell, 2010; NYSDEC, 2011), require proper treatment or disposal in approved landfills, where they can often be used as daily landfill cover. A large volume of wastewater is generated from each well after hydraulic fracturing is completed. *Flowback water*, which is the portion of the injected hydraulic fracturing and native formation fluids that return in the 20–30 days after a well has been fractured, typically represents 10%–20% of the injected hydraulic fracturing volume. *Brine water* (formation water) is generally considered to be the fluids generated from and around the gas-bearing formation after the period of flowback fluid production and when the well is in the gas-production phase, which may represent several barrels of wastewater per day. The flowback and brine fluids contain naturally occurring salts, metals, organics, and NORMs (Fisher, 1998; Kargbo, Wilhelm, and Campbell, 2010; Rowan et al., 2011; Soeder and Kappel, 2009) that occur in the shale. The total dissolved solids concentration in the flowback and brine water may approach 300,000 mg/liter or more [the US secondary maximum contaminant level for total dissolved solids (TDS) is 500 mg/liter (USEPA, 2012)] and therefore requires that the water be treated or diluted for reuse, or properly disposed at a licensed treatment facility or deep injection well. Industry has made significant progress in recycling these wastes, which reduces the volume of freshwater required for hydraulic fracturing and wastewater disposal (Rassenfoss, 2011). However, an assessment of the data showing this trend for the Marcellus Shale's development is lacking.

The Marcellus Shale play is of Middle Devonian age and underlies approximately 246,000 km^2 of the Northeastern US, including large portions of New York, Pennsylvania, Ohio, and West Virginia. Current estimates of recoverable gas from this play range from a mean total undiscovered resources of 84 trillion cubic feet (tcf) (Coleman et al., 2011) to 141 tcf of unproved technically recoverable gas (US Energy Information Administration, 2012). These resource estimates are in addition to the proven reserves calculated by each company developing the Marcellus Shale, which publicly traded companies are required to report to the Securities Exchange Commission. Because of these estimates, the Marcellus Shale play area in Pennsylvania has experienced a rapid increase in the number of wells and associated infrastructure over the past five years. We used 2011 production and waste reports from the Pennsylvania Department of Environmental Protection (PADEP) to examine patterns in fuel and waste production and waste treatment in Pennsylvania. During 2011, an active development year, 1,937 Marcellus-related wells were drilled.[1] We first examined state-level and county-level trends to provide an overall spatial assessment. We then examined how each waste was treated and the transport of waste between political (state) and drainage basin boundaries. Lastly, we examined how trends in waste generation and treatment have changed between the first half and second half of 2011.

Methods

Pennsylvania is underlain by several unconventional shale plays (e.g., Utica, Marcellus, Geneseo/Burket, and Rhinestreet)

that have the potential to produce large volumes of natural gas and condensates. Of recent, the Marcellus play has received the most attention by industry, and over 5,000 unconventional wells have been drilled across the state, with most effort focused on the north-central/eastern and southwestern counties (Figure 1).

Production and waste reports for 2011 were retrieved from the PADEP website for each Marcellus Shale–related well (PADEP, 2012). For the 2011 reporting year, the PADEP separated the files into two reporting periods: Period 1, from January 1 to June 30, 2011; and Period 2, from July 1 to December 31. 2011. Production reports included data on the volume of gas, condensate, and oil produced; whether the well was vertical or horizontal; well operator information; and well location (e.g., county and township where the well was located, and latitude and longitude). Waste reports included the aforementioned well location information, as well as quantities and types of waste produced, disposal method used, and information on the disposal/treatment facility (state, address, latitude, and longitude). For waste facility location, landfill and treatment plants were confirmed with geographic information system (GIS) and Google Earth analyses. For deep injection wells, locations were confirmed with location data provided by the state agency maps [e.g., Ohio Department of Natural Resources (DNR) and PADEP]. Producing well and disposal/treatment facilities were assigned to the major drainage basin (Chesapeake Bay, Delaware Bay, Ohio River, the Great Lakes, and the New York Bay) in which they were located by using site location information and ArcGIS (ESRI, Redlands, CA).

During initial screening of the waste reports, we noticed several inconsistencies/errors in the database. First, some

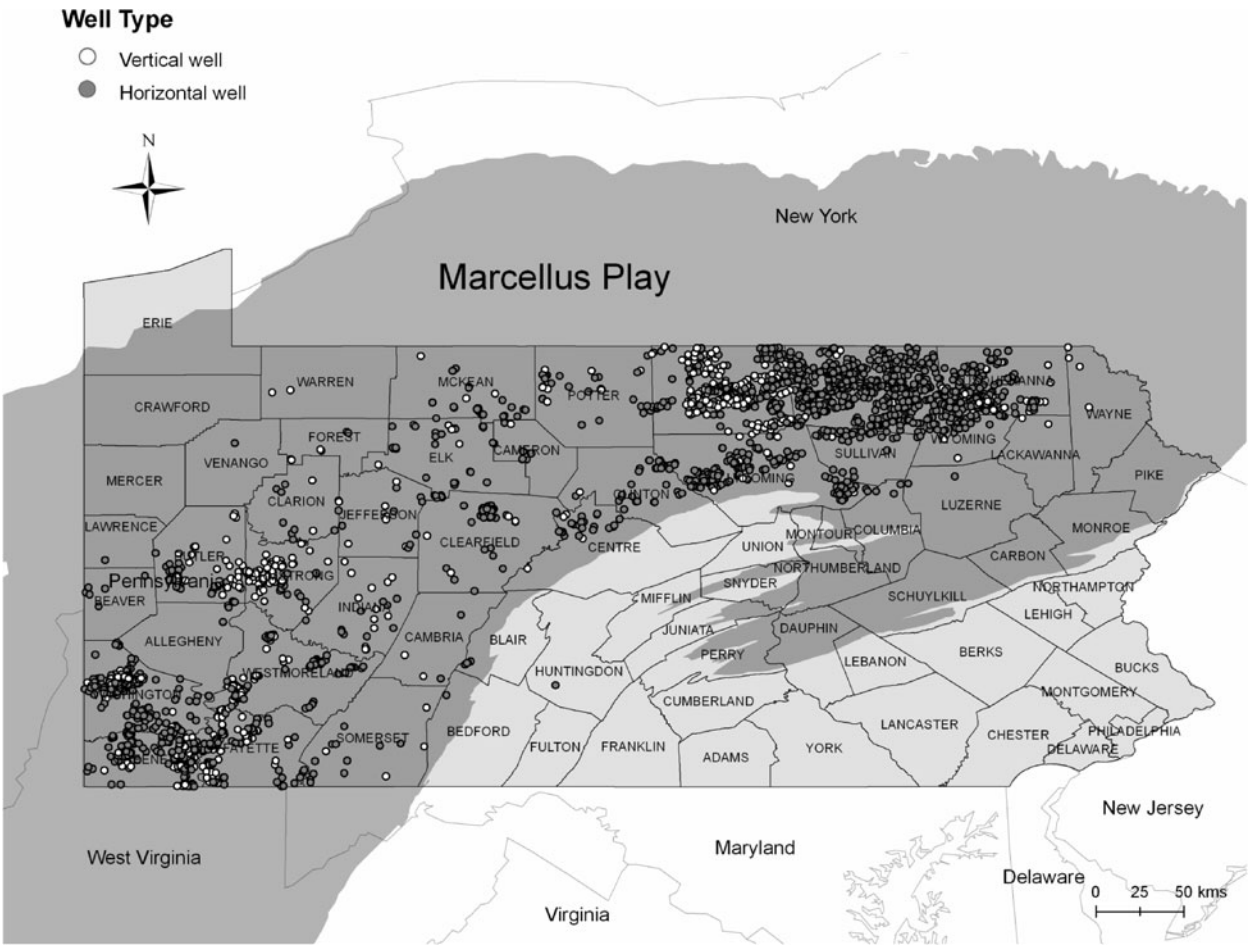

Figure 1. Locations of gas-related Marcellus wells drilled in Pennsylvania as reported in the spud report of December 31, 2011 (N = 4,907; 4,110 horizontal). *Dark shading* is the extent of the Marcellus Shale play.

records with disposal method listed as "Brine or industrial waste treatment plant" had a waste facility permit ID for an injection disposal well; we therefore changed the disposal method for these records to "Injection disposal well." Known recycling waste facilities also were listed as a "Brine or industrial waste treatment plant," which we changed to "Reuse other than road spreading." Finally, we removed waste records for one company that appeared to have reported waste production volumes inconsistently.

We summed the amount of gas, condensate, and oil produced by county for 2011 to assess the cumulative and spatial patterns. For waste, we summed the major types reported, including basic sediment, brine (i.e., formation water), drill cuttings, drilling fluids, flowback fracturing sand, frac fluids (i.e., flowback), and spent lubricants. We examined waste transfer for 2011 at two scales: interstate and interbasin. For the interstate analysis, we summed the amount of each type of waste by receiving state. We also summed the amount of each waste type by the five major receiving basins: Chesapeake Bay, Delaware Bay, Ohio River, the Great Lakes, and the New York Bay.

To identify the major treatment and disposal methods used during 2011, we summed waste by the reported disposal method for the entire state. Six disposal methods were reported: (1) brine or industrial waste treatment plant, (2) injection disposal well, (3) landfill, (4) municipal sewage treatment plant, (5) reuse other than road spreading, and (6) unknown. In April and May 2011, disposal of flowback and brine water via treatment plants that could not meet Chapter 95 of the Pennsylvania Code (Commonwealth of Pennsylvania, 1971) water quality standards for TDS concentration greater than 2,000 mg/liter was discouraged in Pennsylvania because of water quality concerns. As a result, changes were necessary in industry waste fluid management practices. Therefore, we also examined these possible effects by summing total waste by disposal method by reporting period.

Results

Gas production was highest in the northeast/north central part of the state, with Bradford County [2.88×10^8 Mcf (thousand cubic feet)], Susquehanna County (2.02×10^8 Mcf), and Tioga County (1.26×10^8 Mcf) producing the three highest amounts in 2011 (Figure 2). Greene County produced the fourth highest amount (1.19×10^8 Mcf), and Washington County produced the fifth highest (1.14×10^8 Mcf). Condensate and oil production was highest in the southwestern counties, being largely produced from Washington County (condensate 529,685 barrels and oil 384,398 barrels).

Total waste produced across Pennsylvania included 5,313 barrels of basic sediment, 9,065,470 barrels of brine water, 798,623 tons of drill cuttings, 2,374,469 barrels of drilling fluids, 14,947 tons of flowback fracturing sands, 7,878,587 barrels of flowback, and 5,256 barrels of spent lubricants. The highest amounts of brine water were generated in Greene and Washington Counties, and the highest amounts of flowback were reported from Bradford, Greene, Susquehanna, and Washington Counties. Drilling fluids were reported highest from Bradford, Susquehanna, Greene, and Washington Counties (Figure 3).

Industry reused/recycled 71.6% (12,126,068 of 16,944,057 barrels) of the generated flowback and brine water. The vast majority of flowback (96.8%) was managed in Pennsylvania, mainly through reuse/recycling (89.8%) and industrial and wastewater treatment plants (6.8%). For brine water, 71.3% was treated/disposed of in Pennsylvania, largely through brine or industrial wastewater treatment plants (11.6%) and reuse (55.7%), and 27.8% was disposed of in Ohio mainly though deep well injection (Table 1). Drilling fluids were largely managed within Pennsylvania (91.4%), primarily through reuse (70.7%) and brine or industrial waste treatment plants (19.8%). About half of the drill cuttings (50.4%) were disposed of in Pennsylvania largely in landfills; however, 20.0% and 28.5% were disposed of in Ohio and New York, respectively, again largely in landfills.

Only 22.0% of flowback remained in the originating basin, 75.0% had an undesignated receiving basin, and 2.9% was transported among basins. Nearly 10% of brine water (9.8%) was transported across major drainage basins; most brine water either was disposed of within the originating drainage basin (41.0%) or its destination basin was not designated (49.2%; Table 2). Drilling fluids were largely disposed of within the originating basin (46.8%) or had an undesignated receiving basin (47.4%); only 5.8% were transported across major drainage divides. More drill cuttings (63.3%) were disposed of within the originating basin than outside it (36.7%).

Reuse of all fluids (brine water, flowback, and drilling fluids) decreased from 73.1% (7,444,345 of 10,190,388 barrels) in Period 1 to 69.7% (6,360,823 of 9,128,139 barrels) in Period 2. Reuse of brine water decreased from 56.3% (2,746,880 of 4,878,299 barrels) in Period 1 to 55.0% (2,303,307 of 4,187,171 barrels) in Period 2. Reuse of flowback decreased from Period 1 (92.4%; 3,820,057 of 4,134,532 barrels) to Period 2 (86.9%; 3,255,825 of 3,744,055 barrels), and reuse of drilling fluid wastes decreased from Period 1 (74.5%; 877,409 of 1,177,556 barrels) to Period 2 (67.0%; 801,692 of 1,196,913 barrels).

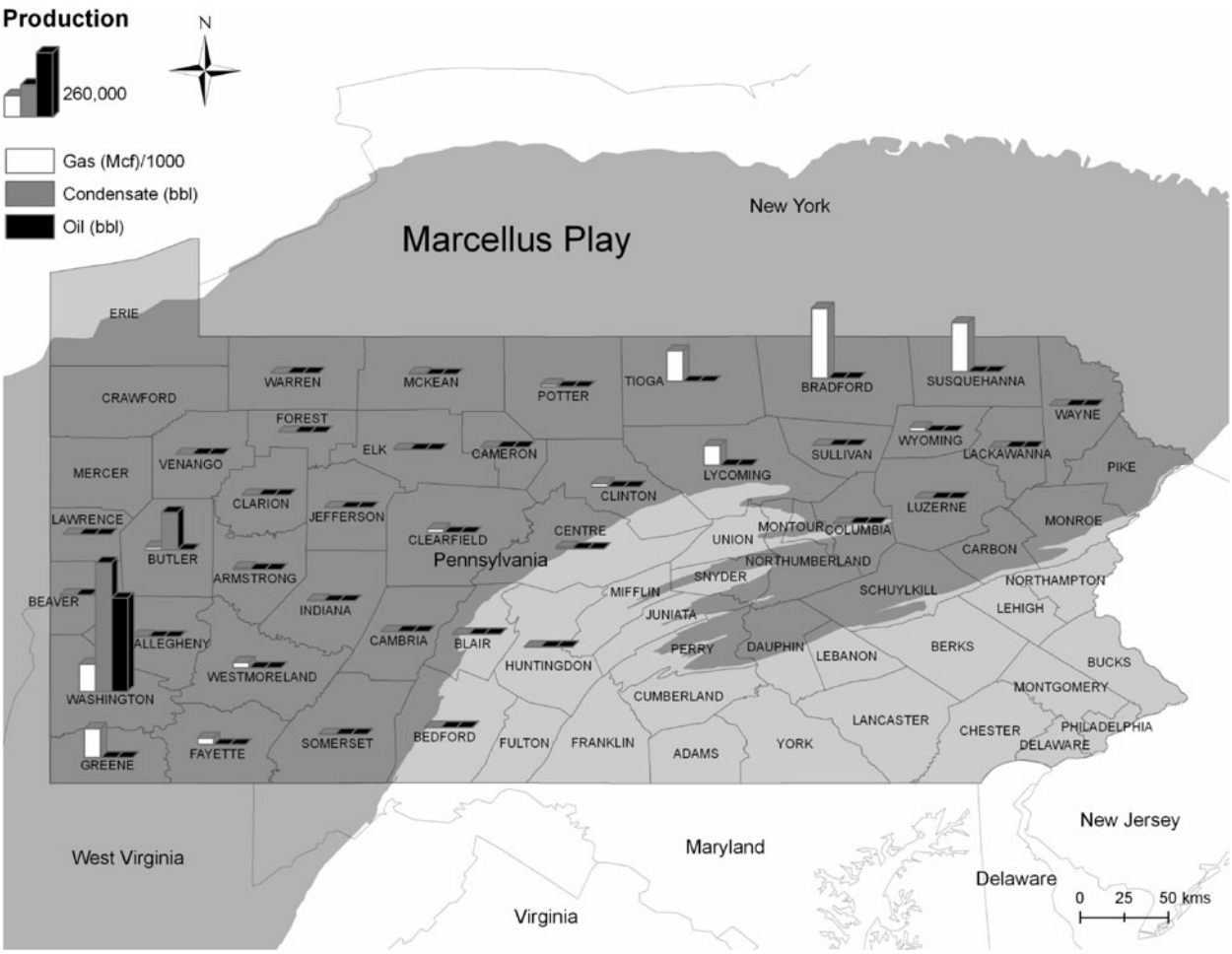

Figure 2. The 2011 county-level estimates of gas, condensate, and oil production for Pennsylvania: data from the 2011 production reports. *Dark shading* is the extent of the Marcellus Shale play. Gas values were divided by 1,000 to scale with other reported production estimates. Mcf, thousand cubic feet; bbl, barrels.

When standardized against the total amount of gas produced, all wastes, except flowback fracturing sands, showed a decrease in Period 2 of 2011 (Table 3). Disposal of waste into injection disposal wells, when standardized for gas production, increased 129.2% between Period 1 and Period 2; all other disposal methods decreased (Table 4). Disposal of waste into municipal sewage treatment plants decreased from 47,221 barrels in Period 1 to 408 barrels in Period 2; production standardized disposal estimates decreased 99.4% between Period 1 and Period 2.

Discussion

The thermal maturity of the Marcellus Shale play increases moving eastward, and therefore the western portion of the play produces wet gas (oil, gas condensates, and methane), whereas the eastern region produces dry gas (primarily methane). Review and analysis of the PADEP Marcellus Shale gas production data set support the wet/dry gas regions because the northeastern and north central counties only produced natural gas, whereas the southwestern counties produced a mixture of natural gas, gas condensates, and oil. This pattern has important ramifications for industry and the future development of the Marcellus Shale play. On May 11, 2012, the Henry Hub natural gas spot price was at $2.37 MMBtu (Oilnergy, n.d.), which is approximately $2.00 less than the previous year. The decrease in the price of natural gas has prompted the gas industry to shift their development activities to the western portion of the Marcellus Shale play and to the Utica Shale, where natural gas liquids and oil can be produced more profitably. This shift will un-

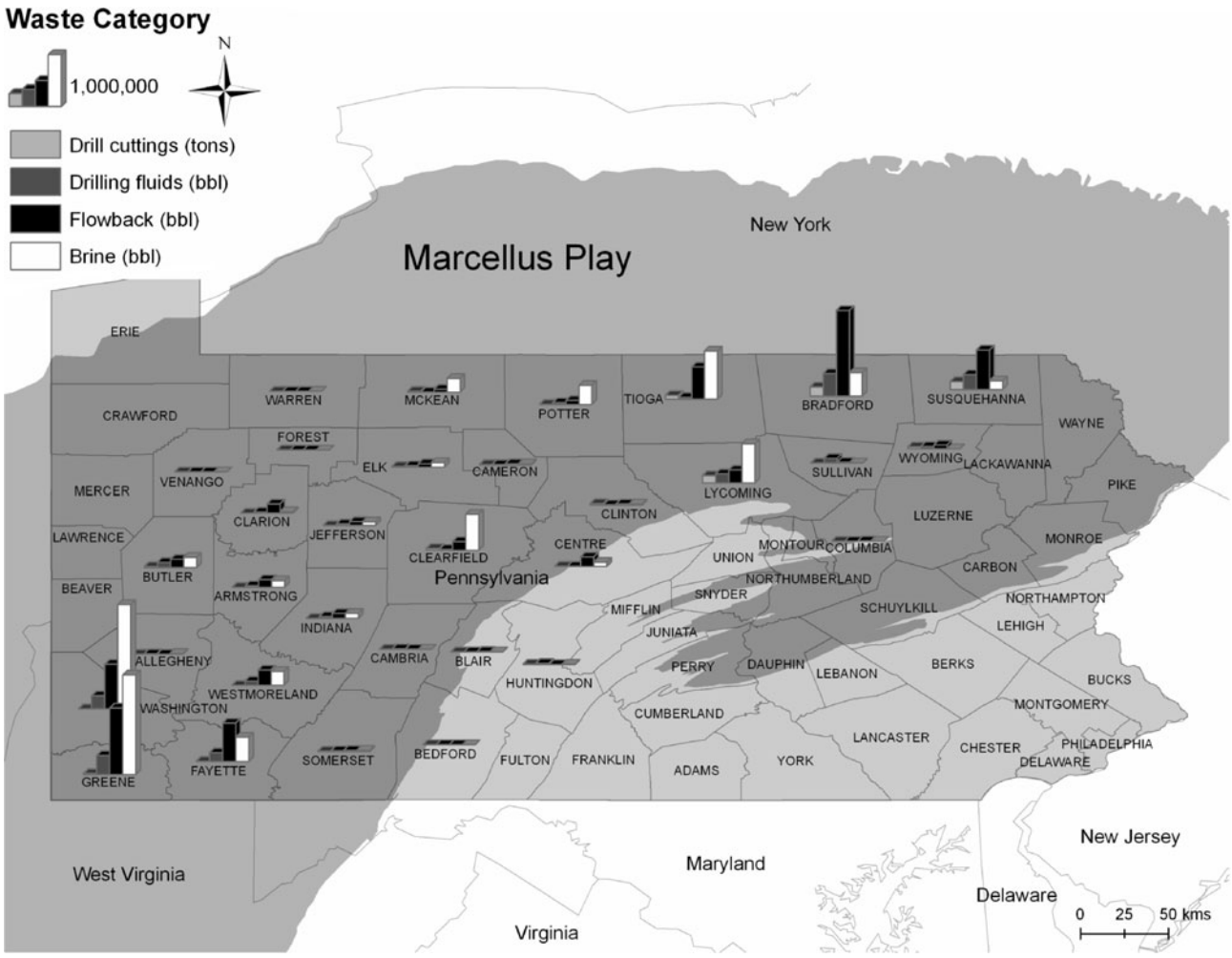

Figure 3. The 2011 county-level waste estimates for brine water, drill cuttings, drilling fluids, and flowback from gas, condensate, and oil production for Pennsylvania: data from the 2011 waste reports. *Dark shading* is the extent of the Marcellus Shale play. bbl, barrels.

doubtedly affect the production of natural gas and waste in Pennsylvania.

The large volume of reported drill cuttings produced in the northeastern and north central part of Pennsylvania was likely because these areas experienced a high number of drilled wells in 2011. For example, Bradford, Lycoming, Susquehanna, and Tioga Counties had 1,155 (59.6%) of the 1,937 total wells drilled in Pennsylvania.[1] Not surprisingly, because cuttings are solid wastes, landfills were the main choice for disposal of these wastes. However, our analyses revealed a high level of interstate and interbasin transfer of these wastes. The reported level of interstate and interbasin disposal of drilling fluids (if reuse is assumed to occur in the same state and drainage where it was produced) was minimal, suggesting that industry reuse practices and local disposal facilities are sufficient to handle this waste without significant transport, at least at 2011 levels.

Disposal of flowback and brine water is of particular concern because of their volume, high salinity, and other constituents. The best option would be to reuse these wastes in future operations because this will reduce the need for freshwater and reduce disposal volumes. Our analyses suggest that 89.8% of the reported flowback in 2011 was reused and that industry reused similar amounts of this waste from the first half to second half of 2011. Flowback waters are those fluids returning after the hydraulic fracturing procedure and before the well is put into production, so they would tend to have a lower salinity, which is more conducive to recycling. Brine

Table 1. Total Marcellus waste generated in Pennsylvania during 2011 separated by state, disposal method, and waste type

		Waste type						
Disposal state	Disposal method	Basic sediment (bbl)	Produced water (bbl)	Drill cuttings (tons)	Drilling fluids (bbl)	Flowback fracturing sand (tons)	Flowback (bbl)	Spent lubricants (bbl)
MD	Brine or industrial waste treatment plant	0	114	0	363	0	0	0
NJ	Landfill	0	0	450	0	0	0	0
NY	Landfill	0	445	227,598	8,598	443	1,320	0
OH	Brine or industrial waste treatment plant	0	171,077	576	113,739	0	97,898	240
OH	Injection disposal well	0	2,348,702	0	47,412	0	140,063	0
OH	Landfill	0	0	149,118	6,550	24	0	0
OH	Other	0	0	10,005	0	0	0	334
PA	Brine or industrial waste treatment plant	116	1,052,182	1,834	469,871	210	531,970	3,853
PA	Landfill	887	95	400,611	5,946	13,877	1,197	830
PA	Injection disposal well	0	5,346	0	1,110	0	110	0
PA	Municipal sewage treatment plant	0	26,379	0	14,466	0	6,784	0
PA	Unknown	0	331,182	0	0	0	14,320	0
PA	Reuse other than road spreading	4,311	2,216,889	405	1,224,431	0	3,774,078	0
PA?	Reuse other than road spreading	0	2,833,297	0	454,670	0	3,301,804	0
PA	Other	0	0	0	0	1	0	0
WV	Brine or industrial waste treatment plant	0	23,484	0	0	0	0	0
WV	Injection disposal well	0	10,305	0	23,775	0	3,964	0
WV	Landfill	0	0	4,815	1,067	391	520	0
Unk	Injection disposal well	0	45,973	0	2,473	0	4,559	0
Unk	Landfill	0	0	3,211	0	0	0	0
	Total intrastate transfer	5,314	6,465,370	402,850	2,170,494	14,088	7,630,263	4,683
	Total interstate transfer	0	2,554,127	392,562	201,504	858	243,765	574
	Unknown state	0	45,973	3,211	2,473	0	4,559	0
	Total	5,313	9,065,470	798,623	2,374,469	14,947	7,878,587	5,256

"Unknown" indicates a treatment/disposal location was not indicated in the waste production report. "PA?" indicates waste reports had no state disposal location, but it was assumed to be reused in Pennsylvania for analyses. "Unk," no identifying record for state; bbl, barrels.

waters are those fluids returning after the well is producing and are often higher in salinity: 55% of this waste was reported as reused in 2011 and, like flowback, industry reused similar relative amounts of this waste in both halves of 2011. Difficulty in treating this waste for reuse (e.g., because of high TDS) might be precluding a higher reuse rate. The higher amounts of brine waters in southwestern Pennsylvania were likely due to the Marcellus Shale in this area being less thermally mature and thus containing natural gas liquids such as ethane, butane, and propane.

Interstate and interbasin transport of brine water and flowback showed different patterns from each other. Outside of reuse, the majority of flowback was disposed of within Pennsylvania in brine or industrial treatment plants, and interbasin transport was minimal if reuse is assumed to occur in the same drainage. Similar to drilling fluids, this suggests that, at least at 2011 levels, industry reuse practices and local disposal facilities are sufficient to handle this waste without significant transport. However, 28.2% of brine water was transported out of state, largely to injection disposal wells in Ohio. Interbasin transfer of brine water was also higher than that for flowback, mostly being transported from the Chesapeake Bay watershed to the Ohio River drainage basin for disposal in injection disposal wells. Our analyses also indicated that reported use of injection disposal wells had increased 129.2% between the first half and second half of 2011. These results indicate that industry reuse practices and local disposal facilities in Pennsylvania are inadequate to dispose of brine waste at the 2011 levels at least in the short term when municipal treatment plant disposal was discouraged.

Table 2. Transport of wastes between major drainage basins

Waste from → to	Basic sediment (bbl)	Brine water (bbl)	Drill cuttings (tons)	Drilling fluids (bbl)	Flowback fracturing sand (tons)	Flowback (bbl)	Spent lubricants (bbl)
Ches → Ohio	887	825,567	185,068	98,691	9,921	106,417	574
Ohio → Ohio	4,427	2,734,730	87,267	830,392	2,480	1,193,742	0
Ches → Unk	0	1,498,908	0	797,833	0	3,178,928	0
Ches → Ches	0	980,061	417,864	281,397	2,248	542,260	978
Ches → Del	0	2,140	0	3,571	0	0	3,705
Ches → GrLakes	0	8,886	85,760	925	199	625	0
Ohio → Unk	0	2,963,596	0	327,459	0	2,733,567	0
Ohio → Ches	0	690	18,506	23,571	98	72,819	0
Ohio → GrLakes	0	50,893	3,708	10,630	0	50,229	0
Ches → NYBay	0	0	450	0	0	0	0
Total interbasin transfer	4,427	3,714,791	505,131	1,111,789	4,728	1,736,002	978
Total interbasin transfer	887	888,176	293,492	137,388	10,218	230,090	4,279
Unknown	0	4,462,504	0	1,125,292	0	5,912,495	0
Total	5,313	9,065,470	798,623	2,374,469	14,947	7,878,587	5,256

"Waste from → to" indicates where the waste was produced ("From") and then what drainage basin it was transported to ("To") for treatment/disposal. "Unk" indicates that a treatment/disposal location was not indicated in the waste production report (mostly reused material in the Ohio and Chesapeake drainages that did not have an exact location provided in the waste report; see the "Reuse other than road spreading" rows in Table 1). "Ches," the Chesapeake basin; "Del," the Delaware basin; "GrLakes," the Great Lakes basin; "NYBay," New York Bay basin; bbl, barrels.

The most obvious change in reported waste disposal practices in 2011 was, in effect, no waste being sent to municipal wastewater treatment plants in the second half of the year. This was likely because the disposal of wastes in treatment plants that could not meet Chapter 95 of the Pennsylvania Code was discouraged. The decreased reporting of disposal of brine or industrial wastes at municipal wastewater treatment plants or the increased disposal of fluid wastes into injection disposal wells also might be due to this discouragement but could not be confirmed with the current analysis and database. A more detailed analysis is needed to determine how such discouragement or regulation affects gas industry waste disposal practices.

While conducting the current analyses, we noted several issues that merit discussion. First, inconsistencies among the geographic coordinates and reported addresses of the waste-receiving facilities obfuscated efforts to determine waste treatment and disposal locations. We were able to use Web searches, Google Earth, GIS, and other state data

Table 3. Waste produced in Pennsylvania by extraction process in 2011 by period of operation: Period 1, January 1 to June 30, 2011; and Period 2, July 1 to December 31, 2011

		Waste quantity		Waste/1,000 Mcf gas produced		
Waste type	Waste unit	Period 1	Period 2	Period 1	Period 2	% Change
Basic sediment	bbl	4,619	694	0.011	0.001	–89.6
Brine water	bbl	4,187,171	4,878,299	9.621	7.726	–19.7
Drill cuttings	tons	401,611	397,012	0.923	0.629	–31.9
Drilling fluid	bbl	1,196,913	1,177,556	2.750	1.865	–32.2
Flowback sands	tons	4,904	10,042	0.011	0.016	41.1
Flowback	bbl	3,744,055	4,134,532	8.602	6.548	–23.9
Spent lubricants	bbl	3,696	1,560	0.008	0.002	–70.9

bbl, barrels; Mcf, thousand cubic feet.

Table 4. Disposal method for waste produced in Pennsylvania during extraction process in 2011 by period of operation: Period 1, January 1 to June 30, 2011; and Period 2, July 1 to December 31, 2011

		Waste quantity		Waste/1,000 Mcf gas produced		
Disposal method	**Waste unit**	**Period 1**	**Period 2**	**Period 1**	**Period 2**	**% Change**
Brine or industrial waste treatment plant	bbl	1,756,289	708,618	4.035	1.122	–72.2
	tons	1,262	1,358	0.003	0.002	–25.9
Injection disposal well	bbl	608,863	2,024,928	1.399	3.207	129.2
Landfill	bbl	19,995	7,459	0.046	0.012	–74.3
	tons	394,842	405,696	0.907	0.642	–29.2
Municipal sewage treatment plant	bbl	47,221	408	0.108	0.001	–99.4
Unknown	bbl	338,618	6,884	0.778	0.011	–98.6
Other	bbl	334	0	0.001	0.000	–100.0
Other	tons	10,006	0	0.023	0.000	–100.0
Reuse other than road spreading	bbl	6,365,134	7,444,345	14.625	11.789	–19.4
	tons	405	0	0.001	0.000	–100.0

bbl, barrels; Mcf, thousand cubic feet.

(e.g., Ohio DNR locations of injection wells) to overcome this limitation. Second, the end use of the waste (e.g., brine or industrial waste treatment plant or deep injection well) in multiple cases was incorrectly reported and had to be rectified by use of the waste facility permit identifier and address. For example, several waste-receiving facilities that recycled waste fluids for reuse were incorrectly identified as brine or industrial wastewater treatment plants. These two issues were time-consuming to correct and would not have been necessary if location data and disposal methods had been reported more consistently and accurately. The third issue concerns the accuracy of the data set. Reporting of all waste (amounts, disposal, treatment, and reuse) is mandatory under Act 15 (General Assembly of Pennsylvania, 2010); so the data set should contain the majority of waste generated in 2011. To test this, we back-calculated the number of newly fractured wells needed to generate the total amount of flowback and brine waters in the 2011 waste report (16,944,057 barrels). From the PADEP production reports, producing wells numbered 1,217 in 2010 and 2,254 in 2011. This suggests the development of 1,037 newly producing wells in 2011. If we assume that each well uses 5 million gallons (119,048 barrels) of water and a total return of 15% fluid, then we estimate that each well would produce an average of 17,857 barrels of flowback and brine water. Dividing the 16,944,057 by 17,857 results in an estimate of 949 wells, which is only slightly less than that reported in the production reports (1,037 wells). Given that these values were close to those reported, we are confident in the data set being representative of production and waste trends in Pennsylvania for 2011. However, a more formal test of database and industry reporting accuracy is needed in order to confirm database accuracy.

The Nature Conservancy estimates full build-out for Pennsylvania might be 60,000 wells (Johnson, 2010). Using these numbers along with the values from the 2011 waste report (1,037 wells), we estimate that development of the entire Marcellus Shale play will create 5.25×10^8 barrels of brine water, 4.56×10^8 barrels of flowback, 1.37×10^8 barrels of drilling fluids, and 4.62×10^7 tons of drill cuttings. Moreover, 3.07×10^5 barrels of basic sediment, 8.65×10^5 tons of flowback sands, and 3.04×10^5 barrels of spent lubricants will be produced. These results highlight the magnitude of waste generated from gas extraction in Pennsylvania and the potential for local issues associated with disposal of this waste. Although waste and production estimates vary geographically, our results can provide background information for areas experiencing similar activities across the US and in many areas of the world.

Conclusion

Extraction of gas and other hydrocarbons from unconventional shale plays is a recent development in many parts of the world. Because of this, little information is available to assess the potential environmental issues associated with this practice. Here, we demonstrated that large quantities of waste solids and liquids are produced from the process and that wastes are routinely transported across political (state) and major drainage borders. We also showed that industry has the ability to modify waste management prac-

tices, especially when regulatory or economic drivers are in place. Integrating all of these factors will be imperative in future assessments of waste generation and disposal from the fuel extraction process from shales.

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Note

1. Data from the PADEP website: http://www.depreportingservices.state.pa.us/ReportServer/Pages/ReportViewer.aspx?/Oil_Gas/Wells_Drilled_By_County (accessed May 10, 2012).

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