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Generation, transport, and disposal of wastewater associated with Marcellus Shale gas development

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[1] Hydraulic fracturing has made vast quantities of natural gas from shale available, reshaping the energy landscape of the United States. Extracting shale gas, however, generates large, unavoidable volumes of wastewater, which to date lacks accurate quantification. For the Marcellus shale, by far the largest shale gas resource in the United States, we quantify gas and wastewater production using data from 2189 wells located throughout Pennsylvania. Contrary to current perceptions, Marcellus wells produce significantly *less* wastewater per unit gas recovered (approximately 35%) compared to conventional natural gas wells. Further, well operators classified only 32.3% of wastewater from Marcellus wells as flowback from hydraulic fracturing; most wastewater was classified as brine, generated over multiple years. Despite producing less wastewater per unit gas, developing the Marcellus shale has increased the total wastewater generated in the region by approximately 570% since 2004, overwhelming current wastewater disposal infrastructure capacity.

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1. Introduction

[2] Organic-rich shale formations have long been known to contain tremendous quantities of natural gas (hereafter "gas"), though the low porosity of shale matrices makes recovering this gas difficult. Recent advances in directional drilling and hydraulic fracturing, which involve injecting large volumes of fluids at high pressure into shale formations to stimulate gas flow, are making shale gas extraction economical. In 2000, shale gas accounted for only 2% (0.01 trillion cubic meters, tcm) of United States gas production; by 2010 shale gas increased to 23% (0.14 tcm) of production [*U.S. Energy Information Administration* (*U.S. EIA*), 2012c]. The surge in shale gas production has caused gas prices to plummet [*U.S. EIA*, 2012b] and, as a result, natural gas has recently surpassed coal as the dominant source of energy in power generation for the first time in U.S. history [*U.S. EIA*, 2012a]. With more than 70 major shale gas basins having been identified in countries outside the United States, shale resources are now estimated to account for more than 40% of the world's recoverable gas reserves [*U.S. EIA*, 2011b].

[3] Several environmental concerns have emerged surrounding shale gas development, notably the potential to contaminate groundwater [*Osborn et al*., 2011; *Warner et al*., 2012] or for natural gas—composed largely of the potent greenhouse gas methane—to escape to the atmosphere [*Howarth et al*., 2011]. These, however, represent *potential* impacts and shale gas development should be possible while minimizing these risks. Wastewater, however, is an obligate by-product of current methods and volumes will unavoidably increase with industry expansion. Recent public and regulatory attention has focused on hydraulic fracturing fluids (hereafter "frac fluids"), which consist of water treated with various chemicals to adjust pH and viscosity, as well as to reduce friction, chemical precipitation, scaling, and biological fouling [*Arthur et al*., 2009; *Marcellus Shale Advisory Commission* (*MSAC*), 2011]. Some of the chemicals used in engineering frac fluids present human health and environmental risks, requiring careful management during use and proper disposal afterward [*MSAC*, 2011]. Managing wastewater is likely to become a defining challenge for the shale gas industry to confront.

[4] Modern hydraulic fracturing has existed since the 1940s and, while having become primarily associated with shale gas production, is commonly used to stimulate gas recovery from conventional gas resources [*Montgomery and Smith*, 2010]. Conventional resources generally consist of porous reservoir formations that accumulate gas from organic-rich sources below and are capped by impermeable barriers above [*U.S. Department of Energy* (*U.S. DOE*), 2009]. Shale gas resources are distinct from conventional resources because gas is extracted directly from the shale formation, which serves as both the source and the

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All supporting information may be found in the online version of this article.

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reservoir for the gas. For shale wells, hydraulic fracturing is essential and applied extensively, requiring large quantities of frac fluid [approximately 11.5–19 ML per well, ML= million liters; *U.S. DOE*, 2009]. Typically, 10–70% of frac fluid returns to the surface during the initial period of production (<4 weeks from onset of gas production) [*American Petroleum Institute* (*API*), 2010], referred to as "flowback."

[5] Although most attention has focused on managing flowback, other important forms of wastewater are generated during natural gas development. In drilling wells, water and drilling additives are used to cool and lubricate the drill head and to clear drill cuttings, generating wastewater referred to as "drilling fluid" often having high total dissolved and suspended solids. Recent advances in directional drilling technology—the ability to drill parallel to the plane of the target formation—have facilitated shale gas development by increasing the amount of the formation contacting the well bore. Such horizontal drilling can radiate outward 1500 m or more [*U.S. DOE*, 2009], resulting in substantially longer bore lengths than conventional natural gas wells (hereafter "conventional wells"), which are typically vertical and drilled to shallower depths. Because wells producing shale gas (hereafter "shale wells") often require more drilling than conventional wells, shale gas drilling likely generates more drilling wastewater.

[6] In addition to drilling and flowback wastewater, water derived from the subsurface is often recovered with natural gas over the life of the well. The porous reservoir formations from which conventional wells produce gas can contain large volumes of produced water—typically highly saline aquifers—commonly referred to as "brine" due to its high salinity. Shale wells also generate wastewater after gas production begins, though this wastewater likely contains residual frac fluid in addition to produced brine originating from within or around the shale formation. Brine produced throughout the Marcellus region often has high concentrations of metals, organics, and, in some cases, radioactive materials [*Veil et al*., 2004].

[7] Wastewater disposal presents a significant challenge and cost for the natural gas industry [*Veil*, 1997; *Veil et al*., 2004]. Conventional gas production in the United States generates approximately 890 $\times$ 10^9 L (5.6 $\times$ 10^9 barrels; 1 barrel = 42 U.S. gal = 159 L) of wastewater annually [*Clark and Veil*, 2009]. Developing shale gas resources will not only increase the wastewater volumes but will also change the geographic distribution of where wastewater is generated and disposed [*U.S. DOE*, 2009]. The Marcellus shale is the largest (8.3–76.5 tcm, gas in place) [*Lee et al*., 2011; *U.S. DOE*, 2009] and most spatially expansive [>246,000 km^2; *U.S. DOE*, 2009] shale gas deposit in the United States. The Marcellus is estimated to account for 29–55% [*U.S. EIA*, 2011a, 2012c] of domestic shale gas reserves, potentially larger than the other 18 known shale gas deposits in the United States combined [*U.S. EIA*, 2011a]. Developing this resource will create one of the largest onshore gas-associated wastewater volumes in the nation. However, while most wastewater from conventional gas production in other regions of the United States is disposed of via reinjection into deep geologic formations (>95%) [*Clark and Veil*, 2009], underground injection disposal is limited in the Marcellus region as the geology needed for safe injection disposal is not generally present [*MSAC*, 2011], challenging industry to identify and develop alternative disposal methods.

[8] Several estimates exist of wastewater volumes generated by Marcellus wells [*Arthur et al*., 2009; *Gregory et al*., 2011; *MSAC*, 2011; *U.S. DOE*, 2009]. In most cases, it is unclear how these estimates have been made or what types of wastewater (drilling, flowback, or brine) they represent. Some estimates are reported as percentages of the volume of frac fluid injected into each well, which have ranged from 10% to 70% [*MSAC*, 2011], although the volume of frac fluid typically injected into an individual well is estimated to range from 11.5 to 19 ML [*API*, 2010; *MSAC*, 2011]. Moreover, most estimates focus on flowback and do not specifically consider drilling and brine wastewater [*Gregory et al*., 2011; *U.S. DOE*, 2009], likely underestimating the total wastewater volume generated. And many estimates can be traced back to when few Marcellus wells existed and information was limiting [*U.S. DOE*, 2009]. To our knowledge, no comprehensive characterization of wastewater volumes generated by Marcellus wells exists using transparent methods and publically accessible data.

[9] We analyzed data from 2189 active Marcellus wells in Pennsylvania and compared gas production and wastewater volumes to conventional well data. While the Marcellus shale underlies several states in the northeast United States, the majority of shale gas development to date has occurred in Pennsylvania. Our objectives were (1) to quantify drilling, flowback, and brine wastewater volumes produced by Marcellus and conventional wells, (2) to assess changes in the cumulative wastewater volume resulting from the rapid expansion of Marcellus wells, and (3) to assess how wastewater disposal options and regulations are changing as the shale gas industry continues to develop.

2. Data and Methods

2.1. Data Sources and Processing

[10] Statewide natural gas and associated wastewater production data for the period of January 2000 through December 2011 were downloaded from the Pennsylvania Department of Environmental Protection (DEP) Bureau of Oil and Gas Management website (available at https://www.paoilandgasreporting.state.pa.us/publicreports/). These data are self-reported by gas well operators in accordance with Pennsylvania law and represent substantially more thorough, albeit still incomplete, accounting of natural gas associated wastewater than is typically available elsewhere [*Clark and Veil*, 2009]. While some companies may either not report or misreport data, this database represents the best available information on wastewater generated from Marcellus well development and is currently being used in investigations aimed at guiding state and federal regulation of hydraulic fracturing [*Environmental Protection Agency* (*EPA*), 2011]. We attempt to account for data omissions and inaccuracies, and to assess data consistency and validity, in order to avoid potential artifacts in our results.

[11] Gas and wastewater records were associated by well permit number, and both data types included well location (latitude/longitude) and an indicator for conventional

versus Marcellus well type. Marcellus wells are further classified as being vertical versus horizontal. While horizontal wells are likely to involve more extensive drilling and hydraulic fracturing than vertical wells, the lengths of the horizontal extensions can vary widely between wells. As a result, we do not differentiate between horizontal and vertical wells and consider our results to be representative of the range of current practices.

[12] Data were initially reported based on calendar year (2000–2009), but in July 2009 data management for Marcellus wells changed so that data were instead reported for the period of July 2009 through June 2010. Gas production data for Marcellus wells during the period of July 2009 through December 2009 were duplicated between the two records. To correct for this duplication, we divided the amount of gas produced over this period by the number of gas production days reported. If the number of gas production days was less than 183, we assumed that the gas was produced after 1 January 2010. If the number of gas production days was greater than 183, we divided the volume of gas produced by the number of producing days and multiplied by 183 to estimate the amount of production in 2010, with the remaining production allocated to 2009. There was no similar overlap in the wastewater data (R. Deitz, PA DEP, personal communication, December 19, 2011). Since July 2010, Marcellus data have been reported on 6-month intervals with no overlap; we aggregated Marcellus well data reported on 6-month intervals during 2010 and 2011 to the calendar year.

[13] A separate issue requiring correction existed in the wastewater data. Each wastewater record specified the volume and type of wastewater generated by a given well and the specific facility for treatment or disposal. However, identical volumes of a given wastewater type for a single well were often repeatedly listed within a given year with each record indicating a different disposal facility. This was true for approximately 16% of all data entries for Marcellus wastewater. In these cases, the volume listed was for the total amount of the wastewater type generated by the well that year, not for the amount taken to each facility (R. Deitz, PA DEP, personal communication, December 19, 2011). The true volume accepted by each facility is unknown, but for the sake of our analyses, we assumed each facility received equal volumes, thus dividing the wastewater amount reported for each well within a given year by the number of entries listing identical values. Approximately 23% of all Marcellus wastewater by volume had to be divided across facilities using this method. Importantly, without this correction, wastewater volumes are overestimated (by up to 45%) as well as systemically biased toward artificial inflation of Marcellus well wastewater, since Marcellus wastewater volumes are often large and more likely to be divided between multiple disposal facilities and thus more frequently listed repeatedly than conventional well wastewater records.

[14] Due to an unrecoverable data loss by PA DEP, waste records for 2007 are not available.

2.2. Estimating Wastewater Volumes

[15] Although drilling fluid and flowback are produced during the construction period or at the early stages of well operation, some wells are completed near the end of a given calendar year and, in these cases, drilling fluid and flowback volumes are not reported until the following calendar year or are split between years. Because of this, we only analyzed drilling fluid and flowback volumes for wells producing in 2010 or earlier to avoid artificially underestimating these values by including wells constructed in 2011 that may have yet to report drilling fluid and flowback volumes.

[16] Many wells (both conventional and Marcellus) report no drilling fluid. Drilling either conventional or Marcellus wells should generate drilling fluid wastewater and we assume missing data values result from lack of reporting by well operators. Within our dataset, drilling fluid volumes were reported for 548 Marcellus wells and 3186 conventional wells during the period 2004–2010. We assume that drilling fluid volumes for wells with data reported represent an unbiased sample of wells.

[17] Similarly, many wells (both conventional and Marcellus) report no flowback. Conventional wells can be produced without hydraulic fracturing and, therefore, if no flowback volume is reported it could be that either hydraulic fracturing did not occur or that hydraulic fracturing did occur and that the flowback volume was not reported. Based on the data available, we are unable to distinguish between these two possibilities. Because of this, of the 49,264 conventional wells included in this study we only use data for conventional wells where nonzero flowback volumes were reported ($n = 5464$). Thus, our estimate for flowback from conventional wells is specific to only those that have been hydraulically fractured. For Marcellus wells, hydraulic fracturing is essential and we assume that a lack of flowback volume indicated for a given well is the result of failure to report data. We characterize Marcellus flowback based on only those wells reporting data ($n = 824$) and assume this represents an unbiased sample of wells.

[18] Preliminary analysis of the distributions of reported drilling fluid and flowback volumes for both conventional and Marcellus wells were strongly right skewed. Therefore, we show distributions of $\log_{10}$ transformed wastewater volumes for each well type using the *density* function in the R statistical software package (R Foundation for Statistical Computing, Vienna Austria, 2010, http://www.R-project.org). To compare wastewater volumes between well types, we estimated 95% bootstrap confidence intervals for 10,000 samples of the nontransformed data.

[19] Brine generation can vary through time and, because of this, we analyzed brine volumes produced by year of production. We defined the first year of production for each well as being the calendar year in which a gas production value was first reported. The first year was often only partial and therefore reported values corresponding to the first year of production are conservative. In many cases, for both conventional and Marcellus wells, brine was not consistently reported each year of well production. We assume that this is primarily a result of lack of reporting rather than a true value of zero and, therefore, omit these instances from the analysis. Because very few Marcellus wells were drilled prior to 2007 ($n = 46$) and because 2007 data are unavailable (see above), we only had sufficient data to adequately quantify changes in brine production during the initial 4 years of well operation (there were $n = 1517$ wells reporting first-year production data, with the sample size

declining to $n = 199$ wells reporting fourth-year production data). We calculated the mean brine production for each of the first 4 years of operation for both Marcellus and conventional wells. We then calculated 95% confidence intervals by bootstrapping data for each waste type within each year 10,000 times.

2.3. Gas to Wastewater Ratios

[20] Both wastewater (drilling fluid, flowback, and brine) and gas production volumes from Marcellus and conventional wells differed and, therefore, it was useful to compare the volume of gas recovered per unit wastewater produced. However, few Marcellus wells ($n = 24$) report all values (drilling fluid, flowback, and 4 years of brine data). Because of this, we sum the mean values for each of the wastewater types calculated across the population of all wells in order to estimate the total wastewater generated by the average well.

2.4. Cross-Validation of Data

[21] Wastewater and gas production data are reported by oil and gas well operators in accordance with Pennsylvania law with no attempt by PA DEP to control data quality. Because of this, we assessed the validity of the data by separately analyzing the data reported by each of the five largest companies operating in the Marcellus region, which together account for >56% of all Marcellus wells. While these self-reported data may contain inaccuracies, it would be highly unlikely that multiple independent companies systematically misreport or misrepresent wastewater data similarly. We found results across companies to be generally consistent, particularly for the sum of all waste types and, further, individual company results were largely consistent with the values determined for the global dataset (see Table S1 for supporting information). The largest differences observed were within the volume estimates for the specific waste types, which is consistent with expectations since operators must often arbitrarily define the distinction between wastewater types, particularly between flowback and brine. While we used the values as reported by well operators, the values reported for the different waste types should be interpreted with more caution than the total wastewater volume reported across waste types.

2.5. Wastewater Transport and Disposal

[22] Wastewater records indicated the disposal facility to which the wastewater was transported, and each waste facility was associated with a specific disposal method (e.g., Industrial Treatment Plant, Municipal Sewage Treatment Plant, and Underground Injection). In some cases, multiple disposal methods were reported. One value typically dominated and, therefore, we applied the modal value to all records associated with each facility assuming that conflicts were due to data entry errors.

[23] When multiple disposal facilities were reported and wastewater from a single well had to be divided equally among them (see section 2.2), the disposal methods used at the different receiving facilities were often the same. For only 15% of the total Marcellus wastewater data were multiple disposal methods listed for a single wastewater volume.

[24] All data included geographic coordinates for the producing wells, though only 13.6% of the data had geographic coordinates specifying the location of the disposal facilities. In many cases, where geographic coordinates were not provided for wastewater disposal facilities, a National Pollution Discharge Elimination System (NPDES) permit number for the facility was listed. We joined this field to the NPDES database maintained by PA DEP (available at http://www.dep.state.pa.us/dep/deputate/watermgt/Wqp/Forms/) and were able to determine the spatial location of the disposal facility for an additional 13.1% of the data. Examining unique wastewater facility names indicated that many facilities had several similar but nonidentical variants of the same name. If coordinates were listed for one name variant but not others, we applied those coordinates to all name variants where it was missing. Further, we were able to assign coordinates based on the reported physical address of the wastewater facility or by obtaining the address through an internet search on the facility name, resulting in 60.0% of the total Marcellus wastewater data having well origination and wastewater facility destination coordinates specified. Of the total wastewater volume, 32.8% was reported as having been recycled ("Reuse Other Than Road Spreading") in which case the location for reuse was not provided. We could not account for the disposal locations of the remaining 7.2% of the wastewater volume based on the available information. We expect that the small amount of data for which we cannot resolve waste facility locations will have little effect on our results.

[25] Using ArcGIS desktop v10.0 [*ESRI*, 2012] we determined the drainage basin (Delaware, Susquehanna, or Ohio) within which each Marcellus well was located. Similarly, we determined both the drainage basin and state where each wastewater disposal facility was located. We could then sum the wastewater records across basins or states to compare where wastewater was being generated versus where it was being disposed.

3. Results and Discussion

3.1. Conventional Versus Marcellus Wells

[26] The first production records for Marcellus wells were recorded in 2004 ($n = 3$), with the number of new wells each year increasing exponentially (Figure 1) resulting in 2189 active wells as of December 2011. Typically,

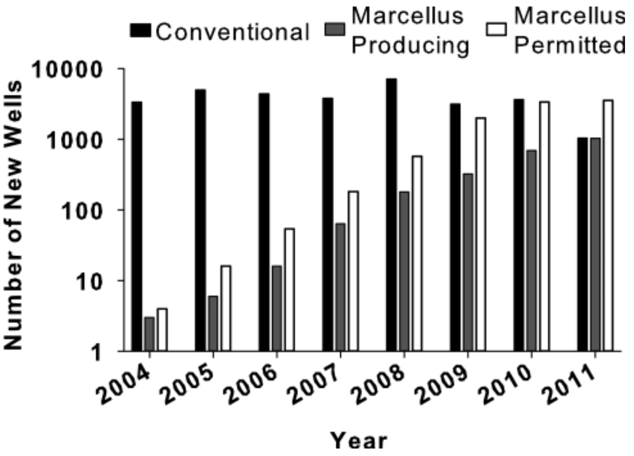

Figure 1. Number ($\log_{10}$ scale) of new conventional and Marcellus wells by year (permit data from PA DEP).

3000–5000 new conventional wells were added each year since 2004 (Figure 1), with 49,294 conventional wells reporting gas production in 2011. There were 3513 Marcellus well permits issued in 2011 (Figure 1), suggesting the number of new Marcellus wells is approaching—and may soon surpass—the rate of conventional well drilling.

[27] While there has been much recent concern surrounding the chemical additives used to engineer frac fluids [*MSAC*, 2011], the vast majority of the dissolved material representing the total pollution load in Marcellus wastewater is derived from the subsurface. This wastewater is often heavily laden with a variety of inorganic ions, metals, organics, and radioactive materials [*Haluszczak et al*., 2013; *Veil et al*., 2004]. *Haluszczak et al*. [2013] recently demonstrated that most flowback and brine from Marcellus shale gas wells is similar in chemical composition to the wastewater produced by conventional wells in this region and, thus, presents similar management challenges.

[28] The average Marcellus well generated six times more drilling waste (0.654 ML, where ML = 1 × 10^6 L; 95% CI = 0.556–0.767 ML) than the average conventional well (0.116 ML; 95% CI = 0.098–0.141 ML) (Figure 2a), likely resulting from more extensive drilling associated with longer well bore lengths. Flowback generated from the average conventional well was small (0.107 ML; 95% CI = 0.102–0.113 ML) compared to the average flowback generated from a Marcellus well (1.683 ML; 95% CI = 1.537–1.843 ML) (Figure 2b). For Marcellus wells, flowback represented 8–15% of the 11.5–19 ML volume typically injected into each well during construction [*U.S. DOE*, 2009]; previously reported values of flowback recovery range from 10% to 70% [*API*, 2010]. Additional flowback may be recovered gradually during gas production, although this wastewater is typically reported as brine shortly after production begins.

[29] On average, each Marcellus well generated 1.365 ML (95% CI = 1.231–1.511 ML) of brine during the first year, with brine generation declining to 0.150 ML (95% CI = 0.116–0.189 ML) by year 4 (Figure 2c). Average brine volumes generated by each conventional well also

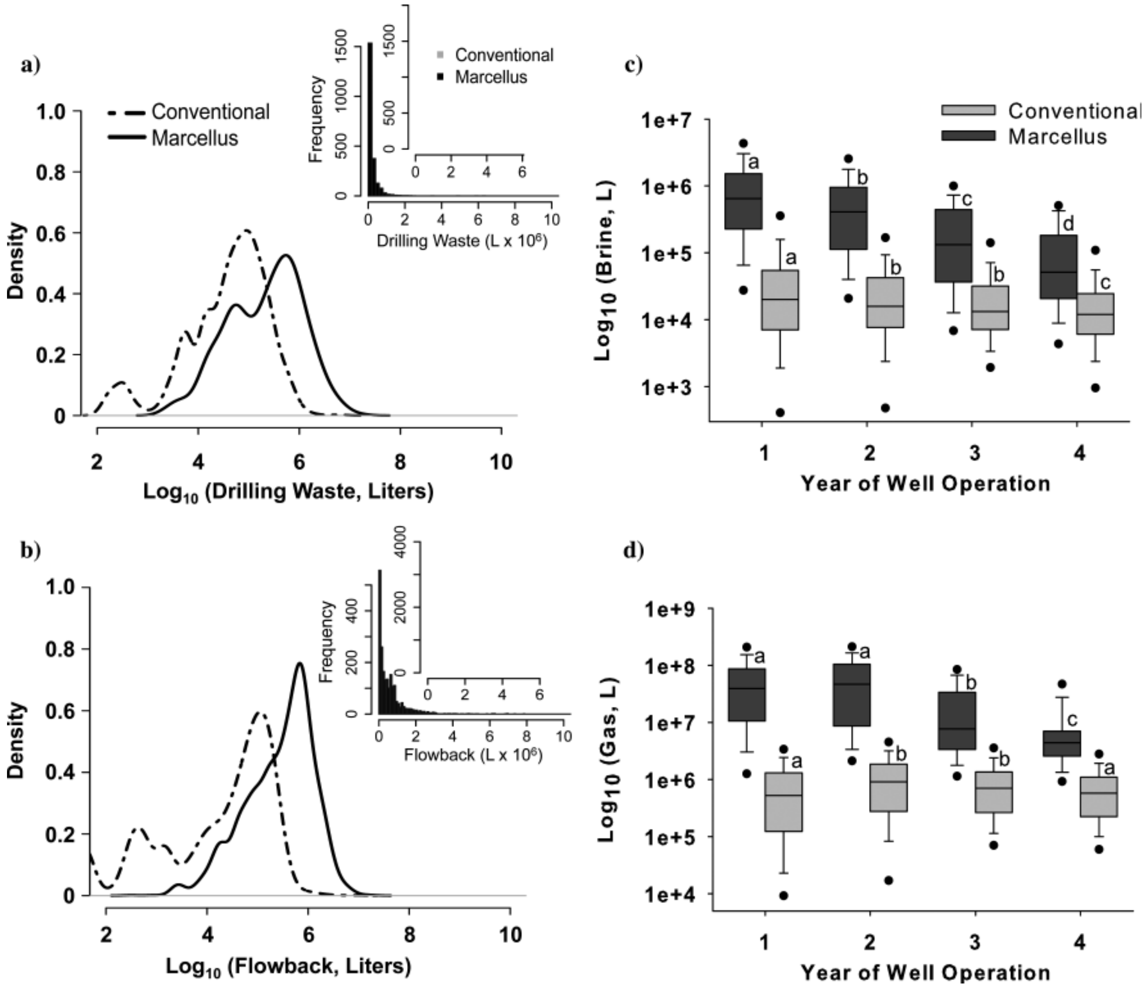

Figure 2. Density distributions of (a) drilling fluid and (b) frac flowback volumes ($\log_{10}$ scale) for conventional and Marcellus wells (insets show untransformed data). Box plots show (c) brine and (d) gas production ($\log_{10}$ scale) by Marcellus and conventional wells; black dots indicate the 95% confidence interval of the data; letters indicate significant differences among groups using a modified one-way analysis of variance (ANOVA) accounting for unbalanced group sizes, nonnormality, and heteroscedasticity [*Herberich et al*., 2010].

Table 1. Mean Estimates of Wastewater and Gas Production Volumes for Conventional and Marcellus Wells[a]

Well Type	Drilling[b] (L × 10^6 per well)	Flowback[b] (L × 10^6 per well)	Brine[c] (L × 10^6 per well)	Total Wastewater[d] (L × 10^6 per well)	Gas[c] (L × 10^6 per well)	Wastewater: Gas Ratio (L waste/MMBtu gas)[e]
Conventional	0.116	0.107	0.291	0.514	1,050.1	13.4
Marcellus	0.654	1.683	2.874	5.211	30,038.7	4.8

[a] Because drilling and flowback fluids are generated during or shortly following well construction, these estimates are complete. Brine and gas volumes are estimated as cumulative production over the first 4 years of well operation and, while incomplete, the majority of production in Marcellus wells occurs within the first 4 years (see section 3.1 for further discussion). Total wastewater estimates are made by summing these values for drilling, flowback, and brine volumes. Although Marcellus wells produce more wastewater in absolute terms, conventional wells generated approximately 2.8 times more wastewater per unit gas recovered.

[b] Values are for the total drilling and flowback volumes produced by each well.

[c] Values were summed over the first 4 years of brine production.

[d] Values based on summing estimates for drilling, flowback, and brine volumes reported in columns 1–3.

[e] Energy content of gas based on data from *U.S. EIA* [2007]; Approximately. 36.2 Btu L^{-1} gas; MMBtu = 1 × 10^6 Btu.

declined from year 1 (0.102 ML; 95% CI = 0.093–0.112 ML) to year 4 (0.042 ML; 95% CI = 0.038–0.045 ML) (Figure 2c). When summed across years, the average cumulative brine volume generated by a single conventional well was only 0.291 ML while brine generated by each Marcellus well was an order of magnitude higher (2.874 ML; Table 1). Importantly, for both well types, brine accounted for the majority of the total wastewater generated (Table 1). While managing flowback volumes has captured considerable attention [*Gregory et al*., 2011], flowback accounted for only 20.8% and 32.3% of the total wastewater generated by conventional and Marcellus wells, respectively.

[30] Along with larger wastewater volumes, Marcellus wells also produced far more gas. During the first year of production, the average Marcellus well produced 11,180.8 ML (95% CI = 10,863.2–11,876.8 ML) of gas compared with 198.0 ML (95% CI = 105.3–218.8 ML) in the first year from each conventional well. However, the mean annual gas production from Marcellus wells declined rapidly, with only 1885.2 ML (95% CI = 1600.4–2088.2 ML) produced in the fourth year of operation (Figure 2d). On average, conventional wells showed a small but significant increase in gas production during years 2 and 3, but year 4 was not significantly different from year 1. When summed across the 4-year period, cumulative mean gas production for a Marcellus well was 30,038.7 ML compared with only 1050.1 ML from an average conventional well (Table 1).

[31] Marcellus and conventional wells were also quite different in how much gas was recovered per unit of wastewater generated. By summing the estimated volumes of the different wastewater types, the average Marcellus well generated 5.211 ML of total wastewater and 30,038.7 ML of gas over the first 4 years of operation (Table 1). For conventional wells, the total wastewater generated was 0.514 ML per well, while gas production was 1050.1 ML (Table 1). Thus, the average Marcellus well produced only approximately 35% of the amount of wastewater per unit gas recovered when compared to conventional wells. Importantly, these estimates are limited to the first 4 years of well operation. Industry reports indicate similarly large declines in gas produced by Marcellus wells over time [*U.S. EIA*, 2011a], though no similar estimates for brine volumes exist. Regardless, Marcellus wells would have to generate an additional 9.5 ML of wastewater—approximately a 280% increase over the current volume generated—as well as zero additional gas in order for the gas to wastewater ratio to approach that of conventional wells (Table 1). Thus, while the gas to wastewater ratio for Marcellus wells may decline in future years, it is unlikely to fall below the current value for conventional wells.

3.2. Wastewater Generated: Regional Scale

[32] Despite Marcellus wells producing less wastewater per unit gas recovered, the Marcellus shale is massive and the cumulative volume of wastewater generated in the region is growing dramatically. Prior to the development of the Marcellus shale, the total wastewater volume generated by all conventional wells each year was small (approximately 800 ML yr^{-1}; Figure 3) and dominated by brine (86.9% ± 3.5%; flowback = 8.5% ± 2.7%, drilling fluid = 4.6% ± 1.0%). However, Marcellus wells collectively generated approximately 570% more wastewater in 2011 (3144.3 ML) than conventional wells (Figure 3) and the average composition of Marcellus wastewater was 44.7% ± 8.2% brine, 43.3% ± 14.7% flowback, and 14.2% ± 5.6% drilling fluid. This composition is skewed toward greater flowback and drilling fluid because within the Marcellus well population most wells are in their first or second year of production; brine should dominate when the number of new wells drilled each year stabilizes.

[33] Predicting increases in the total Marcellus wastewater volume generated annually depends on an accurate estimate of how many Marcellus wells will be drilled and placed into production in the coming years and the rate of

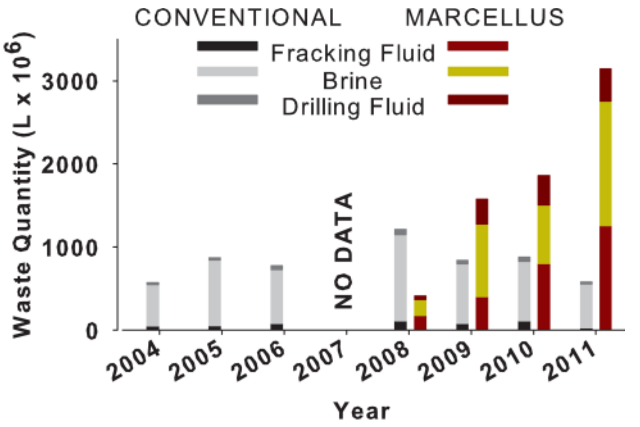

Figure 3. Total wastewater volumes generated by conventional and Marcellus wells by year.

decline in gas production over the long term. Recent estimates predict a quadrupling of active wells to approximately 8250 by 2014 [*Marcellus Shale Education and Training Center* (*MSETC*), 2011]. Assuming no additional brine production beyond the fourth year of operation (a highly conservative assumption), we estimate that the wastewater volume from Marcellus wells will exceed 5370 ML yr^{-1} in 2014, nearly 10 times greater than the volume of wastewater generated by conventional wells a decade earlier and prior to the development of the Marcellus shale (569.8 ML yr^{-1} in 2004, Figure 3).

3.3. Wastewater Disposal

[34] The rapid growth in wastewater volumes is challenging current infrastructure capacity. While underground injection disposal accounts for >95% of natural gas associated wastewater in the United States [*Clark and Veil*, 2009], there is little suitable geology for underground injection in the Marcellus region [*MSAC*, 2011]. Four alternative wastewater management options have been used: (1) treatment at a municipal wastewater treatment facility (i.e., public sewage treatment facility), followed by discharge to a local waterway; (2) treatment at a private industrial wastewater facility, followed by reuse of the treated effluent or discharge into a local waterway; (3) transporting the wastewater greater distances to where underground injection capacity exists; and (4) partial treatment and recycling of wastewater in subsequent wells that will be hydraulically fractured. Road spreading of brines for ice and dust control has been used for conventional wastewater, but is not permitted for Marcellus wastewater [*MSAC*, 2011].

[35] Treatment and disposal of wastewater effluent at municipal and industrial facilities has been used throughout the region for decades to manage wastewater from conventional wells, but the wastewater volumes from Marcellus wells have challenged their practicability. As a result, regulation has coevolved with industry growth. A series of recent changes in regulations that differentially target conventional versus Marcellus wastes—and often identify flowback, brine, and drilling wastes separately—have affected patterns of waste disposal.

[36] Most Marcellus wells are located in northeast and southwest Pennsylvania, while most conventional wells are located in northwest Pennsylvania (Figure 4). Municipal facilities that have accepted natural gas associated wastewater tend to be located throughout Pennsylvania, while

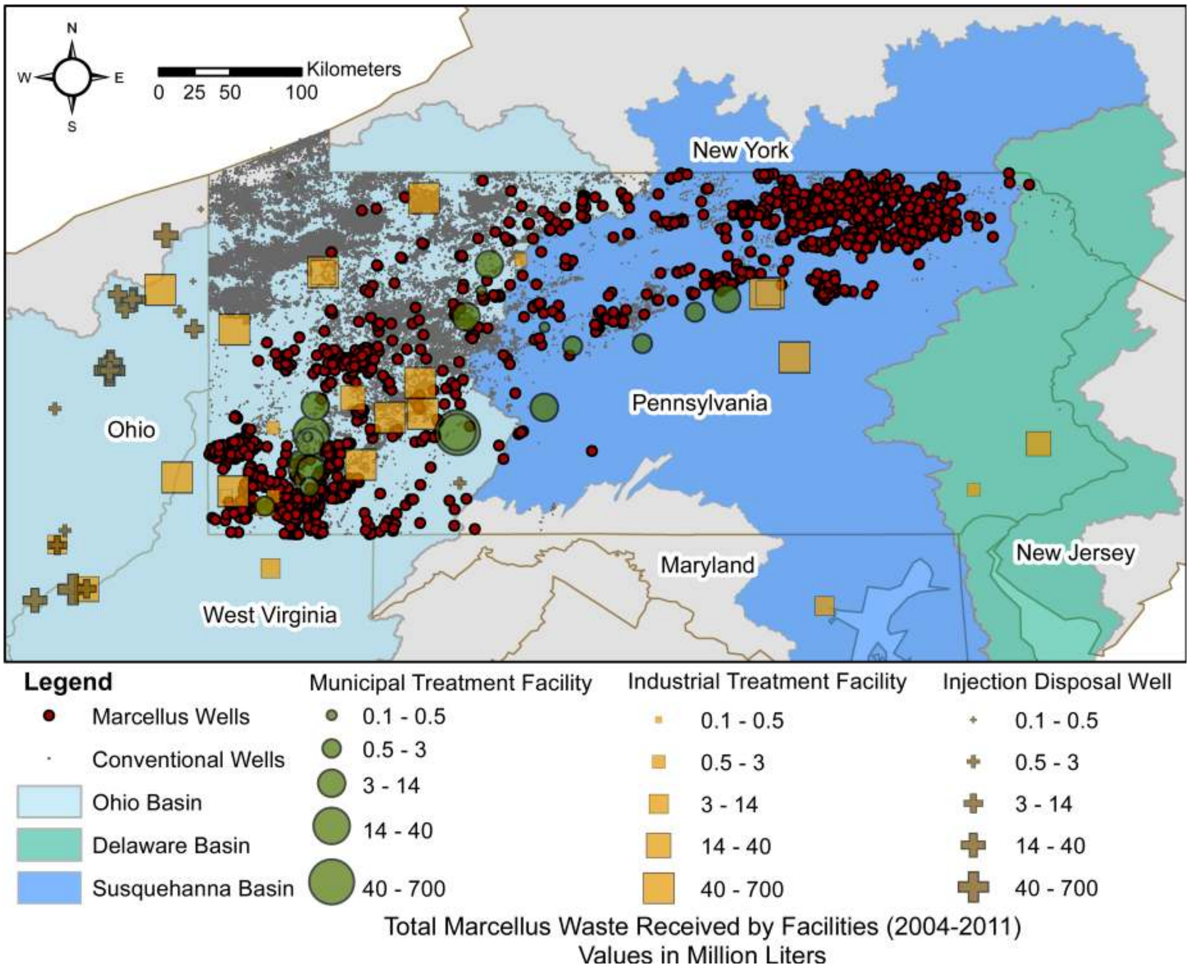

Figure 4. Map of wells and disposal facilities (spatial data from PA DEP) [*Pennsylvania Spatial Data Access* (*PASDA*), 2012].

industrial treatment facilities are located primarily in western Pennsylvania, and most underground injection disposal wells are located in Ohio (Figure 4). As a result, changes in regulations differentially affecting disposal options alter wastewater transport across county and state borders and between major river basins.

[37] Approximately 86.3% of all wastewater generated by Marcellus wells to date has been disposed of within Pennsylvania, primarily at municipal and industrial wastewater treatment facilities. Municipal facilities accepted <30 ML of wastewater per year from conventional wells prior to Marcellus development (2001–2004). In 2008, however, municipal facilities accepted 460.8 ML of wastewater (Figure 5a). Wastewater generated by Marcellus wells often has high total dissolved solids (TDS) (typically ranging from 35,000 to 400,000 mg L^{-1}) [*Blauch et al.*, 2009; *Clark and Veil*, 2009], and municipal facilities are generally not capable of removing TDS [*Veil*, 2010]. In 2008, high conductivity values reported in the Monongahela River basin prompted a temporary mandate from PA DEP limiting municipal facilities from accepting large amounts of Marcellus wastewater [*Kargbo et al.*, 2010; *Tetra Tech*, 2009]. Despite formal regulation not occurring until April 2011, the volume of gas-associated wastewater taken to municipal facilities declined after 2008 (Figure 5a). In 2009, wastewater volumes taken to municipal facilities declined by 59.8% and, by 2011, wastewater volumes delivered to municipal facilities returned to values typical before Marcellus gas development and were composed almost entirely of wastewater from conventional wells. Conventional well operators continue to dispose of wastewater at municipal facilities [*Perry*, 2011].

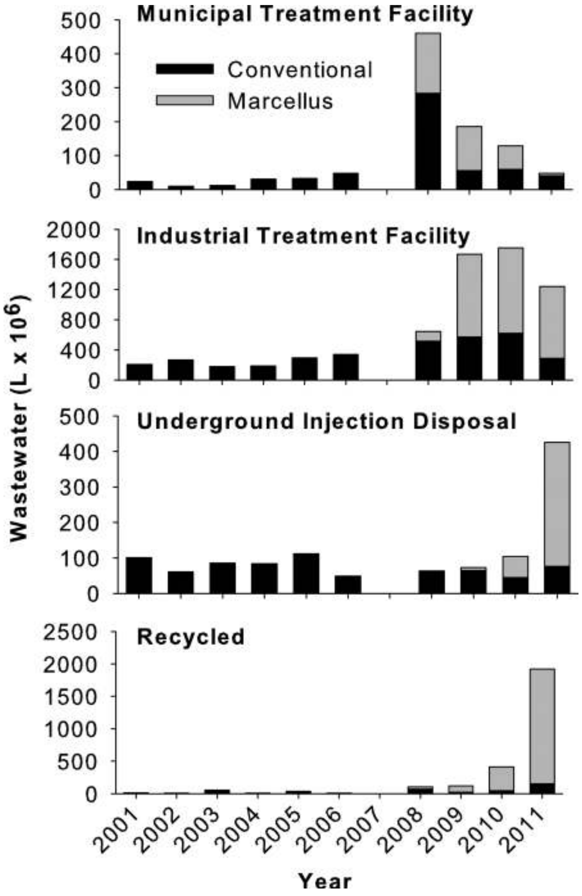

Figure 5. Conventional and Marcellus wastewater volumes by year for each wastewater management method.

[38] As the role of municipal facilities declined, the volume of wastewater produced by Marcellus wells continued to increase (Figure 3), resulting in more wastewater processed at industrial treatment facilities: volumes taken to industrial facilities increased from 187.4 ML in 2004 to 644.4 ML in 2008 and 1752.8 ML in 2010 (Figure 5b). This treatment facility shift also created a spatial shift—an interbasin transfer—in wastewater disposal because most industrial treatment facilities are located in western Pennsylvania, largely within the Ohio River basin (Figure 4). From 2008 to 2009, wastewater generated by Marcellus wells located within the Ohio River basin increased by a factor of approximately 1.7 (2008 = 258.0 ML; 2009 = 440.2 ML), yet the volume of wastewater treated at industrial facilities in the Ohio River basin increased by a factor of approximately 3.3 (2008 = 290.1 ML; 2009 = 943.1 ML). Between 2009 and 2011, of the 1614.2 ML of wastewater generated from wells in the Delaware or Susquehanna River basins, 49.3% (796.3 ML) was disposed at facilities in the Ohio River basin.

[39] While industrial treatment facilities often employ methods capable of precipitating metals and flocculating suspended solids, few facilities currently have the capacity to remove ions comprising the majority of the TDS load [*Veil*, 2010]. Prior to 2011, most treated effluent from industrial facilities—still carrying high TDS loads—was discharged to rivers. As a result, water quality continued to decline in the Monongahela as effluent discharges from industrial facilities were increasing despite discharges from municipal facilities declining. In response, the Pennsylvania legislature established new effluent standards that included strict limits on TDS [Pa. Code § 95.10., 2010]. While existing industrial treatment facilities were waived from this requirement, the gas industry, represented by the Marcellus Shale Coalition, voluntarily ceased deliveries of Marcellus wastewater to many of these facilities by 19 May 2011 [*Perry*, 2011]; a decline in Marcellus wastewater volumes treated by industrial treatment facilities was observed in 2011 (Figure 5b).

[40] With transport to industrial and municipal facilities being constrained while wastewater volumes continued to increase, demand for underground injection disposal increased in 2011 (Figure 5c). Prior to 2010, only 79.8 ± 20.4 ML (±SD) of wastewater was disposed via underground injection. In 2011, however, this volume surged to 425.7 ML, of which 349.4 ML was from Marcellus wells (Figure 5c). Most underground injection wells are located in Ohio ($n = 184$), with only three commercial facilities in West Virginia and seven in Pennsylvania [*Veil*, 2010]. Just as the shift from municipal to industrial treatment facilities instigated an interbasin transfer of wastewater, the shift to greater underground injection instigated both an interbasin and interstate transfer of wastewater. However, recent earthquakes presumed to be associated with Ohio injection wells resulted in a series of new regulations likely to constrain future underground injection disposal [*Ohio Department of Natural Resources* (*ODNR*), 2012].

3.4. Recycling

[41] Prior to 2011, only 13% of wastewater was recycled for subsequent well development. With other disposal options becoming increasingly constrained, however, 56% (1763.2 ML) of wastewater, largely flowback water, was recycled in 2011 (Figure 5d). Reusing wastewater presents challenges: high concentrations of ions can result in sulfate-, carbonate-, and iron-based scales that impede gas flow, abundant anaerobic bacteria can cause corrosive by-products (e.g., H_2S) and biological fouling, and variation in salinity can compromise well integrity by affecting clay shrinking and swelling within the formation [*Blauch*, 2010; *Montgomery and Smith*, 2010]. Although a variety of developments are facilitating wastewater recycling [*Blauch*, 2010], there are also logistical issues surrounding the timing and transport of water generated at one well to the next [*Mantell*, 2009]. Despite pressure to increase wastewater recycling in 2011 (Figure 5d), 44% was still sent to wastewater facilities or underground injection wells. Existing infrastructure capacity cannot accommodate a similar percentage of wastewater in future years if volumes continue increasing at current rates. Further, while recycling is presently feasible because the number of new wells being constructed outnumbers those in production (such that demand for recycled wastewater is high), recycling must necessarily contract when new well construction declines.

3.5. Future Development

[42] Advances in directional drilling and hydraulic fracturing have revolutionized natural gas production, positioning the United States to become the largest natural gas producer worldwide [*International Energy Agency* (*IEA*), 2012]. Yet as the vast production potential from these resources becomes increasingly realized, so too do the environmental costs and associated management challenges. Wastewater management and disposal have emerged as central concerns and drivers of the controversy surrounding these new methods and have affected regulatory decisions governing the development of the Marcellus shale in particular and shale gas resources in other regions generally. Yet basic quantification and characterization of wastewater dynamics have been lacking, allowing rhetoric to precede understanding.

[43] Natural gas from conventional wells has been produced in the Marcellus region since the 1800s, though there have been and continue to be few concerns about the environmental impacts associated with these wells and managing the wastewater that they produce. Yet our analysis shows that conventional wells produce nearly 3 times as much wastewater per unit gas recovered compared to Marcellus wells. While the large wastewater volumes being generated in the Marcellus region have fostered a perception that shale gas development is comparatively wastewater intensive, in reality the rapid increase in wastewater generated is a consequence of the resource size rather than the development methods employed.

[44] The immense size of the Marcellus shale, combined with limited underground injection disposal, has made it a proving ground that is shaping technology, policy, and industry activity simultaneously. Recent large shifts observable among disposal options (Figure 5) demonstrate how alternative methods for managing wastewater have been tested iteratively, fostering a dynamic coevolution of industry expansion and environmental regulation. However, these shifts also demonstrate that existing wastewater disposal capacity is being quickly saturated. This becomes critical as less than 1% of the Marcellus shale has been explored to date [*U.S. EIA*, 2012c]. More than 45,000 km^2 of undeveloped area is estimated to have production potential and, based on current well spacing (approximately 1 well per 0.5 km^2), developing this area could require >90,000 additional wells [*U.S. EIA*, 2012c]. Because the current wastewater volume generated by only 2189 active wells threatens to overwhelm existing infrastructure capacity, future development of what is potentially the most important natural gas resource in America's energy future is likely to become increasingly dependent on novel logistical or technological solutions for wastewater management.

[45] Not more than a decade ago, extracting natural gas from the Marcellus shale was commercially unfeasible. Yet technological advances have made unconventional gas production a reality. Potential technological solutions for wastewater management are being pursued, such as distillation and reverse osmosis, but currently come at high costs [*Gregory et al.*, 2011; *Veil*, 2010]. Likewise, ample underground injection capacity exists outside the region [*Clark and Veil*, 2009], though requires high transportation costs. Advances in unconventional methods for wastewater management, comparable to the advances that facilitated the development of unconventional gas resource, are now needed.

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