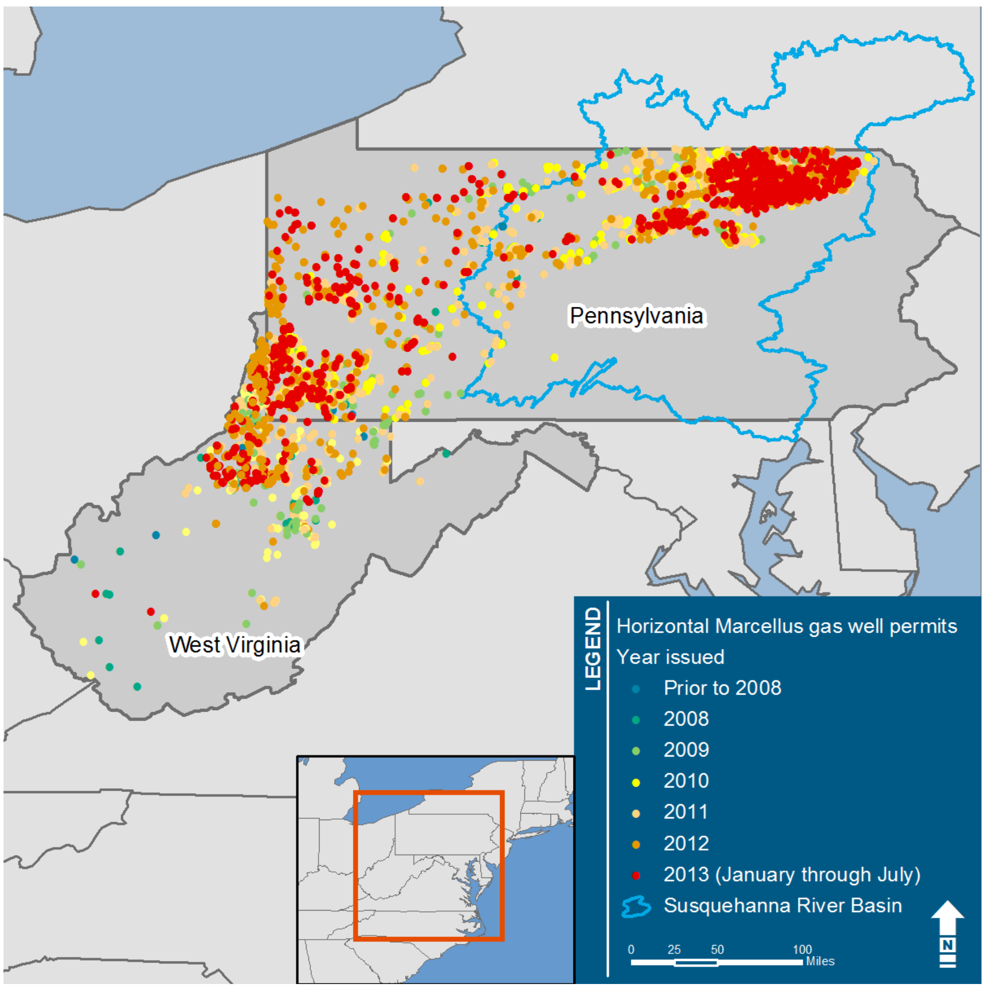
Water Resource Reporting and Water Footprint from Marcellus Shale Development in West Virginia and Pennsylvania



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ABBREVIATIONS

API	American Petroleum Institute
ATSDR	Agency for Toxic Substances & Disease Registry
BOGM	Bureau of Oil and Gas Management (Pennsylvania)
BTEX	benzene, toluene, ethylbenzene, and xylene
CFR	Code of Federal Regulations
CSR	Code of State Rules
DOE	Department of Energy
EIA	Energy Information Administration
ISO	International Organization for Standardization
Mcf	thousand cubic feet
mcm	million cubic meters
MWh	megawatt-hour
NPDES	National Pollutant Discharge Elimination System
NYSDEC	New York State Department of Environmental Conservation
PADEP	Pennsylvania Department of Environmental Protection
PASDA	Pennsylvania Spatial Data Access
POTW	publicly owned treatment works
SRB	Susquehanna River Basin
SRBC	Susquehanna River Basin Commission
STRONGER	State Review of Oil and Natural Gas Environmental Regulations, Inc.
TCF	trillion cubic feet
TDS	total dissolved solids
TSS	total suspended solids
UIC	underground injection control
US	United States
USEPA	United States Environmental Protection Agency
USGS	United States Geological Survey
WVDEP	West Virginia Department of Environmental Protection

EXECUTIVE SUMMARY

Freshwater resources around the world are under threat from fossil fuel development, and these threats are emerging in new places with the rapid growth in recent years of natural gas extraction from shale using horizontal drilling and hydraulic fracturing. This technique has been criticized for its environmental impacts, including dewatering streams and surface- and groundwater pollution. Many specific instances of water impacts remain under scientific investigation, and in Pennsylvania and West Virginia, a number of researchers have documented the potential impacts of fracking on water resources.

This report focuses on the extraction of natural gas from the Marcellus Shale in Pennsylvania and West Virginia. While conventional gas production has been conducted here for decades, unconventional wells that utilize advances in horizontal drilling have grown considerably more common in the past decade. Nearly nine thousand horizontal Marcellus Shale natural gas wells have been permitted in these two states from 2005 to 2012, and more than eleven thousand such wells will likely be permitted by the end of 2013.

As permitted wells have been developed and started production, they have drastically increased gas production in these two states. These wells have also made an important contribution by growing the regional workforce and contributing to state taxes, a significant economic benefit during a time of economic stagnation.

In recent years, West Virginia and Pennsylvania have improved their regulation and oversight of water use and pollution from natural gas extraction. Both states now require recordkeeping and public reporting of key water quality and quantity information. In this report, we use these databases to document water withdrawals, fluid injections, and waste recovery and disposal, including the transport of waste to neighboring states. We also apply the concept of life cycle analysis to calculate the water footprint of the extraction phase of natural gas from Marcellus Shale.

In addition, we provide recommendations for improving data collection and reporting requirements to appropriately inform future management decisions by policy makers, regulators, and operators. More broadly, these recommendations will help regulators—and the industry itself—ensure that water withdrawals, fluid injection, and waste disposal are undertaken in such a manner as to protect the region's groundwater and surface water resources.

Key West Virginia findings

- Approximately 5 million gallons of fluid are injected per fractured well.
- Surface water taken directly from rivers and streams makes up over 80% of the water used in hydraulic fracturing and is by far the largest source of water for operators. Because most water used in Marcellus operations is withdrawn from surface waters, timing is important, and withdrawals during low flow periods can result in dewatering and severe impacts on small streams and aquatic life.
- Reused flowback fluid accounts for approximately 8% of water used in hydraulic fracturing.
- On average, only 8% of injected fluid is recaptured. The remaining 92% remains underground, completely removed from the hydrologic cycle.
- The flowback fluid reported as waste in West Virginia represents only approximately 38% of total waste volume. Because of inadequate state reporting requirements, the fate of 62% of fracking waste is unknown.

- At present, the three-state region—West Virginia, Pennsylvania, and Ohio—is tightly connected in terms of waste disposal. Almost one-half of flowback fluid recovered in West Virginia is transported out of state. Between 2010 and 2012, 22% of recovered flowback fluid was sent to Pennsylvania, primarily to be reused in other Marcellus operations, and 21% was sent to Ohio, primarily for disposal via underground injection control wells.
- The amount of water used per well is higher than previously estimated for Marcellus Shale wells. The blue water footprint of wells started in West Virginia from 2010 to 2012, which represents the volume of water removed from the hydrologic cycle per unit of gas produced, ranges from 1.6 to 2.2 gallons/Mcf. When considering the sensitivity of these results to higher gas production estimates, the range dropped to 1.2 to 2.0. Previous estimates of water use ranged from 0.677 to 1.2.

Key Pennsylvania findings

- Approximately 4.3 million gallons of fluid are injected per fractured well.
- On average, only 6% of injected fluid is recaptured. The remaining 94% remains underground, permanently removed from the hydrologic cycle.
- In Pennsylvania, three primary waste categories are tracked: flowback fluid, brine, and drilling waste, with flowback fluid representing approximately 38% of the total.
- As Marcellus development has expanded, waste generation has increased. In Pennsylvania, operators reported an almost 70% increase in waste generated from 2010 to 2011—rising to a reported 613 million gallons of waste in 2011.
- More than 50% of waste generated by Pennsylvania Marcellus wells is treated and discharged to surface waters—either through brine/industrial waste treatment plants or municipal sewage treatment plants. This stands in stark contrast to West Virginia, where virtually no flowback fluid is reported to be discharged to surface waters.
- In Pennsylvania, approximately one-third of total waste is reused, although data are not available to determine whether it is reused in Pennsylvania or elsewhere. Approximately 5% of total Pennsylvania Marcellus waste is injected in UIC wells, mostly in Ohio.
- There is significant potential for Marcellus development in Pennsylvania to impact water quality because a large percentage of waste is treated at plants that discharge to the state's rivers and streams.
- At present, the three-state region— West Virginia, Pennsylvania, and Ohio—is tightly connected in terms of waste disposal. While most Pennsylvania waste remains in-state, a significant amount of waste is shipped to UIC wells in Ohio, and Pennsylvania reuses flowback fluid received from West Virginia.
- In Pennsylvania, the blue water footprint, which represents the volume of water removed from the hydrologic cycle per unit of gas produced, ranges from 3.2 to 4.2 gallons per Mcf from 2009 to 2011 on a 4-year production basis. When considering the sensitivity of these results to higher natural gas estimates, the range dropped to 1.2 to 3.9. Previous estimates of water use ranged from 0.677 to 1.2.

Recommendations

- Modify reporting systems so that operators report withdrawals by individual well, not by well site.
- Fix mistakes in databases, make data entry less error-prone, and provide searchable online datasets.
- Unify the two units within the West Virginia Department of Environmental Protection with responsibilities related to oil and gas. Currently, staff at one office may not be fully cognizant of other aspects of reporting requirements, and it may also lead to inconsistencies between databases that are being maintained for the same gas wells.
- In Pennsylvania, make Marcellus-specific withdrawal data fully and freely available across the entire state.
- Require operators to report all aspects of water use and waste production, treatment, and disposal along the entire life cycle of shale gas extraction.
- Effectively enforce new rules governing surface water withdrawals and increase oversight of industry surface water withdrawals in order to protect rivers and streams.
- Develop new methods to reduce water and waste at all stages of shale gas production.

Summary

The findings of this report suggest that the volumes of water used to fracture Marcellus Shale gas wells are substantial and the quantities of waste generated are significant. While West Virginia and Pennsylvania have recently taken steps to improve data collection and reporting related to gas development, critical gaps persist that prevent researchers, policymakers, and the public from attaining a full picture of trends. Given this, it is highly likely that much more water is being withdrawn and more waste is being generated than is known.

While a considerable amount of flowback fluid is now being reused and recycled, the data suggest that it still displaces only a small percentage of freshwater withdrawals, which will limit its benefits except in times of drought where small percentages could be important. While West Virginia and Pennsylvania are generally water-rich states, these findings indicate that horizontal drilling and hydraulic fracturing operations could have significant impacts on water resources in more arid areas of the country. However, if existing techniques are applied to the much deeper and thicker Utica Shale that lies below the Marcellus, than even water-rich regions could find that shale gas operations make water supplies vulnerable.

In short, the true scale of water impacts can still only be estimated, and considerable improvements in industry reporting, data collection and sharing, and regulatory enforcement are needed. The challenge of appropriately handling a growing volume of waste to avoid environmental harm will continue to loom large unless such steps are taken.

1. INTRODUCTION

It is widely agreed that the freshwater resources around the world are under threat from fossil fuel development (Gleick 1994; McMahon and Price 2011). These threats are emerging in new places with the rapid growth in recent years of natural gas extraction from shale using horizontal drilling and hydraulic fracturing (”fracking”). This technique has been criticized for its environmental impacts, including dewatering streams (Entrekin et al. 2011) and surface- and groundwater pollution (Olmstead et al. 2013). Many specific instances of water impacts remain under scientific investigation (USEPA 2012; USEPA 2011a; USEPA 2011b), and in Pennsylvania and West Virginia, a number of researchers have documented the potential impacts of fracking on water resources (Abdalla 2010; Lutz et al. 2013; Quaranta et al. 2012; WVDEP 2013d; West Virginia Water Research Institute 2013; Ziemkiewicz et al. 2013; Kargbo 2010; Lavelle 2010).

This report focuses on the extraction of natural gas from the Marcellus Shale in Pennsylvania and West Virginia.[1] While conventional gas production has been conducted here for decades, unconventional wells that utilize advances in horizontal drilling have grown considerably more common in the past decade. Nearly nine thousand horizontal Marcellus Shale natural gas wells have been permitted in these two states from 2005 to 2012: 7,081 in Pennsylvania and 1,680 in West Virginia (See Figure 1 and Table 1) (PADEP 2013h, WVDEP 2013c). Including the estimated number of permitted wells in 2013, more than eleven thousand such wells will likely be permitted by the end of 2013.

Most of the recent permits have been issued in northern West Virginia, southwestern Pennsylvania, and northeastern Pennsylvania.[2] As permitted wells have been developed and started production, they have drastically increased gas production in these two states. These wells have also made an important contribution by growing the regional workforce, with an estimated 29,320 people employed in core industries for shale gas extraction (Marcellus Shale Coalition 2013). Companies developing these shale resources have paid more than $1.6 billion in state taxes from 2006 to 2012 (Marcellus Shale Coalition 2013), a significant economic benefit during a time of economic stagnation.

In recent years, West Virginia and Pennsylvania have improved their regulation and oversight of water use and pollution from natural gas extraction. Both states now require recordkeeping and public reporting of key water quality and quantity information related to water withdrawal, fluid injection, and waste disposal.

While these data collection and reporting requirements provide a key backdrop, the core of this report is our use of these databases to document water withdrawals, fluid injections, and waste recovery and disposal, including the transport of waste to neighboring states.[3] We also apply the concept of life cycle analysis to calculate the water footprint of the extraction phase of natural gas from Marcellus Shale.

[1] When reviewing data collection and reporting requirements, it is important to clarify how each state distinguishes between Marcellus and other wells, unconventional and conventional wells, and vertical and horizontal wells. In this report, we use the term “unconventional” interchangeably with “Marcellus.” In the Pennsylvania reporting systems, the term “unconventional” is used to distinguish Marcellus wells from wells in other formations, and the systems therefore include both vertical and horizontal wells. However, the West Virginia Frac Water Reporting Database contains data for horizontal wells only. As of now, this database only includes wells in the Marcellus formation. Now that drilling in the Utica formation has begun, this database will soon also contain data for horizontally drilled Utica wells. Vertical wells are not included in this West Virginia database because these wells require much smaller volumes of water for drilling, and reporting is only required if a well used more than 750,000 gallons of water.

[2] In neighboring Ohio, the pace of shale gas development has been much slower and has focused on the Utica Shale, which is beneath the Marcellus.

[3] Freshwater is sometimes also transported across state lines; however, we do not distinguish between instate and out-of-state freshwater withdrawals.

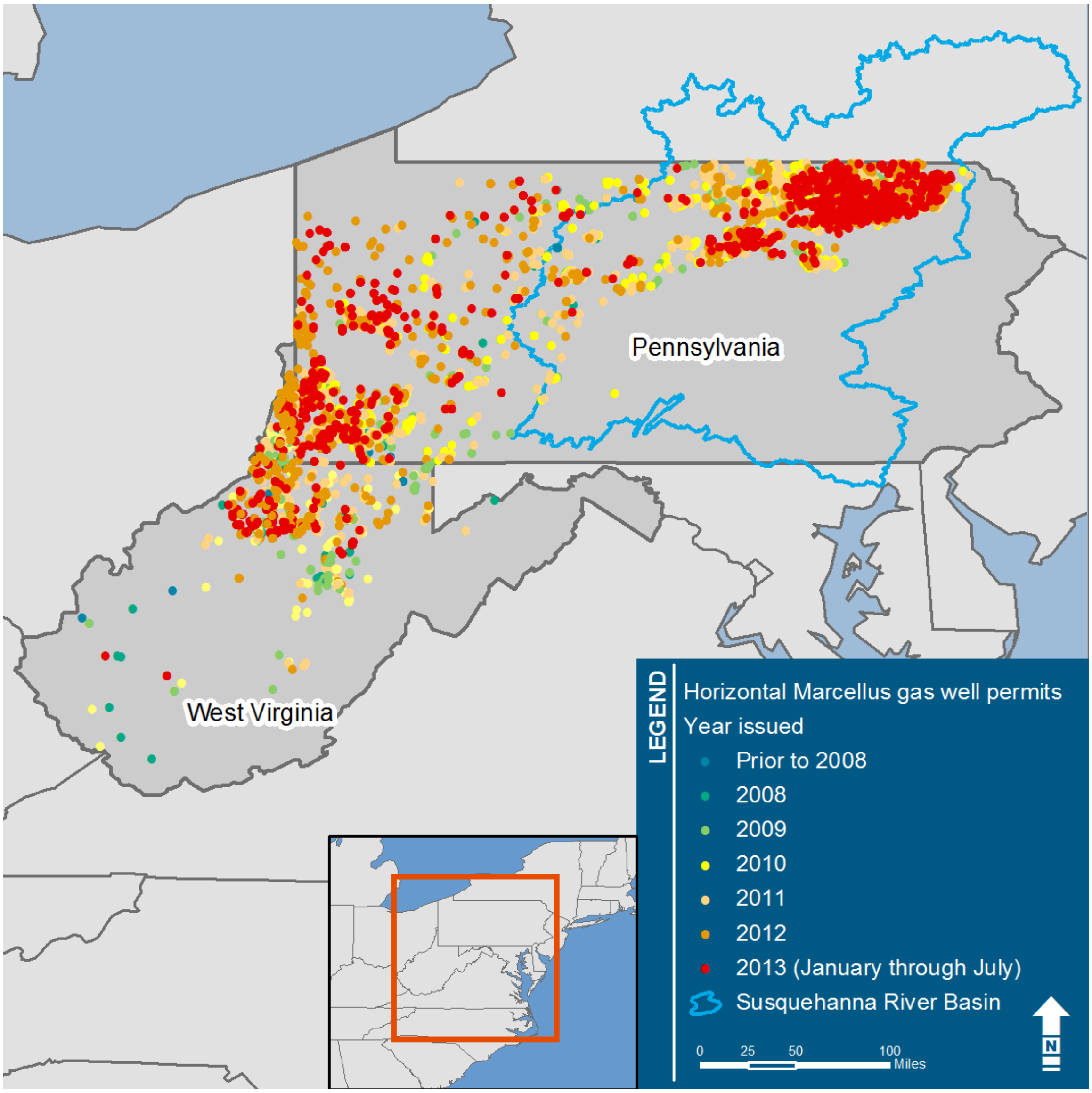
Water footprints are indicators that represent impacts to water resources by estimating water quantities in addition to impacts on water quality (Hoekstra et al. 2011). The approach divides water use into three components. First, the blue water footprint estimates the volume of surface and groundwater withdrawn, consumed, or removed from the hydrologic cycle to produce a product.[4] Second, the grey water footprint is an indicator of water pollution, and is defined as the amount of water required to assimilate water pollution to an acceptable threshold or standard. Finally, the green water footprint "refers to the human use of the evaporative flow from the land surface" (Hoekstra et al. 2011, p. 20). Because the green water footprint largely applies to products produced in agriculture or forestry, it was not considered relevant to the water footprint approach used here.

Through the process of collecting and analyzing the West Virginia and Pennsylvania data, we found that the data reported by operators are sometimes incomplete, inaccurate, unavailable to the public, or inconvenient to query. Despite these challenges, these datasets represent the best information currently available with which to characterize impacts of Marcellus wells on water resources. As the datasets become more complete and accurate, we expect the estimates in this report to be refined.

Our analysis allows us to draw conclusions about patterns of water withdrawals, fluid injections, waste disposal, and water footprints. We also provide recommendations for improving data collection and reporting requirements to appropriately inform future management decisions by policy makers, regulators, and operators. More broadly, these recommendations will help regulators—and the industry itself—ensure that water withdrawals, fluid injection, and waste disposal are undertaken in such a manner as to protect the region's groundwater and surface water resources.

[4] Deciding to use withdrawals, consumption, or removal from the hydrologic cycle would depend on what is deemed most important about the product system.

Figure 1: Horizontal Marcellus gas well permits in West Virginia and Pennsylvania



Sources: Well data from WVDEP (2013c) and PADEP (2013h). Susquehanna River Basin boundary from PASDA (2013). Note: The number of permitted wells is greater than the number actually drilled.

Table 1: Horizontal Marcellus gas well permits in West Virginia and Pennsylvania

Year	West Virginia	Pennsylvania	Total
2005-2007	6	34	**40**
2008	60	156	**216**
2009	261	1,064	**1,325**
2010	288	1,958	**2,246**
2011	477	2,067	**2,544**
2012	588	1,802	**2,390**
2013 (estimate)	624	2,244	**2,868**
Total	**2,304**	**9,325**	**11,629**

Sources: WVDEP (2013c) and PADEP (2013h). Note: The number of permitted wells is greater than the number actually drilled. The 2013 estimates were calculated by doubling the number of wells permitted from January through June 2013.

2. THE SHALE GAS BOOM AND THE ENERGY-WATER NEXUS

In the United States (US), about 30% of electricity was produced from natural gas in 2012, up from 23% just a decade ago (EIA 2011; EIA 2012). This growth in natural gas use for electricity has tracked increases in domestic production, which has been aided by developments in hydraulic fracturing and horizontal drilling that have made recovery of shale gas resources economically feasible. By 2010, shale gas approached 25% of US gas production (EIA 2012), and it continues to grow rapidly. One of the fastest areas of shale gas growth is the Marcellus Shale play, where gas production more than doubled from 2010 to 2011 (Table 2).

Table 2: Shale gas production in the United States and the Marcellus play (TCF, 2010-2011)

Area	2010	2011
United States	5.4	8.0
Marcellus play	0.5	1.4
West Virginia Marcellus play	0.1	0.2
Pennsylvania Marcellus play	0.4	1.1

Source: EIA (2013b).

In the future, shale gas is anticipated to gain a greater share of overall natural gas production and is poised to grow to 13.6 trillion cubic feet (TCF) in 2035 (EIA 2013a). For comparison, overall US natural gas demand is estimated at 25.5 TCF in 2012 (EIA 2013a). As technological development drives down the costs of extraction, shale gas reserves have grown, and are likely to continue to grow (Table 3).

Table 3: Shale gas reserves in the United States and the Marcellus play (TCF, 2010-2011)

Area	2010	2011
United States	97.4	131.6
Marcellus play	13.2	31.9
West Virginia play	2.5	6.0
Pennsylvania play	10.7	23.6

Source: EIA (2013b). Note: Shale gas reserves are as of December 31 of the given year. The Energy Information Administration (EIA) reports proven reserves, which are conservative estimates.

However, natural gas extraction from shale has renewed attention to the impacts of fossil fuel extraction on water resources. Accessing shale gas resources via current technologies requires significant quantities of freshwater compared to historical practices and has raised numerous water quality concerns. As natural gas production from shale continues to expand with the potential unlocked by high-volume hydraulic fracturing combined with horizontal drilling, there will be increasing attention to this energy-water nexus (Scown et al. 2011). Electricity and compressed natural gas are poised to gain a greater share of energy resources for transportation (EIA 2013c), and shale gas will make up an increasing portion of the natural gas portfolio. Hence, if the potential water impacts of shale gas development are not properly managed, freshwater impacts can be expected to become more widespread and appear in new regions over time as resource development proceeds.

2.1 The fracking process: From permits to production

As we describe in this report, the growth of fracking has raised numerous questions about impacts to water resources. These impacts can occur because of the large water quantities needed for production, as well as faulty engineering, poor decisions, accidents, or poor processing practices at several points along the life of a well. Well development proceeds through the following stages:

- **Permitting.** Well permits are generally required by state regulatory agencies before construction can begin. State laws and regulations for well permits differ. For example, setbacks from structures or sensitive landscape features vary among states, and data collection and reporting requirements are also different.
- **Site development.** If a well is being developed at an undeveloped site, a "pad" must be constructed before drilling can begin. Pads provide a level working surface free of obstructions. As enabled by horizontal drilling methods, multiple wells or horizontal legs may be advanced from a single pad. In addition to the well pad, site development may be required for areas associated with pipelines or other supporting infrastructure.
- **Water acquisition**. Water is acquired via direct extraction by the operator from surface or groundwater, by purchasing water, or by reusing fluid from previously drilled and fractured Marcellus sites.
- **Drilling and casing.** Once proper permits are approved and the site is prepared, drilling can commence. Starting the drilling process is sometimes referred to as "spudding" a well. Unconventional Marcellus Shale wells begin with a vertical borehole. The vertical segments of the boreholes are then lined with a surface casing composed of steel that is sealed into place with cement to a depth of up to one thousand feet (Soeder 2012). Properly installed, casing protects fresh groundwater, and it is common to extend the surface casing several hundred feet below any aquifers. With a surface casing in place, the borehole begins to curve and an intermediate casing to prevent fluid migration and prevent borehole collapse is installed up to a point known as the kickoff (Soeder 2012). From here, the borehole is deviated laterally to run within the shale bed. A production casing is installed that runs inside the surface and intermediate casings, all the way through the end of the borehole.
- **Hydraulic fracturing.** After the well is drilled, explosive charges are used to perforate the production casing. This puts the production casing in contact with the shale production zone. After a brief cleaning with hydrofluoric acid, it is hydraulically fractured with a fluid composed of water, sand, and chemicals. This fluid is injected under steadily increasing pressure, and the sand or other proppant material holds the fractures open after pressure is released. This process is known as "completion."

  Once the fracking process is completed, fluid that returns to the surface is referred to as "flowback" and is directed to temporary onsite storage where it is ultimately disposed of or reused. This flowback water typically returns to the surface within the first seven to 14 days (American Petroleum Institute 2010), but can continue for months. In addition to flowback, naturally present brine fluid also returns to the surface.
- **Production.** Once a well begins producing gas, it can continue to produce for decades, although annual production volumes decrease rapidly.

As documented in this report, different types of data are collected and reported at different stages. For example, in both Pennsylvania and West Virginia, completion reports with information on chemicals used in the fracking fluid must be submitted. And in both states, production reports must be submitted that periodically document the volume of natural gas that was produced. See Chapter 3 and Appendix A and B for more detail on these and other data collection and reporting requirements.

2.2 Impacts of shale gas extraction on water resources

The well development process described above has the potential to generate numerous impacts to water resources. Researchers have investigated potential impacts to both water quantity and quality, which can vary across different geologic basins. Research on the impacts to water from shale gas extraction can broadly be categorized into research on water quality indicators and research on water and wastewater quantities. Many of these studies attempt to characterize ecosystem and habitat effects, both aquatic and terrestrial, and human health impacts, but a number simply seek to understand water use and pollution in general.

Research on water resource impacts has been performed at universities (Lutz et al. 2013; Jackson et al. 2013); by government agencies (USEPA 2012; USEPA 2011a; USEPA 2011b; USGS Powell Center for Analysis and Synthesis 2012; Soeder and Kappel 2009); and by non-governmental organizations such as the Pacific Institute (Cooley and Donnelly 2012), Environmental Working Group (Horwitt 2011), Environment America (2013), and National Ground Water Association (National Ground Water Association 2011).

Despite the important information revealed about impacts to water quality and quantity from this body of research, it remains challenging to interpret the results and/or assess the tradeoffs between concerns about water quantity and those about water quality. Key questions remain: Are the concerns for one greater than the other? Do regulations need to be adjusted for water withdrawals, waste disposal, or both?

While water quality and quantity are inextricably linked, the local context may influence public perceptions. Water footprint indicators can help understand how industry trends and practices may change impacts to water over time. In this section, we survey prior research to understand the breadth of methods, data, and assumptions used to understand the impacts of natural gas extraction from shale. We review the published literature on impacts from fracking and related activities with the goal of identifying gaps in the literature, noting critical research needs, and informing our data analysis.

2.2.1 *Groundwater quality*

Fracking for natural gas can put groundwater in and around the well site at risk. Impacts to groundwater quality include methane migration (Osborn et al. 2011), shale formation brine and associated metals migration (Saiers and Barth 2012; Warner et al. 2012), and contamination of groundwater from drilling or flowback fluids (USEPA 2011). Groundwater that is close to the surface is often relied upon as drinking water, while deeper groundwater usually is not. There is much debate and ongoing scientific research to determine the hydraulic connectivity between deep and shallow groundwater (Warner et al. 2012). Arguably the most probable way to contaminate shallow groundwater is through poor onsite management of flowback and drilling fluids (Holloway and Rudd 2013; Howarth and Ingraffea 2011). Poorly managed and sited waste pits can also impair water quality via mechanical failure, such as when liners rupture and create direct contact with groundwater (Folger et al. 2012; Rich and Crosby 2013; USGS 2012). Buried waste also poses water quality risks. Obviously, intentional dumping—which has been found to happen (USEPA 2013a)—will impact water quality. Though it has not been documented with certainty to date, damage to wells that occurs close to the surface might lead to the direct contamination of groundwater as fracking or flowback fluid can be introduced to the subsurface, and possibly to groundwater resources, from the site of well failure (Folger et al. 2012).

2.2.2 *Surface water*

Similarly, shale gas extraction can impact surface water by above-ground land management and off-site waste treatment. Spills, leaks, and other releases of flowback fluid can directly impair surface water because these fluids contain low-level radiation (Rowan et al. 2011), heavy metals, and other contaminants. Olmstead et al. (2013) examined how surface water in Pennsylvania was impacted by the permitted release of treated shale gas waste. They looked at the impacts of land use change and the release of treated shale gas waste on total suspended solids (TSS) and chloride concentrations. Increased TSS concentrations would occur from runoff associate with well pads, pipelines, and roads. The source of chloride is brine and flowback fluid. They found that chloride concentrations did impact downstream water quality, but were not able to detect increased TSS concentrations (Olmstead et al. 2013). Numerous other studies are ongoing or underway.

2.3 Marcellus waste disposal options

A variety of types of wastes are generated when Marcellus wells are drilled and hydraulically fractured. Between 2004 and 2011, the volume of waste disposed in Pennsylvania has increased by 570% (Lutz et al. 2013).

Fluids that are recovered soon after fracking are referred to as flowback fluid. Arthur et al. (2008) estimate that 10% to 30% of initial volume of water is recovered as flowback from Marcellus Shale wells. The Susquehanna River Basin Commission (SRBC) estimates that 8% to 12% is recovered as flowback (Richenderfer 2010). A public presentation by Penn State Extension (Yoxtheimer 2012) puts this range from approximately 8% to 10%.

The data analyzed in this report found a value similar to the low values, at approximately 8% in West Virginia and 6% in the Susquehanna River Basin (SRB) in Pennsylvania based on the methodology we document later. If not disposed of properly, this waste can impair water quality—both groundwater and surface water. But even industry best practices for disposal can have water quality implications (Olmstead et al. 2013).

There are limited options for managing waste that returns to the surface after fracking, which includes flowback fluid, brine generated from within the target formation, and other types of waste. Generally, the best option is to reuse flowback fluids to perform fracturing at another Marcellus well. This option eliminates the need to locate a disposal site and lessens the water withdrawal requirements for future fracturing efforts. As discussed below, our analysis shows that, as a percentage of total waste disposal, the reuse of flowback fluids has increased dramatically in Pennsylvania (Table 21) but has actually decreased in recent years in West Virginia (Table 11). While reuse is an appealing alternative, recycled flowback fluid must be treated and diluted with freshwater, and another well must be available at which to use it again.

In recent years, the most common option in many regions of the US is to pump waste fluids underground via underground injection control (UIC) wells. These wells are intended to dispose of waste far below ground, and the Safe Drinking Water Act regulates UIC use and operation. There are five types of UIC wells. Class II wells are specifically built to inject fluids to enhance recovery or to dispose of flowback fluid, brine, and other residual waste generated by oil and gas operations (USEPA 2013).[5]

According to West Virginia Department of Environmental Protection (WVDEP), there are 62 active Class II UIC wells in West Virginia (WVDEP 2013e). Most of these wells are owned by drillers and used to dispose of fluids produced in their own operations; however, 14 are commercial wells (WVDEP 2013e) and accept fluids from more than one oil and gas operation. In West Virginia, WVDEP has primacy over its UIC program and therefore administers permits for Class II UIC wells.

In Pennsylvania, there are seven Class II UIC wells (Platt n.d.). The Pennsylvania Department of Environmental Protection (PADEP) has not been granted primacy over the program; therefore, the United States Environmental Protection Agency (USEPA) administers the Class II UIC well program in Pennsylvania.

Much of the waste generated by wells in Pennsylvania and West Virginia is disposed of in UIC wells in Ohio (See Table 13 and Table 22). Ohio has almost two hundred Class II UIC wells available for drilling waste disposal (Adgate 2013).

Treatment and discharge to surface water is a third option. Especially when the Marcellus play began to be developed, waste was trucked to publicly owned treatment works (POTWs) in both West Virginia and Pennsylvania. These plants eventually discharge to surface waters. However, over time, it became clear that POTWs were not effectively treating natural gas fluids before discharging to receiving streams (Olmstead et al. 2013; Volz 2011). Flowback fluid with significant levels of sodium and chloride can raise total dissolved solids (TDS) levels in the POTW's effluent (USEPA 2011). They are also not equipped to treat fluids that contain radium, a contaminant commonly found in flowback water (Rowan et al. 2011). When high levels of bromide and chloride are present, as is common in the Marcellus Shale, POTWs can synthesize brominated and chlorinated constituents in the effluent. These compounds can include brominated and chlorinated trihalomethanes, which have been linked to human cancers and birth defects (USEPA 2005).

With the high volumes of flowback fluid being generated, there are also questions about whether POTWs are over capacity. Riha and Rahm (2010) modeled the impacts to water resources in New York's undeveloped section of the SRB using hypothetical withdrawal and disposal data and found that POTWs could be over capacity without investments in private industrial waste treatment plants specifically outfitted to treat hydraulic fracturing waste.

As regulators have increasingly frowned upon sending these fluids to POTWs, their use has stayed negligible in West Virginia (Table 11) and has become less common in Pennsylvania (Table 21). Brine or industrial waste treatment plants present another option for treating hydraulic fracturing waste before discharging to surface waters. While these plants are prevalent in Pennsylvania (Table 21), they are not currently used in West Virginia (Table 11).

Disposing of brine, which returns to the surface over a longer time period than flowback fluid, also presents water quality concerns. Ohio regulators are considering whether to allow solidified brine to be disposed of in its 40 landfills (Downing 2013).

[5] While UIC permits are required for the disposal of fluids related to Marcellus gas production, they are not needed for Marcellus wells themselves.

2.4 Shale fossil fuels and water use

It was known early in the evolution of shale gas extraction that hydraulic fracturing requires substantial quantities of water. By 2006, an estimated 35,000 wells were already fractured across the US (Halliburton, 2008; cited in USEPA 2011a), requiring an estimated 70 to 140 billion gallons per year (USEPA 2011). According to USEPA at the time, “this is equivalent to the total amount of water withdrawn from drinking water resources each year in roughly 40 to 80 cities with a population of 50,000 or about one to two cities of 2.5 million people” (2011, p. 22a). With the boom in shale gas production not starting in earnest until 2008, the volume of water required to frack for natural gas has increased by an order of magnitude or more.

The amount of water used per shale gas well varies, but hydraulic fracturing at a single horizontal well can require 1.9–9.1 million gallons of water-based fracturing fluids (Sutherland et al. 2011). The US Department of Energy (DOE) puts the input requirements for hydraulic fracturing between 2.9 to 5.0 million gallons of water, 1,300–2,300 kilograms of sand, and 29,000–50,000 gallons of chemicals on average per well (DOE 2009; cited in Lewis 2012).

Nicot and Scanlon (2012) estimated net water use in shale-gas production in Texas based on well-completion data. They found that cumulative water use in the Barnett Shale play totaled 145 million m^3 (38 billion gallons), roughly 9% of the water use of Dallas’ population of 1.3 million. They found that these water withdrawals were less than 1% of overall water use for entire state of Texas, but could have important local impacts in times of low water availability. Because a large portion of the water injected is removed from the hydrologic cycle, there could be long-term impacts to water availability in arid areas of Texas. Formation characteristics suggest that more of the initial volume of water returns to the surface in the Barnett than the Marcellus; however, in 2011, there were no published estimates of the volume of water withdrawals that return to the surface for the Barnett Shale (Mantell 2011).

Water use varies across different basins. Annual estimates of total water use across the Barnett Shale ranged from 2.6 to 5.3 billion gallons per year from 2005 through 2007 (Bene et al. 2007; cited in Galusky 2007). Estimates for North Dakota’s Bakken Shale project water use at nearly 5.5 billion gallons of water per year for oil and gas production (Kellman and Schneider 2010).

2.5 Marcellus Shale gas and water use

Drilling and fracking Marcellus Shale wells likewise require millions of gallons of water per well. SRBC—the interstate commission that manages one of the largest river basins atop the Marcellus Shale—“projects 30 million gallons a day of consumptive use associated with full development of just the Marcellus play” within the SRB (Drohan et al. 2012, p. 395). In fact, on a per-well basis, the Marcellus Shale appears to require more water—between 4.1 and 5.6 million gallons—than the Fayetteville, Haynesville, and Barnett Shale plays (Table 4). The variability can be attributed to differences in shale formation geology, depth, and well type, which vary over space and time.

Table 4: Water requirements per well for fracking by shale play (million gallons)

Shale play	Typical range
Barnett	2.3–3.8
Fayetteville	2.9–4.2
Haynesville	2.7–5.0
Marcellus	4.0–5.6

Sources: Groundwater Protection Council & ALL Consulting (2009) and Clark et al. (2011), which cites Mantell (2010). These values assume one frack per well. Per-well water requirements will be higher if re-stimulation occurs, but there is a dearth of information about water use from re-stimulation.

Estimates of water requirements for Marcellus wells vary but fit within the range noted above. Drohan et al. (2012) note that SRBC estimates an average of 4.4 million gallons per well. Range Resources (2010) finds the water volume per well to be over 4.6 million gallons. Using operational data from Chesapeake Energy, Mantell (2010; 2011) finds water use requirements to be 4.1 and 5.6 million gallons respectively.[6] Researchers at Argonne National Laboratory estimate water use in the Marcellus Shale to be approximately 4.0 million gallons per well (Clark et al. 2013).

Table 5: Range of estimates of water used per well in the Marcellus Shale (million gallons)

Water volume	Research team
4.4	SRBC; cited in Drohan et al. 2012
4.6	Range Resources 2010
5.6	Mantell 2011
4.1	Mantell 2010
4.0	Clark et al. 2013

To put these values into a similar context that USEPA used in 2011, the Pittsburgh Water & Sewer Authority produces 70 million gallons of water per day to serve its 83,000 customers (Pittsburgh Water & Sewer Authority 2010). The approximately 6,000 Marcellus wells in Pennsylvania have injected about as much water as Pittsburgh supplies to its customers in one year.

Put another way, the entire flow of the Susquehanna River contributes 26 billion gallons of water per day to the Chesapeake Bay (Drohan et al. 2012). The cumulative volume of water used by all wells in Pennsylvania is roughly equal to the daily flow from the entire river basin. These cumulative impacts are especially important because such a large percentage of the water injected does not return to the surface and is lost to the hydrologic cycle. The volume of water injected to date in Pennsylvania is also roughly 1% of the 2.5 trillion gallons of total surface water in Pennsylvania alone (Abdalla 2010). While overall, 1% might be seen as only a marginal impact, these volumes could be critical in times of drought. Also, as drilling expands, the cumulative impacts are likely to grow proportional to water use. The development of the deeper and thicker Utica Shale that underlies the Marcellus with similar techniques will require substantially more water.

[6] Mantell (2010) uses 2009 operational data from Chesapeake Energy. The increase in volume in Mantell 2011 in Table 5 is likely due to deeper wells.

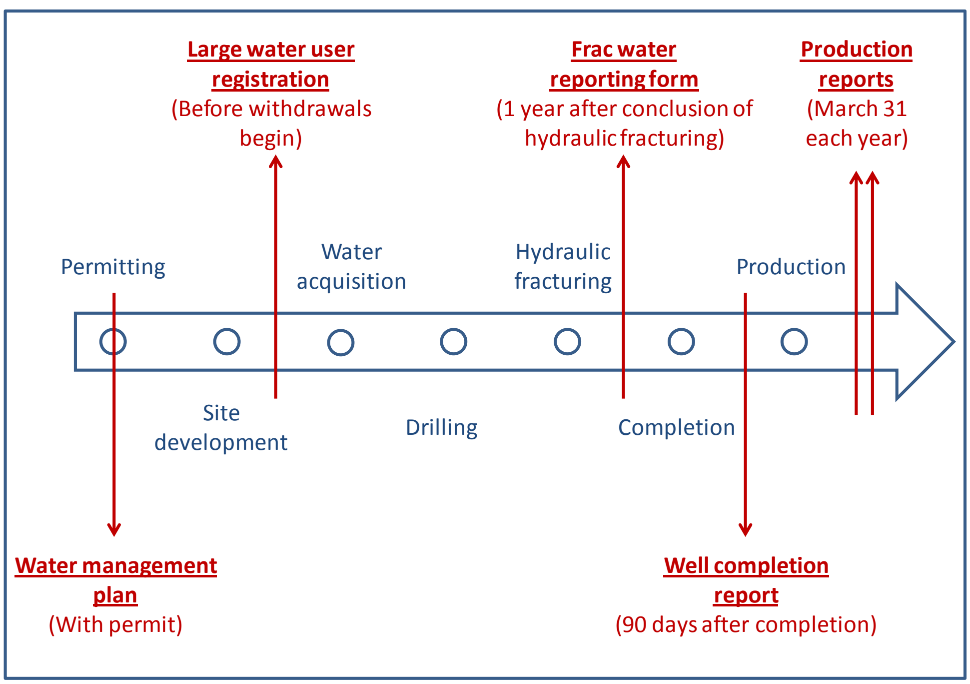
3. DATA COLLECTION AND REPORTING REQUIREMENTS

3.1 West Virginia

Data collection and reporting requirements have evolved rapidly in recent years in West Virginia as new laws, regulations, and policies have been enacted. In West Virginia, water withdrawals, water used in development of horizontal Marcellus wells, and disposal of flowback fluid are regulated by two acts and their associated rules: the Natural Gas Horizontal Well Control Act and the Water Resources Protection and Management Act. The Natural Gas Horizontal Well Control Act,[7] passed by the West Virginia Legislature in 2011, recognized that advanced natural gas drilling practices require use and disposal of unprecedented quantities of water. Existing oil and gas regulations, which focused on conventional drilling techniques, were not adequate for the increased number of wells drilled and the copious volumes of water used and waste produced as a result of hydraulic fracturing and horizontal drilling. This Act created a regulatory framework to address the large volumes of water injected during drilling and fracturing and the disposal of flowback fluid. However, as described below, many of the reporting requirements stem from a previous law, the Water Resources Protection and Management Act,[8] which was updated in 2008.

As illustrated in Figure 2, a variety of water, waste, and production data must be collected and reported to WVDEP, starting with the water management plan submitted with the permit, and ending with annual production reports. Appendix A provides detailed descriptions of each of these forms and reports.

Figure 2: West Virginia reporting forms



Source: Appendix A.

[7] W.Va. Code §22- 6A.
[8] W.Va. Code §22-26.

FRACFOCUS AND SKYTRUTH

FracFocus is an online chemical disclosure registry for the oil and gas industry maintained by two non-profit organizations: the Interstate Oil and Gas Compact Commission and the Groundwater Protection Council. All data uploaded to the online database is self-reported by well operators. The online database contains the volume of fracking fluid injected into each well and the chemical additives present in the fracking fluid, with the exception of chemical components determined to be proprietary. All information contained in this database is searchable online and free to the public; however, search results are only provided for single wells.

Until recently, all information contained in the FracFocus database was voluntarily disclosed by well operators. According to a recent Harvard Law School study, 11 states direct or allow well operators to use FracFocus; Pennsylvania is one of these states (Konschnik et al. 2013). More recently, the West Virginia Legislature changed state rules to require additive reporting to the WVDEP Office of Oil and Gas and to FracFocus (35 CSR 8-10). This change took effect on July 1, 2013.

SkyTruth is a nonprofit organization that uses remote sensing, digital mapping, and other techniques to monitor mining, oil and gas drilling, deforestation, fishing, and other human activities. One service provided by this organization is its FracFocus Chemical Database Download, which compiles FracFocus data into a downloadable, searchable database (SkyTruth 2013). This source was used to compile certain information from FracFocus for this report.

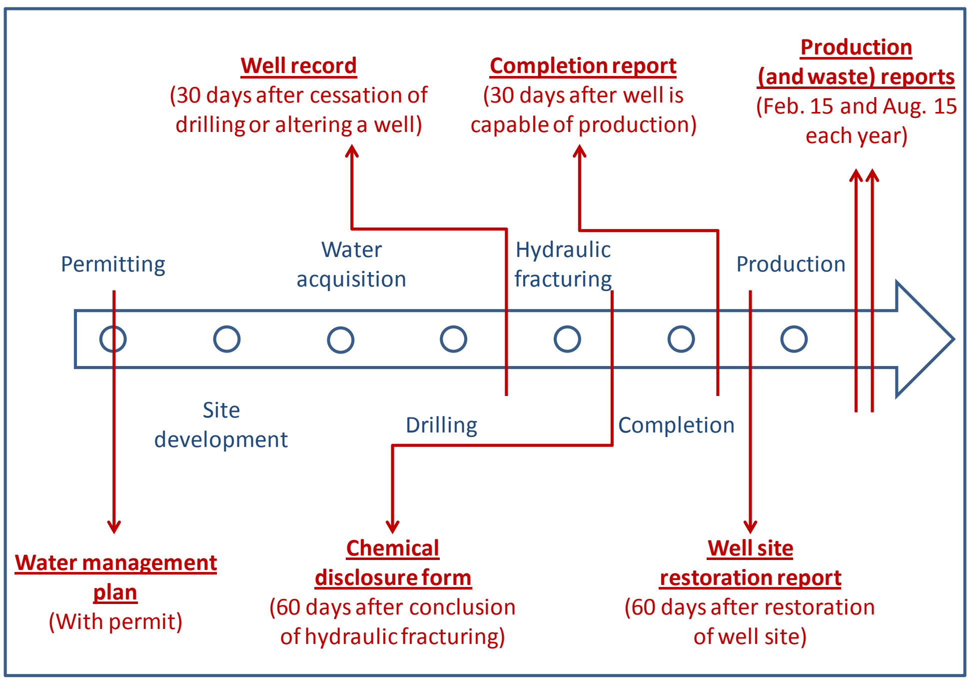
For this analysis, only the fluid injection volumes in FracFocus were used. Even for this parameter, FracFocus does not compile data into a searchable database. As such, FracFocus is of limited usefulness for researchers who desire data for numerous wells. SkyTruth's FracFocus Chemical Database Download, however, turns the FracFocus data into a searchable database that is publicly available, thereby drastically increasing the usefulness of data collected by FracFocus.

3.2 Pennsylvania

In Pennsylvania, several statutes and regulations govern Marcellus Shale gas exploration and production, and a series of policies and manuals provide further guidance (PADEP 2013a; STRONGER 2013). As in West Virginia, data collection and reporting requirements for Marcellus operations have also evolved in recent years in Pennsylvania, particularly with the passage of the Oil and Gas Act, also known as Act 13, in 2012. As illustrated in Figure 3, PADEP, like WVDEP, requires operators to collect and report a variety of water, waste, and production data in a set of plans, forms, and reports.

Certain of these reporting requirements are similar to those in West Virginia: water management plans submitted with permit applications, completion reports filed after well completion, and gas production reports filed periodically after wells begin producing. However, many of the reporting requirements are different. For example, Pennsylvania requires operators to submit waste disposal information for a wide variety of waste types in well site restoration reports and along with the production reports, while waste reporting in West Virginia is limited to flowback fluid and is submitted only once. Appendix B provides detailed descriptions of each of these forms and reports.

Figure 3: Pennsylvania reporting forms



Source: Appendix B.

SUSQUEHANNA RIVER BASIN COMMISSION

SRBC plans for the conservation, utilization, development, management, and control of the water and related natural resources of the SRB, which includes part of New York, Pennsylvania, and Maryland (18 CFR §801.0). SRBC regulates all withdrawals of surface water and groundwater and consumptive water uses within the basin for natural gas development in the Marcellus Shale (SRBC 2013a).

Prior approval from SRBC through an application process is required for water withdrawals and consumptive uses for natural gas development. Consumptive water uses at natural gas drilling pads are handled through an administrative general permit process, known as Approval by Rule, and are reviewed and acted on by SRBC's Executive Director. SRBC does not, however, regulate water quality. (SRBC 2013a)

SRBC does not directly regulate the capture, storage, transport, treatment, recycling, or disposal of fluid recovered from Marcellus wells from drilling or fracking. However, the injection of water for fracking is regulated as a consumptive use by SRBC. SRBC therefore approves the consumptive use of water at drilling pads and requires natural gas companies to abide by all other agencies' water quality and waste management requirements. SRBC also requires natural gas companies to report post-hydrofracking information. These reports allow SRBC to track the quantities of freshwater, recycled flowback fluids, and all other water used, the sources or origin of all freshwater/wastewater used, and destinations of wastewater and unused freshwater whether it be to a permitted treatment facility or reuse at another drilling pad. (SRBC 2013a)

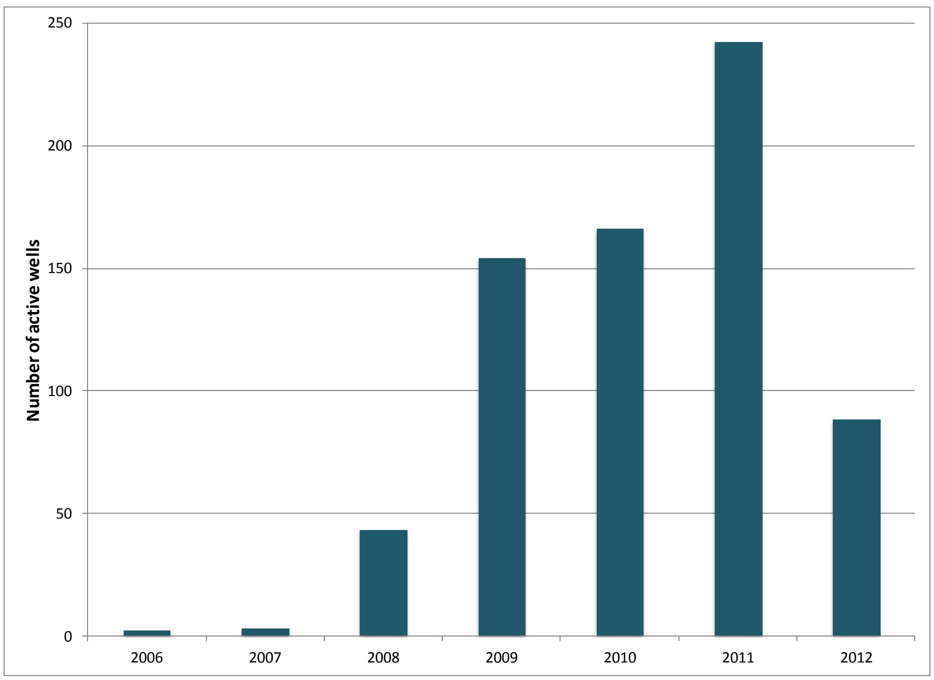
SRBC withdrawal and consumption data, as well as SRBC post-hydrofracking information, are relevant for the current analysis.

4. INJECTION, RECOVERY, AND DISPOSAL OF FLUIDS IN WEST VIRGINIA

4.1 Drilling progress in the Marcellus Shale

The first Marcellus wells in West Virginia were drilled vertically, but with the advent of horizontal drilling techniques, the number of permitted Marcellus wells has grown dramatically. Since 2007, WVDEP issued more permits each year for horizontal Marcellus wells, reaching almost 600 newly-issued permits in 2012 (See Table 1, above). As of August 9, 2013 2,064 horizontal Marcellus gas wells had been permitted in West Virginia. Figure 4 illustrates the number of currently active horizontal Marcellus wells among those permitted in a given year. As of August 9, 2013, 698 horizontal Marcellus wells were active in West Virginia (WVDEP 2013c).

Figure 4: Currently active horizontal Marcellus wells in West Virginia, by permit year



Source: WVDEP (2013c). Note: The number of active wells represents the number of wells permitted each year that were active as of August 9, 2013. On this date, no wells permitted in 2013 were active.

4.2 Withdrawals

Withdrawal data were obtained from the WVDEP Water Use Section through a Freedom of Information Act request. Water withdrawal volumes in West Virginia are reported by extraction event and by well site—not by individual well.[9] In most cases, a well site contains more than one well, and water may be stockpiled in a single pond for fracturing multiple wells at that site or on entirely different pads. Further complicating the reporting of withdrawals, water used at a single site may be withdrawn from multiple sources at different times. It is therefore not possible to determine the volume of water withdrawn for use at any individual well.

Still, WVDEP collects a variety of useful information about withdrawals, including withdrawal source name, location, watershed, and volume withdrawn. This information is reported to WVDEP through the online Frac Water Reporting Form.

As shown in Table 6, the number of withdrawals and well sites included in this database has increased substantially between 2009 and 2012. In 2009, data for 13 withdrawals for seven different well sites were reported. By 2011, the dataset included 355 total withdrawals for 112 different well sites. The 2012 dataset is not yet complete.

Table 6: West Virginia withdrawal data summary (2009-2012)

Data	2009	2010	2011	2012 (partial year)
Number of withdrawals	13	184	355	169
Number of well sites	7	58	112	59

Source: WVDEP (2013a). The number of withdrawals refers to the number of withdrawals with a withdrawal "begin date" in each year.

Our analysis of the West Virginia water withdrawal data focuses on the three years with the most data: 2010 through 2012 (See Table 6 and Figure 5). During this time, water for use in drilling and hydraulic fracturing was withdrawn from groundwater and surface water—lakes, ponds, rivers, and streams. Water was also purchased from public and private water providers. In addition, reused flowback fluid captured at wells following injection was transferred to other wells and used again.

From 2010 through 2012, almost 2 billion gallons of water withdrawals were reported for Marcellus wells in West Virginia. As the number of horizontal wells in the Marcellus climbed from 2010 through 2011, the volume of fluid required to service these wells increased by almost 200 million gallons. During all years, surface water was the most widely utilized source of water used in Marcellus well development—81% of the total from 2010 through 2012. Since 2010, more than 1.6 billion gallons of water have been withdrawn from West Virginia's surface waters for injection into horizontal wells in the Marcellus.

When flowback fluid is reused, it lessens demands for withdrawals from groundwater and surface water. Reuse as a percent of total withdrawals has increased somewhat, from 6% in 2010 to 10% in 2012.[10] As described later in this report, the percentage has been somewhat higher in the SRB in Pennsylvania, where it increased from 10% in 2010 to 18% in 2012 (See Table 19).[11]

[9] While withdrawals per well are not known, the volume of fluid injected per well is known, and is reported below in Table 10.

[10] The reuse percentages in Table 7 represent the percentage of total withdrawals that come from reused flowback fluid. This is different from the percent of flowback fluid that is recycled and reused, which is shown in Table 11. While Table 11 suggests that most flowback fluid is recycled and reused, Table 7 clarifies that this reused flowback fluid still represents a small percentage of total withdrawals.

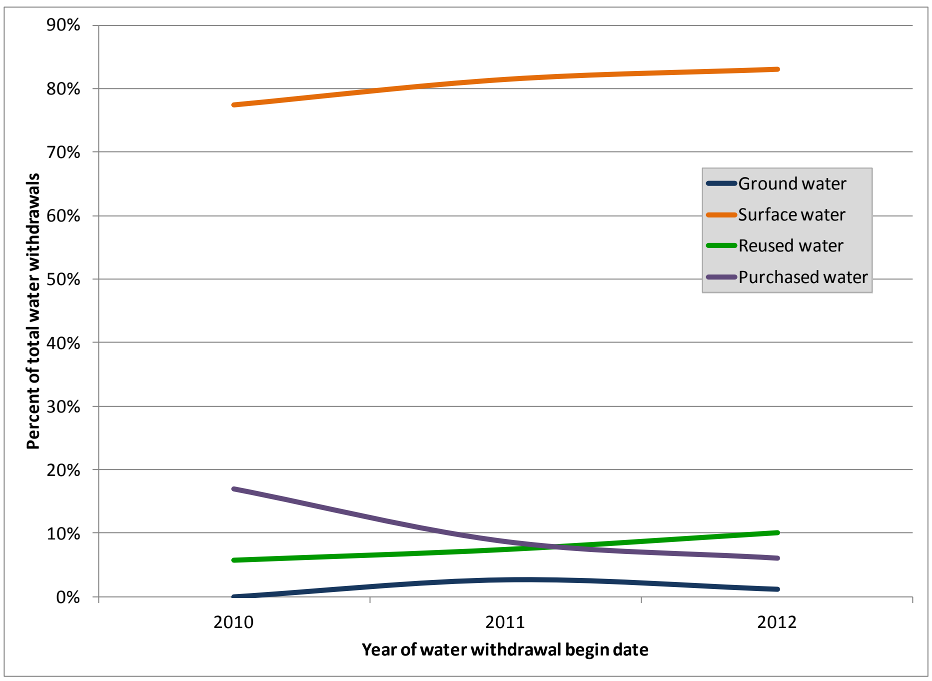
[11] In Pennsylvania, we calculate the percentage of injection volumes from that come from reused flowback fluid. In West Virginia, we calculate the percentage of withdrawals (including reused flowback fluid) that come from reused flowback fluid. These calculations, while not exactly the same, convey a similar result.

Table 7: Reported water withdrawals for Marcellus wells in West Virginia (million gallons, % of total withdrawals, 2010-2012)

Source	2010	2011	2012 (partial year)	Total
Groundwater	0 0%	21.2 3%	1.5 <1%	**22.7** **1%**
Surface water	476.8 77%	662.2 81%	466.9 83%	**1,605.8** **81%**
Purchased water	104.0 17%	70.0 9%	34.7 6%	**208.6** **10%**
Reused flowback fluid	35.1 6%	60.0 7%	57.2 10%	**152.2** **8%**
Total	**615.8** **100%**	**813.4** **100%**	**560.2** **100%**	**1,989.3** **100%**

Source: WVDEP (2013a). Note: Surface water includes lakes, ponds, streams, and rivers. The dataset does not specify whether purchased water originates from surface or groundwater. As of August 14, 2013, the Frac Water Reporting Database did not contain any well sites with a withdrawal "begin date" later than October 17, 2012. Given that operators have one year to report to this database, the 2012 data are likely very incomplete.

Figure 5: Reported water withdrawals for Marcellus wells in West Virginia (% of total withdrawals, 2010-2012)



Source: WVDEP (2013a).

4.3 Quality control and completeness of the injection, recovery, and disposal dataset

Injection, recovery, and disposal data were obtained from the WVDEP Water Use Section through a Freedom of Information Act request. The dataset provided by WVDEP includes total injection volume, injection "begin dates" and "end dates," recovery amount, and recovery "begin dates" and "end dates" by American Petroleum Institute (API) number for horizontal wells targeting the Marcellus formation. It also includes volume reused, volume disposed of in UIC wells, and volume disposed of at POTWs for each API number or West Virginia well ID.[12] These data were self-reported by well operators to WVDEP using the online Frac Water Reporting Form.

Prior to performing data analysis, the data were reviewed and quality control methods were implemented to ensure that only representative data were included in our analysis. Appendix C describes the quality control steps that were taken, and Table 8 summarizes the number of West Virginia wells with reporting data and remaining after quality control.

To assess trends in water use and disposal over time, wells were separated by the year that injection began. As shown in Table 8, a significant number of wells were removed from the West Virginia dataset before performing calculations. Of the 398 wells for which injection began in 2010, 2011, or 2012, just over two-thirds remain after quality control.

Table 8: West Virginia wells with reporting data and remaining after quality control (2010-2012)

	2010	2011	2012 (partial year)	Total
With reporting data	109	159	130	**398**
Remaining after quality control	84	140	46	**270**
Percent of data eliminated	23%	12%	65%	**32%**

Source: WVDEP (2013a). Note: Years represent the year that injection began.

WVDEP provided the well and injection data separately from the waste data. The WVDEP well ID was used to join the disposal data to the injection data so that injection volume, recovery volume, total disposal volume, and disposal volume by method were available for each API number and corresponding well ID.[13] This joined dataset was used for further analysis.

To assess the completeness of this dataset, we calculate a reporting rate for each year. WVDEP's Gas Well Permit Database (WVDEP 2013c) was obtained from the WVDEP Technical Applications & Geographic Information System Unit and was used to calculate the total number of wells for each year that should have been required to report water data. This database was filtered to show only wells targeting the Marcellus formation that are also horizontal wells. Assuming that water has been used at all active wells, the data was further filtered to wells with an active status. These wells were then separated according to the year in which they were permitted.

We then searched the entire Frac Water Reporting Database for the API numbers that correspond to the wells that were legally required to report water data.[14] The reporting rate we calculate is not meant to measure the accuracy of the data reported, but the percentage of required reports that exist in the database; therefore, we searched the ***entire*** Frac Water Reporting Database for each API

[12] These West Virginia well IDs, while different from API numbers, were unique and could be cross-referenced against the API numbers.

[13] The disposal year for reuse is not included in the Frac Water Reporting Database; thus, the year for reuse was determined by joining the well ID for the reuse waste volume to the well ID in the well information database. All waste data are tied to the injection date of the well that produced the waste.

[14] The Frac Water Reporting Database contained numerous wells that did not exist in the Well Permit Database.

number identified as described in the previous paragraph, and not just the wells remaining after quality control in Table 8.

To estimate reporting rates for the Frac Water Reporting Database, we divided the number of wells that reported to this database (WVDEP 2013a) by the total number of active horizontal Marcellus wells from the Gas Well Permit Database (WVDEP 2013c). Reporting rates, shown in Table 9, were only calculated for 2010 and 2011. The Frac Water Reporting system was not established prior to 2010, so reporting rates for earlier years were not estimated. Even though 91 horizontal Marcellus wells with a permit date in 2012 are listed as active in the permit database, we assume that the reporting rate calculated using this method for these wells would not be accurate due to the one-year lag time in reporting following water injection.

Only 35% of the wells permitted in 2010 and 2011, on average, have reported to the Frac Water Reporting Database. This combined reporting rate was applied, as described below, to the total reported volume injected, total reported volume disposed, and total reported volume removed from the hydrologic cycle to obtain an estimated statewide total for each category. The estimated totals were calculated by dividing the reported total by the average reporting rate of 35%. Even though the combined reporting rate is based on 2010 and 2011 alone, it was applied to 2010, 2011, and 2012.

Table 9: Completeness of West Virginia Frac Water Reporting Database (2010-2011)

Year of permit issuance	Active, horizontal, Marcellus wells	Wells that reported to the Frac Water Database	Percent of wells that reported to the Frac Water Database
2010	166	71	43%
2011	242	70	29%
Total	**408**	**141**	**35%**

Sources: Active, horizontal, Marcellus wells from WVDEP (2013c). Wells that reported to the Frac Water Database from WVDEP (2013a). Note: Even though 91 horizontal Marcellus wells with a permit date in 2012 are listed as active in the permit database, we assume that the reporting rate calculated using this method for these wells would not be accurate due to the one-year lag time in reporting following water injection.

4.4 Injections

The total reported volume of water injected for 2010, 2011, and 2012 was calculated by summing the injection amounts reported for all wells with injection "begin dates" in each year. The per-well average in Table 10 was calculated by dividing the total reported volume by the number of active wells as represented by the dataset. Because the Frac Water Reporting Database does not contain data for all wells in West Virginia, we calculated an estimated total volume to represent all active horizontal Marcellus wells in the state. As described above, the estimated total was calculated by dividing the total reported volume by the average reporting rate of 35%.

A total of 1.4 billion gallons of fluid were reported to have been injected into horizontal wells in the Marcellus since 2010. Given that the Frac Water Reporting Database is incomplete, we calculate that the actual total may be estimated at 3.9 billion gallons during this period.

Table 10: Injection volumes for horizontal Marcellus wells in West Virginia (million gallons, 2010-2012)

Injection volume	2010	2011	2012 (partial year)	Total
Average per well	5.0	4.7	6.0	**5.0**
Total, reported wells	423	661	275	**1,359**
Total, estimated	1,209	1,889	786	**3,884**

Note: As of August 14, 2013, the WVDEP Frac Water Reporting Database did not contain any wells with an injection "begin date" later than October 25, 2012. Given that operators have one year to report to this database, the 2012 data are likely very incomplete.

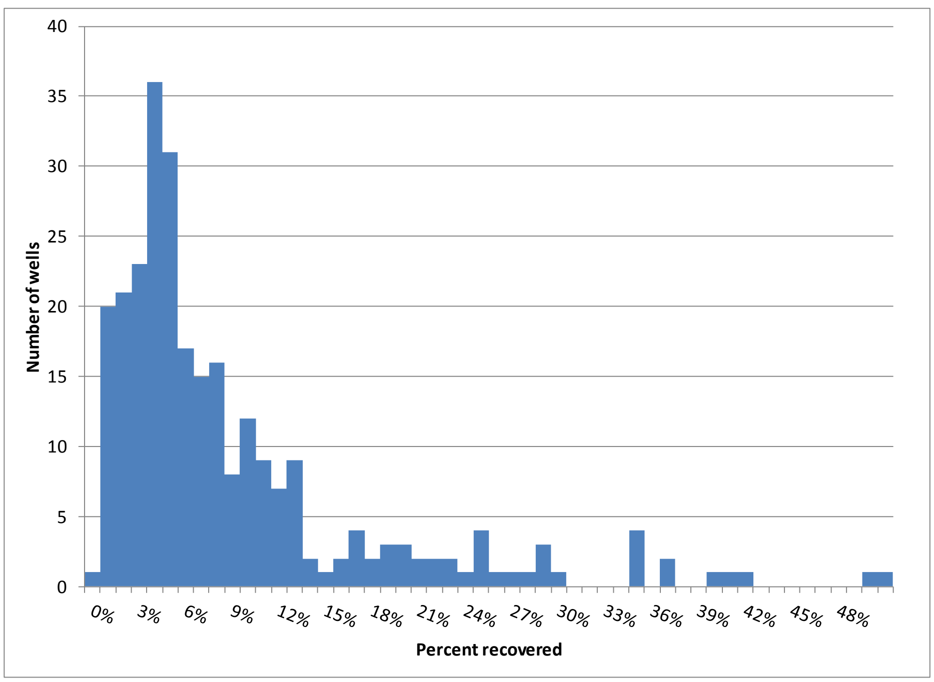
4.5 Recovery and disposal

As opposed to Pennsylvania where all waste types are reported, West Virginia rules only require that operators report flowback fluid, defined as all fluid recovered in 30 days following injection or 50% of the injected volume, whichever occurs first. Therefore, recovery and disposal data analyzed in this chapter are for flowback fluid only.

A large portion—greater than 90%—of the water injected into Marcellus wells does not return to the surface in the time frame captured by the reporting requirements. After injection, this water remains deep underground and, thus, is lost to the hydrologic cycle. As illustrated in Figure 6, most wells recovered 7% or less.

During 2010 through 2012, an average of 8% of the total injected volume was recovered at horizontal wells in the Marcellus. In 2010, recovery averaged approximately 12%, and in 2011 and 2012, the percentages recovered were even lower: 6% and 8%, respectively.

Figure 6: Percent of injected fluid that is recovered for Marcellus wells in West Virginia (2010-2012)



Source: WVDEP (2013a). Note: One well reported that 98% of the fluid injected was recovered; this outlier is not included in the chart.

Following injection, flowback fluid along with naturally occurring brine returns to the surface. Well operators must collect this waste and properly dispose of it. As shown in Table 11, Figure 7, and Figure 8, most flowback fluid has been recycled and reused in other wells in each of the three years included in this study. The percent of total flowback that was reused has gradually decreased from 2010 through 2012, however, from 88% to 65%.[15] During this time, the portion of total flowback disposed of in UIC wells has gradually increased. In 2010, UIC wells accepted only 12% of flowback fluids, but by 2012, they accepted 35% of flowback fluids from Marcellus wells in West Virginia. Disposal at POTWs was utilized only in 2010 and 2011, and even then, POTWs only received 1% or less of total waste.

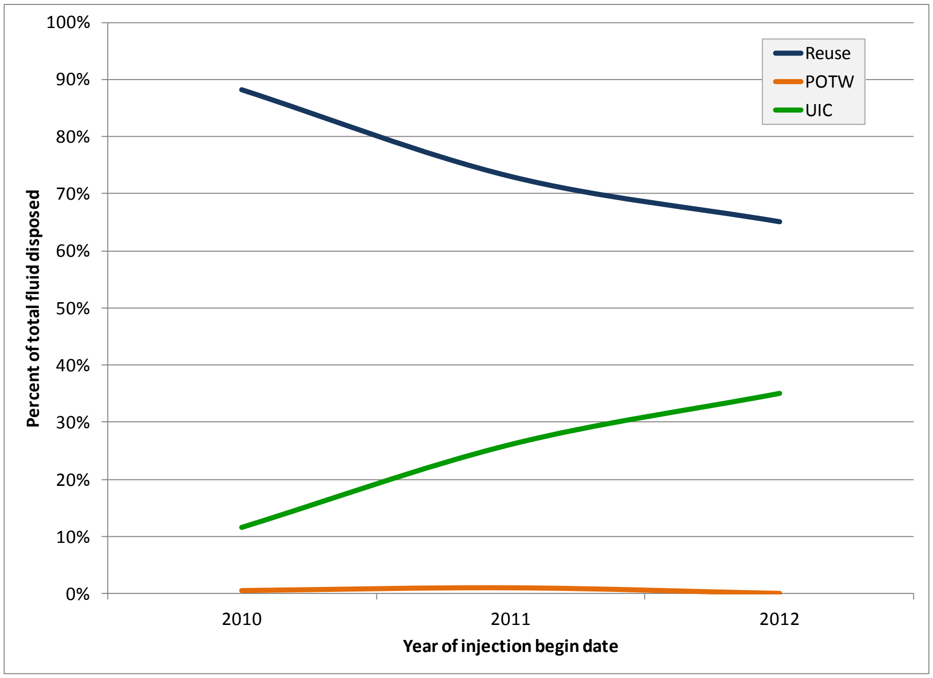
Table 11: Flowback fluid disposal volumes by method in West Virginia (gallons, % of total, 2010-2012)

Disposal method	2010	2011	2012 (partial year)	Total
POTW				
Average per well	1,365	3,363	0	**2,168**
Total, reported wells	114,660	470,834	0	**585,494**
Total, estimated	327,600	1,345,240	0	**1,672,840**
Percent of total	<1%	1%	0%	**1%**
UIC				
Average per well	60,145	74,515	155,861	**83,903**
Total, reported wells	5,052,207	10,432,040	7,169,624	**22,653,871**
Total, estimated	14,434,877	29,805,829	20,484,640	**64,725,346**
Percent of total	12%	26%	35%	**22%**
Reuse				
Average per well	457,824	206,818	292,057	**299,431**
Total, reported wells	38,457,186	28,954,545	13,434,604	**80,846,335**
Total, estimated	109,877,674	82,727,271	38,384,583	**230,989,528**
Percent of total	88%	73%	65%	**78%**
Total disposed				
Average per well	519,334	284,696	437,235	**385,503**
Total, reported wells	43,624,053	39,857,419	20,604,228	**104,085,700**
Total, estimated	124,640,151	113,878,340	58,869,223	**297,387,714**
Percent of total	100%	100%	100%	**100%**

WVDEP (2013a). Note: As of August 14, 2013, the WVDEP Frac Water Reporting Database did not contain any wells with an injection "begin date" later than October 25, 2012. Given that operators have one year to report to this database, the 2012 data are likely very incomplete.

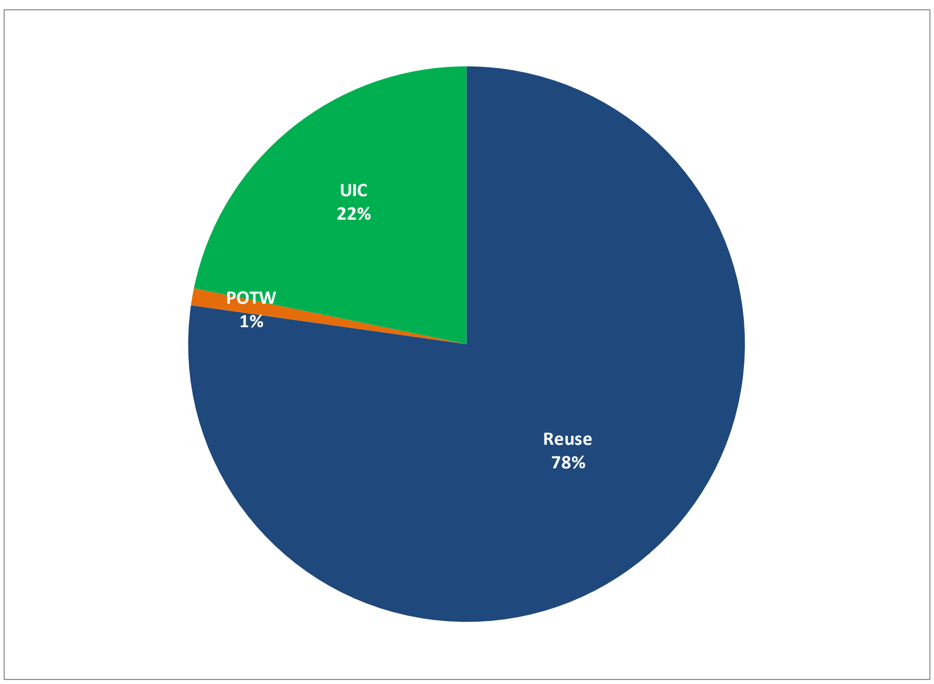
[15] The reuse percentages in Table 11 represent the percent of flowback fluid that is recycled and reused. This is different from the percentage of total withdrawals that come from reused flowback fluid in Table 7. While Table 11 suggests that most flowback fluid is recycled and reused, Table 7 clarifies that this reused flowback fluid still represents a small percentage of total withdrawals.

Figure 7: Flowback fluid disposal by method over time in West Virginia (2010-2012)



WVDEP (2013a). Note: As of August 14, 2013, the WVDEP Frac Water Reporting Database did not contain any wells with an injection "begin date" later than October 25, 2012. Given that operators have one year to report to this database, the 2012 data are likely very incomplete.

Figure 8: Flowback fluid disposal by method in West Virginia (average, 2010-2012)



WVDEP (2013a). Note: As of August 14, 2013, the WVDEP Frac Water Reporting Database did not contain any wells with an injection "begin date" later than October 25, 2012. Given that operators have one year to report to this database, the 2012 data are likely very incomplete.

Both the disposal dataset (Table 11) and the withdrawal dataset (Table 7) document flowback fluid that, rather than being disposed, was instead recycled and reused. However, as documented in Table 12, these two datasets do not agree well, particularly in 2011 and 2012. In 2011, the disposal dataset suggests that 29 million gallons of flowback fluid was recycled and reused, but the withdrawal dataset suggests that twice that volume—approximately 60 million gallons—was recycled and reused. The discrepancy in 2012 is even greater; however, reporting has not been completed for wells for which injection began in 2012.

It is possible that these discrepancies can be explained by time lags between when fluids are recycled and reused, operators that report one but not the other value, fluid captured at wells in West Virginia or Pennsylvania that is reused at wells in the other state, or other explanations. At the current time, they remain unexplained.

Table 12: Discrepancies related to recycled and reused flowback fluid reporting (million gallons, 2010-2012)

Reported recycled and reused flowback fluid	2010	2011	2012 (partial year)	Total
In disposal dataset	38	29	13	**81**
In withdrawal dataset	35	60	57	**152**

Sources: Recycled and reused flowback fluid reported in disposal dataset from Table 11, and reused flowback fluid reported in withdrawal dataset from Table 7.

As shown in Figure 9, while much of the flowback fluid generated by West Virginia's horizontal Marcellus wells stayed in West Virginia, a significant amount was shipped to the neighboring states of Ohio and Pennsylvania.[16] In fact, from 2010 through 2012, only 57% of flowback fluid from horizontal Marcellus wells in West Virginia actually stayed in West Virginia. As illustrated in the bottom section of Table 13, 21% was shipped to Ohio and 22% was shipped to Pennsylvania.

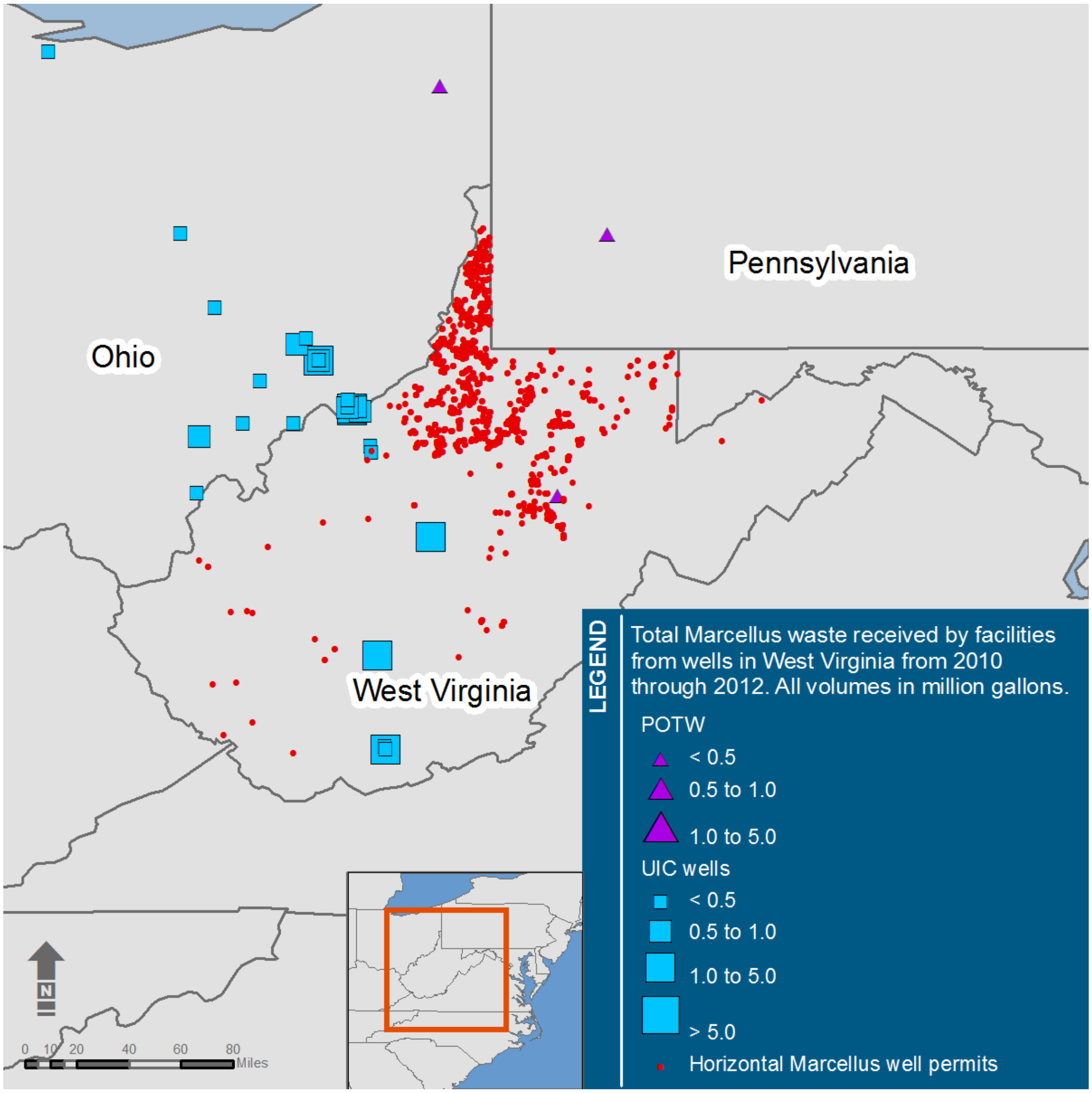
Of all flowback fluid generated in these years, one-half was reused at wells in West Virginia, and 21% was reused at wells in Pennsylvania. An additional 21% was sent to UIC wells in Ohio. Together, these three destinations account for more than 90% of the flowback fluid generated at Marcellus wells in West Virginia.

Of the flowback fluid disposed of in UIC wells, approximately three-quarters was shipped to Ohio in 2010 through 2012; the remaining one-quarter was sent to UIC wells within West Virginia (Table 13).

Fluids were also sent to POTWs in all three states; however, the total amount of fluids sent to POTWs is extremely small as compared to the other disposal options.

[16] Obvious errors in the dataset related to locations of UIC wells and POTWs were corrected.

Figure 9: Destination of flowback fluid from West Virginia Marcellus wells (2010-2012)



Sources: WVDEP (2013a and c). Note: Marcellus wells that reuse flowback fluid from West Virginia wells are not distinguished from other wells in this map. Only those UIC wells in this dataset are displayed.

Table 13: Interstate transport of flowback fluid from West Virginia Marcellus wells (2010-2012)

Destination state	Percent of total disposed	Percent of disposal type total
UIC		
West Virginia	6%	24%
Ohio	21%	76%
Pennsylvania	0%	0%
Subtotal, UIC	**27%**	**100%**
POTW		
West Virginia	<1%	<1%
Ohio	<1%	46%
Pennsylvania	<1%	54%
Subtotal, POTW	**1%**	**100%**
Reuse		
West Virginia	50%	70%
Ohio	1%	1%
Pennsylvania	21%	30%
Subtotal, reuse	**72%**	**100%**
Total		
West Virginia	57%	
Ohio	21%	
Pennsylvania	22%	

Source: WVDEP (2013a). Note: As of August 14, 2013, the WVDEP Frac Water Reporting Database did not contain any wells with an injection “begin date” later than October 25, 2012. Given that operators have one year to report to this database, the 2012 data are likely very incomplete. The percentages in the middle column of this table are similar to, but not exactly the same as, those reported in the final column of Table 11 and charted in Figure 8. This is because some data included in Table 11 and Figure 8 were omitted from this table due to insufficient disposal site location information.

4.6 Water removed from the hydrologic cycle

During hydraulic fracturing, water is injected deep below the Earth’s surface. As described above, only 8% of this water injected between 2010 and 2012 has returned to the surface where it is recovered by well operators. The water that is injected but not recovered is removed from the hydrologic cycle. In addition, the flowback fluid injected into UIC wells is also removed from the hydrologic cycle. Therefore, the total volume of water removed from the hydrologic cycle was calculated by adding the volume of water that was injected but not recovered to the volume of water disposed of in UIC wells.

As shown in Table 14, Marcellus wells in West Virginia, on average, removed about 4.7 million gallons from the hydrologic cycle in recent years. In total, according to the database of operator-reported water use, more than 1.2 billion gallons were removed from the hydrologic cycle from 2010 through 2012. When accounting for the fact that this database is incomplete, the true total for the state may be closer to an estimated 3.7 billion gallons during this time period.

In 2012, the average per-well volume removed from the hydrologic cycle increased by more than one million gallons per well, as compared with 2010 and 2011. On average, proportionately more waste was disposed of in UIC wells in 2012 than in previous years (See Table 11); however, the increase in water removed from the hydrologic cycle is primarily explained by the large increase in injection volume between 2011 and 2012 (See Table 10).

Table 14: Water removed from the hydrologic cycle by Marcellus wells in West Virginia (million gallons, 2010-2012)

	2010	2011	2012 (partial year)	Total
Average per well	4.6	4.5	5.7	**4.7**
Total, reported wells	385	632	262	**1,280**
Total, estimated	1,101	1,806	749	**3,657**

Source: WVDEP (2013a). Note: As of August 14, 2013, the WVDEP Frac Water Reporting Database did not contain any wells with an injection "begin date" later than October 25, 2012. Given that operators have one year to report to this database, the 2012 data are likely very incomplete.

5. INJECTION, RECOVERY, AND DISPOSAL OF FLUIDS IN PENNSYLVANIA

5.1 Drilling progress in the Marcellus Shale

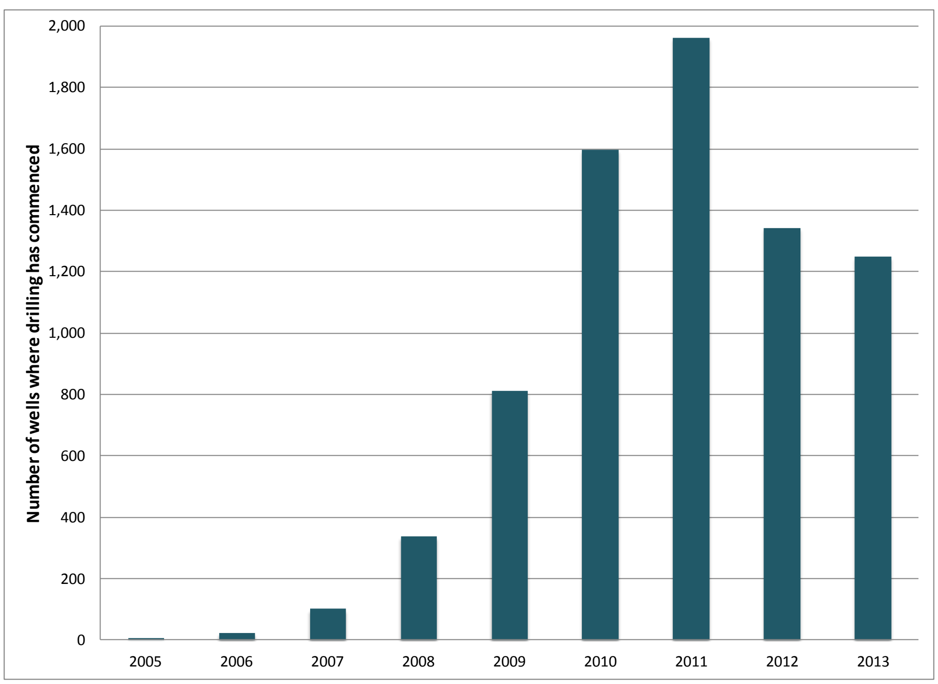
The development of Marcellus wells in Pennsylvania began in 2005 when the first Marcellus well, a Range Resources vertical well, was completed (Soeder 2012). During that same year, drilling commenced for three additional Marcellus wells.

Since 2009, PADEP has issued more than one thousand permits each year for horizontal Marcellus wells, and more than two thousand such permits were issued in 2011 (See Table 1). As of August 8, 2013 8,418 horizontal Marcellus gas wells had been permitted in Pennsylvania.

As illustrated in Figure 10, drilling has increased rapidly in recent years. In 2010, drilling commenced for 1,594 Marcellus wells, and in 2011 that figure increased again to 1,959. Based on the number of wells reported for the first half of 2013, it is estimated that more than 1,200 Marcellus wells may be drilled in 2013.

The issuance of Marcellus well permits has outstripped the actual drilling of wells. This has resulted in a backlog of permitted wells. This backlog, however, is being addressed. At the end of 2011, only 49% of active wells were producing. By the end of 2012, this percentage reached 63%, and by June 30, 2013, it reached 67% (Henderson 2013).

Figure 10: Pennsylvania Marcellus wells that commenced drilling in specified year



Source: PADEP (2013d). Note: 2013 values estimated by doubling the reported values for January through June 2013. This figure contains data for all Marcellus gas wells in Pennsylvania. Table 1, Figure 1, and Figure 4 show data for horizontal Marcellus wells only.

Statewide data are not available on the number of wells that have been hydraulically fractured. However, within the SRB watershed, SRBC reports that 778 wells were hydraulically fractured in 2011, and 806 were hydraulically fractured in 2012 (See Table 15).

Table 15: Marcellus wells hydraulically fractured within the Susquehanna River Basin

Year	Number of wells
2008	10
2009	147
2010	449
2011	778
2012	806
2013 (partial year)	221

Source: SRBC (2013b). Note: 2013 includes first and second quarters only.

5.2 Withdrawals

In West Virginia, a single statewide database is available to track water withdrawals, fluid injections, flowback fluid recovery, and flowback fluid disposal. In Pennsylvania, however, no such database is available. Instead, data analyzed in this chapter is collected from multiple sources—some data for Pennsylvania as a whole and other data for the SRB only.

One database of interest is PADEP's database of all water acquisitions by water users that withdraw greater than 10,000 gallons per day in any given 30-day period in all Pennsylvania river basins except the SRB (PADEP 2013g). While this database tracks water withdrawals by individual withdrawal points and purchases, it is not possible to relate this data to individual wells or well pads. It can be filtered to acquisitions for use by the oil and gas industry, but it is not possible to filter for withdrawals for drilling and fracturing in the Marcellus formation. Therefore, the database is not used in this report.

Without these data, we are left with withdrawal and consumption data from Marcellus wells within the SRB, which is collected by SRBC As shown in Table 16, SRBC separates withdrawals into non-docketed and docketed categories. Docketed withdrawals are from surface and groundwater, while non-docketed sources are mainly comprised of public water systems, but can include sources such as abandoned mine discharges, industrial and municipal wastewaters, and pad stormwater.

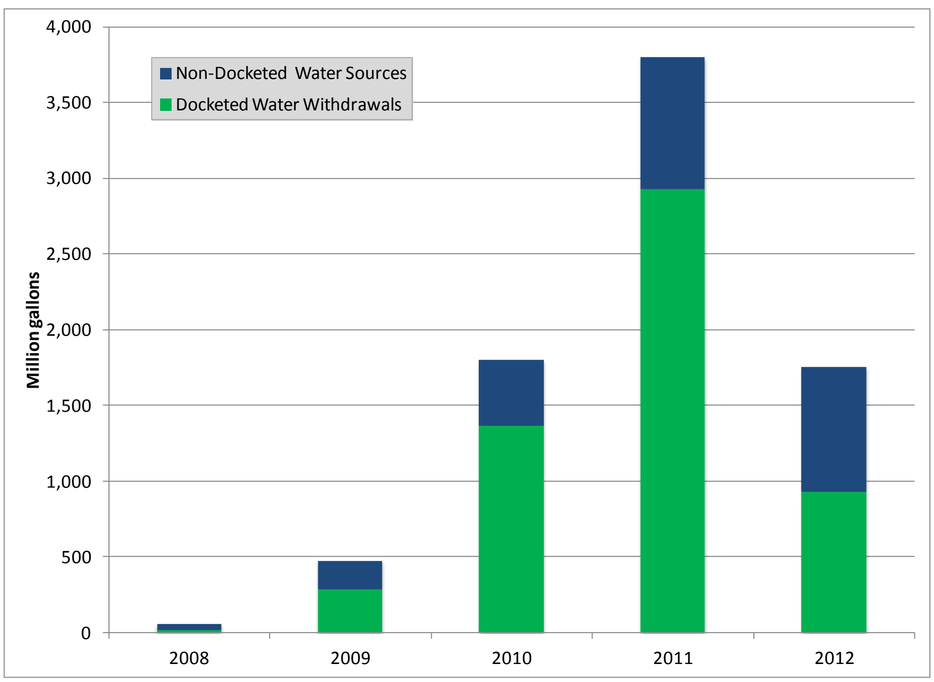
In the SRB, more than 8.3 billion gallons of water were withdrawn for use at Marcellus wells between 2008 and the first quarter of 2013. Of this total, 6.0 billion gallons were withdrawn from surface and groundwater. In 2010 and 2011, docketed surface and groundwater withdrawals made up a much larger percentage of total water consumed than other sources.

Table 16: Water withdrawals by Marcellus wells in the Susquehanna River Basin (million gallons, %, 2009-2012)

Source type	2009	2010	2011	2012	Total
Docketed					
Average per well	1.9	4.1	3.8	1.2	**2.7**
Total, reported	283	1,856	2,925	927	**5,991**
Percent of total	60%	81%	77%	53%	**72%**
Non-docketed					
Average per well	1.3	1.0	1.1	1.0	**1.1**
Total, reported	191	438	873	826	**2,328**
Percent of total	40%	19%	23%	47%	**28%**
Total					
Average per well	3.2	5.1	4.9	2.2	**3.8**
Total, reported	475	2,293	3,798	1,754	**8,320**
Percent of total	100%	100%	100%	100%	**100%**

Source: SRBC (2013c). Note: Docketed withdrawals are from surface and groundwater. Non-docketed sources are mainly comprised of public water systems, but can include sources such as abandoned mine discharges, industrial and municipal wastewaters, and pad stormwater. Average values were calculated by dividing the total volumes by the total number of wells in the SRB that have been hydraulically fractured, as reported in Table 15. Consumptive use may not equal the sum of docketed and non-docketed withdrawals due to rounding in original data source. Docketed water withdrawals in fourth quarter 2010 were adjusted from 753 to 556 million gallons to correct an apparent mistake in the original data source.

Figure 11: Water withdrawals by Marcellus wells in the Susquehanna River Basin



Source: SRBC (2013c).

5.3 Injections

Since April 2012, operators in Pennsylvania have been required to submit reports to FracFocus that include, among other things, injection volumes. Before then, many well operators voluntarily disclosed water injection volumes to FracFocus. As described above, the FracFocus data analyzed here was obtained from SkyTruth (2013).

For each year, the rate at which Pennsylvania operators report to FracFocus was estimated by dividing the number of Pennsylvania wells in the FracFocus database that began fracturing in that year by the number of wells that commenced drilling that year, as reported to PADEP (See Figure 10, above).[17]

While the FracFocus database is still not complete, the percentage of operators reporting to FracFocus has increased significantly in recent years. As shown in Table 17, in 2010, just 3% of drilled Pennsylvania wells reported to FracFocus, but two years later, 85% of wells were reported to this database. This coincides with the implementation of Act 13, which requires well operators to disclose chemical additives and injection volumes to FracFocus.

Table 17: Reporting rate for Pennsylvania Marcellus wells reported to FracFocus (2009-2012)

	2009	2010	2011	2012	Total
Number of wells reported to FracFocus	16	55	1,147	1,135	**2,353**
Reporting rate	2%	3%	59%	85%	**41%**

Sources: Number of wells in FracFocus from SkyTruth (2013). Number of wells drilled from PADEP (2013d).

As illustrated in Table 18, 4.3 million gallons of fluid, on average were injected into each Pennsylvania Marcellus well in recent years. A total of 10 billion gallons have been reported via FracFocus, and this corresponds to an estimated total of approximately 24 billion gallons, after taking into account the reporting rates shown in Table 17.

Table 18: Injection volumes for Pennsylvania Marcellus wells reported to FracFocus (million gallons, 2009-2012)

	2009	2010	2011	2012	Total
Average per well	2.8	3.9	4.5	4.1	**4.3**
Total, reported	44	220	5,118	4,666	**10,051**
Total, estimated	2,245	6,373	8,740	5,513	**24,366**

Source: SkyTruth (2013).

In addition to injection data available from FracFocus via SkyTruth, additional injection data are available for Marcellus wells in the SRB from SRBC. As shown in Table 19, from 2009 through 2011, the total injection volume in the SRB steadily rose to 3.6 billion gallons annually. In 2012, the total volume injected decreased slightly to 3.4 billion gallons.

In each year since 2010, recycled flowback fluid has made up a larger percentage of total injection volumes. In 2012, reuse rose to 18% of the total volume injected. For comparison, the percentage of West Virginia withdrawals made up of reused flowback fluid has also increased, but only reached 10% in 2012 (Table 7).[18]

[17] These percentages do not reflect the possibility that a well may have been drilled the year before it was fractured; therefore, the year-by-year percentages should be treated as rough estimates. The total percentage, however, more accurately represents the percentage of drilled wells that have reported to FracFocus within this time period.

[18] Injection volumes of freshwater and recycled flowback fluid are reported separately to SRBC. In West Virginia, the volume of recycled flowback fluid is reported as a withdrawal. Although the terminology is different, the percentages convey similar results.

Table 19: Injection volumes for Marcellus wells in the Susquehanna River Basin (million gallons, 2009-2012)

	2009	2010	2011	2012	Total
Freshwater injected	486 90%	1,732 90%	3,064 86%	2,796 82%	**8,078** **86%**
Flowback injected	55 10%	189 10%	492 14%	627 18%	**1,363** **14%**
Total	**541** **100%**	**1,921** **100%**	**3,556** **100%**	**3,423** **100%**	**9,440** **100%**
Average per well	3.7	4.3	4.6	4.2	**4.3**

Source: SRBC (2013b). Note: Data presented in this table and in Table 16 are from SRBC; however, the percentage of freshwater is significantly different. Some portion of the non-docketed withdrawal volumes in Table 16 represent fresh water from public water systems, but this portion is not known. Further, withdrawal volumes in Table 16 are reported for well sites, but injection volumes in this table are reported for individual wells. Assuming that water withdrawn is injected, the percentage of each source type should be similar.

5.4 Recovery and disposal

A significant portion of the water injected during hydraulic fracturing does not return to the surface. Statewide electronic data are not publicly available for injection and recovery volumes for Marcellus wells across Pennsylvania; however, SRBC reports recovery percentages for wells within the SRB. Between 2009 and 2012, an average of 6% of the fluid injected into Marcellus wells in the SRB was captured at the surface (See Table 20). This is similar to, but slightly less than, the average of 8% for West Virginia Marcellus wells between 2010 and 2012 (See Section 4.5 and Figure 6).

Table 20: Fluid recovery in the Susquehanna River Basin

Year	Percent recovered
2009	9%
2010	5%
2011	4%
2012	5%
Total	**6%**

Source: SRBC (2013b).

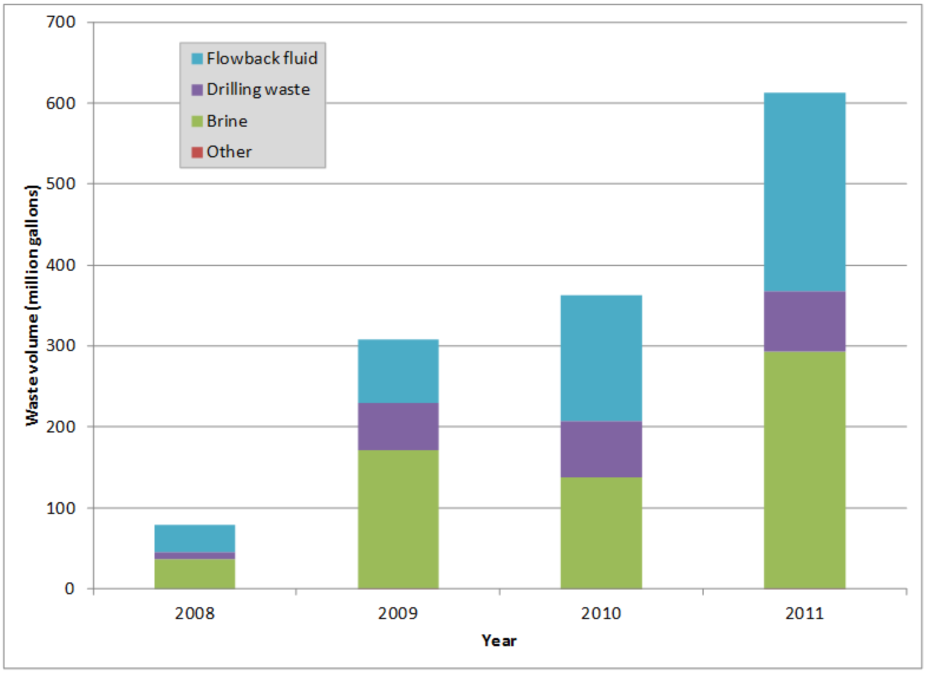
While fluid recovery data are not available statewide, flowback disposal data are. These data are reported to PADEP together with other waste disposal volumes. These data are available for download from PADEP for the years 2000-2012 (PADEP 2013f). Lutz et al. (2013) and Lewis (2012) analyzed these data and found several inaccuracies that required editing. Rather than downloading the raw data and performing the same edits, we instead started with the peer-reviewed data set provided by Lutz. All waste disposal data reported here are from this edited dataset, which was originally sourced from PADEP (Lutz 2013a). Appendix D describes the quality control steps taken by Lutz, which are incorporated into this edited dataset.

Pennsylvania rules require operators to report total volumes of waste produced every six months along with production data for the life of the well.[19] In contrast, West Virginia rules only require that operators report flowback fluid, defined as all fluid recovered in 30 days following injection or 50% of the injected volume, whichever occurs first. As illustrated in Figure 12 and Figure 13, flowback fluid

[19] The rectified Pennsylvania dataset, originally obtained from PADEP, includes information for many types of waste: drilling waste, brine, basic sediment, fracking fluid, servicing fluid, and spent lubricant (Lutz et al. 2013). These categories are slightly different from the current PADEP categories: basic sediment, produced fluid, drill cuttings, flowback fluid, drilling fluid, flowback fracturing sand, servicing fluid, and spent lubricant (PADEP 2013f).

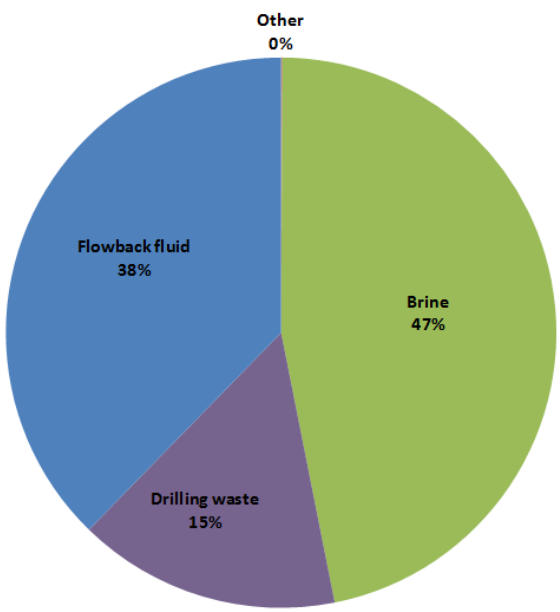
constitutes only approximately 38% of the total volume of waste generated by Marcellus wells in Pennsylvania.[20]

Figure 12: Waste generated from Pennsylvania wells by fluid type (2008-2011)



Source: Lutz et al. (2013). Note: The category "other" includes basic sediment, servicing fluid, and spent lubricant.

Figure 13: Total waste generated from Pennsylvania Marcellus wells, by type (2008-2011)



Source: Lutz et al. (2013). Note: The category "other" includes basic sediment, servicing fluid, and spent lubricant.

[20] Of the 1,363 million gallons of waste reported from 2008 through 2010, 514 million gallons of flowback fluid were reported (Lutz et al. 2013).

Table 21 presents a full breakdown of waste disposal for Marcellus wells in Pennsylvania by method: brine/industrial waste treatment plant, UIC well, municipal sewage treatment plant, other, and reuse. The total volume of wastewater generated by Marcellus wells has continued to increase each year. From 2010 to 2011, the volume increased by almost 70%.

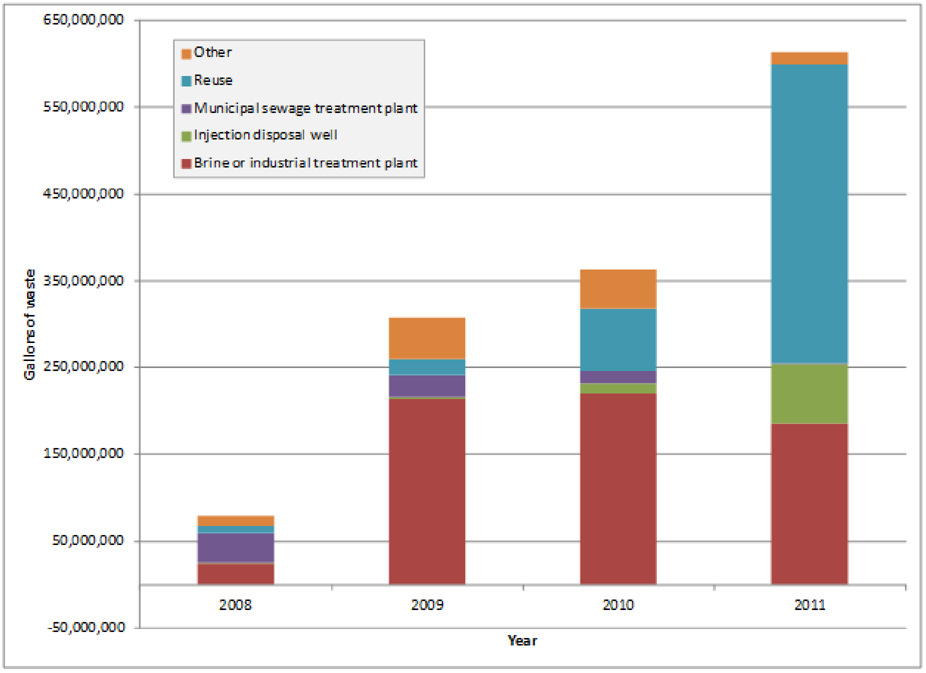
Table 21: Waste disposal method in Pennsylvania (gallons, % of total, 2008-2011)

Disposal method	2008	2009	2010	2011	Total
Brine/industrial waste treatment plant					
Average per well	93,690	375,088	130,343	58,647	**113,202**
Total, reported	25,296,280	214,175,137	220,931,766	186,321,692	**646,724,875**
Percent of total	32%	70%	61%	30%	**47%**
UIC					
Average per well	706	2,962	6,865	21,444	**14,291**
Total, reported	190,726	1,691,220	11,636,441	68,126,753	**81,645,140**
Percent of total	<1%	1%	3%	11%	**6%**
Municipal sewage treatment plant					
Average per well	127,889	44,275	8,004	465	**13,102**
Total, reported	34,530,105	25,280,839	13,567,123	1,476,510	**74,854,577**
Percent of total	43%	8%	4%	<1%	**5%**
Other					
Average per well	45,463	83,620	26,637	4,212	**20,752**
Total, reported	12,275,088	47,747,056	45,149,889	13,382,541	**118,554,574**
Percent of total	15%	16%	12%	2%	**9%**
Reuse					
Average per well	26,559	32,982	42,165	108,211	**77,238**
Total, reported	7,171,024	18,832,831	71,469,602	343,786,587	**441,260,044**
Percent of total	9%	6%	20%	56%	**32%**
Total					
Average per well	294,308	538,927	214,015	192,979	**238,586**
Total, reported	79,463,223	307,727,083	362,754,821	613,094,083	**1,363,039,210**

Source: Lutz et al. (2013). Note: Per-well averages refer to the volume of waste produced by an average well during each year. Older wells produce significantly less waste than newer wells. These averages include both new and old wells.[21]

[21] Marcellus wells produce a large volume of waste during the first year of production, and then this volume decreases throughout the life of the well. Lutz et al. (2013) found that a Pennsylvania Marcellus well produced an average of 360,595 gallons of brine during the first year, which decreased to 39,626 gallons of brine during the fourth year of production. On average, Pennsylvania Marcellus wells produced 759,230 gallons of brine during the first four years of production (Lutz et al. 2013). The per-well averages shown in Table 21 represent something different—the average amount of waste generated by the wells active in a single year, including both old and new wells.

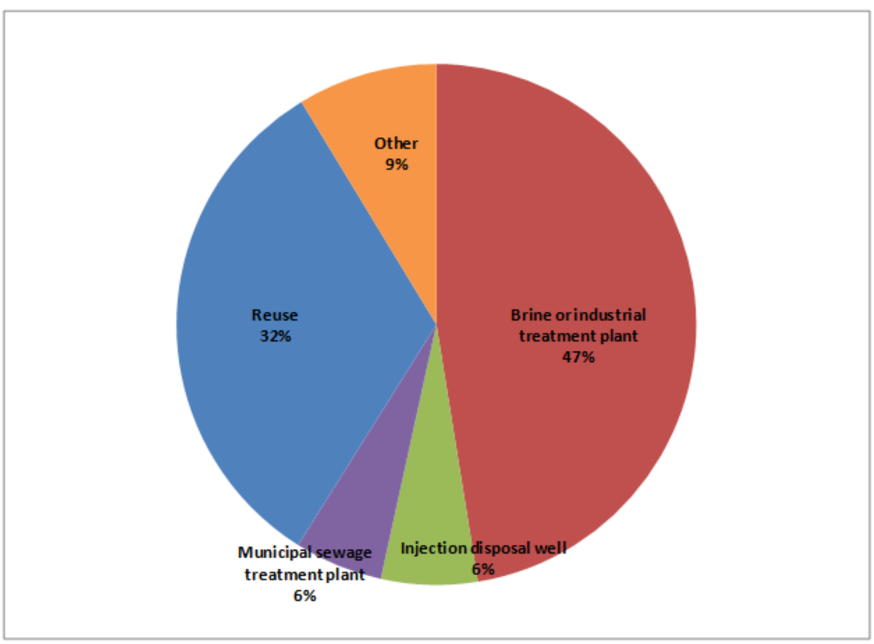
Figure 14: Waste disposal by method over time in Pennsylvania (2008-2011)



Source: Lutz et al. (2013).

As illustrated in Figure 14, as the total volume of waste produced by Marcellus wells has increased, an increasing proportion of this waste has been reused in other wells and sent to UIC wells for disposal. As both reuse and UIC wells have become more popular disposal methods, the volume treated at municipal sewage treatment plants and brine or industrial treatment plants has declined.

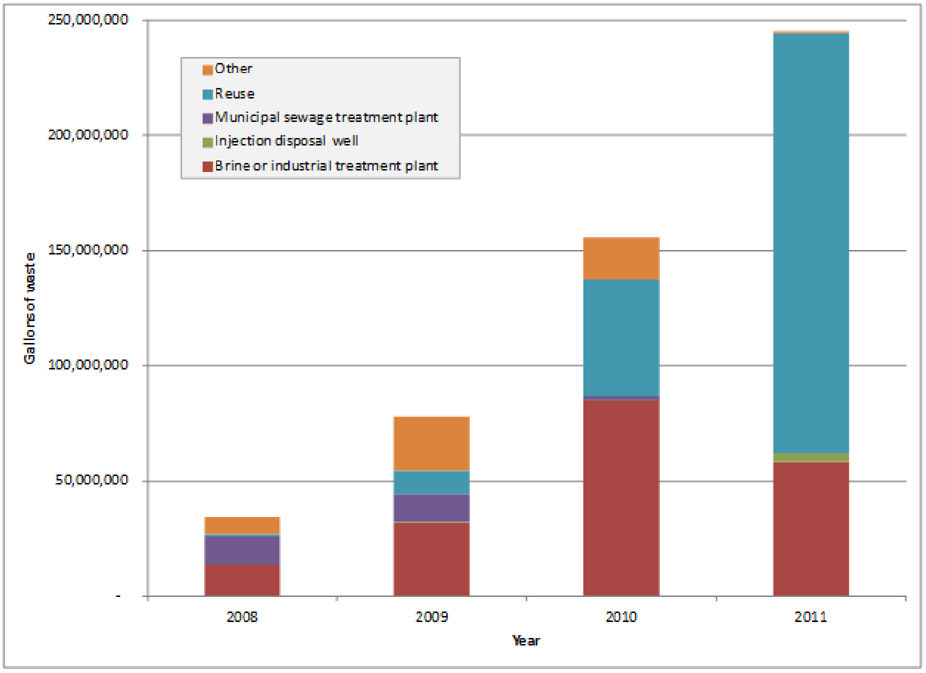
Figure 15: Waste disposal by method in Pennsylvania (average, 2008-2011)



Source: Lutz et al. (2013).

On average, almost one-half of recent Marcellus waste in Pennsylvania was sent to brine or industrial treatment plants, and almost one-third was reused and recycled in other wells (Figure 15).

Figure 16: Flowback fluid disposal by method over time in Pennsylvania (2008-2011)



Source: Lutz et al. (2013).

For comparison with West Virginia results, an analysis of disposal method of flowback fluid alone was conducted. As illustrated in Figure 16, this analysis shows that flowback fluid shows similar trends as for all waste types combined. However, higher percentages of this waste type have been reused at other wells. In 2011, 74% of all flowback fluid in Pennsylvania was reused.

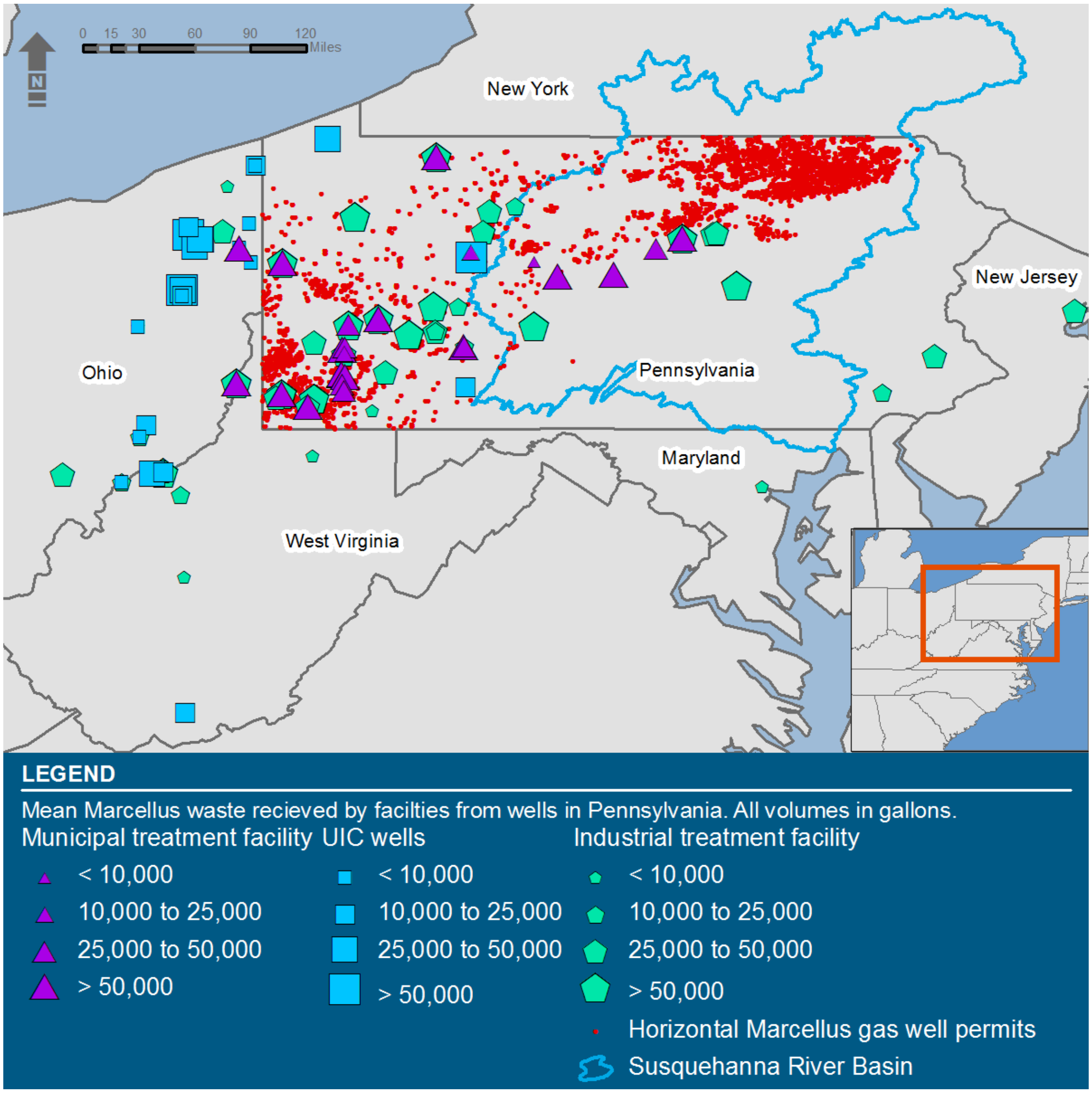
As shown in Figure 17, while much of the waste generated by Pennsylvania's horizontal Marcellus wells stayed in Pennsylvania, a significant amount was shipped to the neighboring states of Ohio and West Virginia. From 2008 through 2011, 88% of waste from horizontal Marcellus wells in Pennsylvania actually stayed in Pennsylvania.[22] As illustrated in the bottom section of Table 22, 9% was shipped to Ohio and 2% was shipped to West Virginia.

Most of the waste fluid generated in these years was kept in-state for treatment and discharge to surface waters: 39% was sent to brine or industrial waste treatment plants located in Pennsylvania and an additional 15% was sent to municipal sewage treatment plants in Pennsylvania (Table 22).

Approximately 32% of wastes were reused, and 4% were sent to UIC wells in Ohio for disposal. All other combinations of treatment destination states and systems took only 1% or less of total wastes from Pennsylvania.

[22] This percentage does not take into account waste fluid that was recycled and reused or disposed of in "other" category because locations are not available for these data.

Figure 17: Destination of waste from Pennsylvania Marcellus wells (2008-2011)



Sources: Lutz et al. (2013), PASDA (2013). Note: Marcellus wells that reuse flowback fluid from Pennsylvania wells are not distinguished from other wells in this map. Only those UIC wells in this dataset are displayed.

Table 22: Interstate transport of waste from Pennsylvania Marcellus wells (2008-2011)

Destination state	Percent of total disposed	Percent of disposal type total
Brine or industrial waste treatment		
Pennsylvania	38%	96%
Ohio	1%	2%
West Virginia	<1%	1%
Other	<1%	0%
Subtotal, brine or industrial waste treatment	**39%**	**100%**
UIC		
Pennsylvania	<1%	4%
Ohio	4%	96%
West Virginia	<1%	<1%
Other	0%	0%
Subtotal, UIC	**5%**	**100%**
Municipal sewage treatment plant		
Pennsylvania	15%	94%
Ohio	<1%	<1%
West Virginia	1%	6%
Other	0%	0%
Subtotal, municipal sewage treatment plant	**15%**	**100%**
Reuse	**32%**	**100%**
Other	**9%**	**100%**
Total (excluding reuse and other)		
Pennsylvania	88%	
Ohio	9%	
West Virginia	2%	
Other	<1%	

Source: Lutz et al. (2013). Note: Reuse and other volume is not separated by state because locations are not available for disposal data in these categories. The percentages in the middle column of this table are similar to, but not exactly the same as, those reported in the final column of Table 21 and charted in Figure 14 and Figure 15. This is because some data included in Table 21 and these figures were omitted from this table due to insufficient disposal site location information.

5.5 Water removed from the hydrologic cycle

During hydraulic fracturing, water is injected deep below the Earth's surface. Some, but not all of this water eventually returns to the surface where it is recovered by well operators.

Data are not available for the state as a whole, but between 2009 and 2012, an average of 6% of the fluid injected into Marcellus wells in the SRB was captured at the surface (See Table 20). Injected water that is not recovered is removed from the hydrologic cycle. Disposing of waste using UIC wells, which is becoming increasingly popular, also removes water from the hydrologic cycle. Therefore, the volume of water removed from the hydrologic cycle was calculated by adding the volume of fluid that was injected but not recovered from Marcellus wells to the volume of waste disposed of in UIC wells.

In contrast to West Virginia, where a single dataset was available from which to estimate totals across the state, Pennsylvania calculations require a slightly different approach. The average volume of water disposed of at UIC wells as reported to PADEP (See Table 21) was added to the average volume that was not recovered according to the SRBC data (See Table 19 and Table 20). To generate a statewide estimate based on these per-well averages, we multiplied the averages by the total number of wells drilled in the state (See Figure 10, above).

As shown in Table 23, approximately four million gallons of water was lost from the hydrologic cycle at each well during the years 2009 through 2011. This is close to the estimated 4.3 million gallons injected, on average, per well in Pennsylvania (See Table 18 and Table 19). Between 2009 and 2011, an estimated total of 17.8 billion gallons of water were removed from the hydrologic cycle across Pennsylvania.

Table 23: Water removed from the hydrologic cycle by Marcellus wells in Pennsylvania (million gallons, 2009-2011)

	2009	2010	2011	Total
Average per well	3.4	4.1	4.4	**4.1**
Total, estimated	2,716	6,489	8,653	**17,858**

Source: Calculated in this report.

6. WATER FOOTPRINT OF MARCELLUS SHALE GAS PRODUCTION

6.1 The water footprint approach

The approach used to understand and represent impacts of shale gas extraction on water resources in West Virginia and Pennsylvania is a "virtual" or water footprint framework (Hoekstra et al. 2011). The water footprint approach aims to integrate dimensions of water withdrawals, consumptive use, and water quality impacts into representative metrics of water impact. The purpose of the water footprint is to understand impacts and trends, raise awareness, and develop policy that encourages best practices and the disclosure of water impacts.

Other studies have attempted to compare natural gas to other electricity sources or transportation fuels on a water per unit energy basis (Clark et al. 2011; Scown et al. 2011). The results of this body of research have several generalizable conclusions about the relationship between natural gas and water resources:

- Electricity from natural gas generally requires less water in the extraction phase than coal extraction (Gleick 1995; Fthenakis and Kim 2010);
- More water is withdrawn for cooling natural gas powered thermoelectric power plants with open loop cooling than is used for conventional natural gas extraction (Younos et al. 2009);
- Electricity from natural gas with open loop cooling requires fewer water withdrawals and lower water consumption than coal and nuclear, but has an order of magnitude lower water requirement than for geothermal (Dominguez-Faus et al. 2009); and
- Water withdrawal and consumption for solar, wind, and hydropower is negligible in comparison to natural gas (Fthenakis and Kim 2010).

The purpose of a water footprint approach is to better understand how to represent the cumulative and relative significance of impacts caused by water use and water pollution. While it has been used to measure water impacts of products for some time, it has more recently been applied as an indicator of water use in the energy sectors—for example biofuels (Gerbens-Leenes et al. 2009) and hydroelectricity (Herath et al. 2011). New water footprint guidelines are available through the World Business Council for Sustainable Development (Hoekstra et al. 2011) and ISO 14046 (ISO 2013).

The basic framework for a water footprint analysis is to understand and represent impacts to water resources where there are impacts to both water quantity and water quality from producing a particular commodity. While an overall water footprint metric can be produced from this framework, there are three components. The ***blue water footprint*** refers to the volume of surface and groundwater consumed (or evaporated) as a result of the production of a commodity. The approach to the blue water footprint is similar to other efforts to understand the water use intensity of fossil fuel extraction from shale. The ***grey water footprint*** of a product refers to the volume of freshwater that is required to assimilate the load of pollutants to an acceptable threshold or standard. The ***green water footprint*** refers to the rainwater consumed and is typically reserved for agricultural commodities where a significant amount of water is lost through respiration.

We use the water footprint approach as a framework to quantify water consumed and understand the relative significance compared to impacts to water quality. Water use is typically described as water withdrawals and water consumed. "Withdrawals" refer to any freshwater that is temporarily or permanently removed from its source, whereas "consumption" is limited to water that is not returned to its original watershed in the short term or permanently removed form the hydrologic cycle (Hoekstra et al. 2011; Scown et al. 2011).

This water footprint analysis focuses on the fuel acquisition stage of the life cycle of natural gas production. The fuel acquisition stage is the point where natural gas is taken from its reservoirs in the shale rock formations. Other research has estimated the amount of both water withdrawals and water consumption for conventional natural gas extraction (Fthenakis and Kim 2010; Younos et al. 2009). But for shale gas extraction, most prior studies of water use focused only on water withdrawals. In this research, our water footprint methodology focuses on water consumed, which we refer to as water removed from the hydrologic cycle.

Much of this research has been normalized based on electricity. Fthenakis and Kim (2010) put water withdrawals to extract natural gas at 34.3 gallons per megawatt-hour (MWh) for onshore and 0.2 gallons per MWh offshore, estimated water consumption to be negligible, and estimated withdrawals onsite at 51.9 gallons per MWh for overall fuel extraction and acquisition.[23] Inhaber (2010) reports that electricity from natural gas requires 20,605.4 gallons of water per MWh overall, but this is mostly withdrawals for cooling gas turbines. This water use is considered non-consumptive, notwithstanding thermal pollution and evaporative losses.

The scope of the water footprint is the blue and grey water footprint. Green water (evaporated rainwater) was determined to be not relevant for this project. The process we evaluated was natural gas extraction from Marcellus Shale and the unit of analysis was gallons of water per thousand cubic feet (Mcf) of natural gas. We base our analyses on statewide datasets from Pennsylvania and West Virginia in which the natural gas industry self-reports data on withdrawals, injections, recovery, and disposal.

6.2 Water footprint per unit energy

Water volumes alone are not enough, however, to appreciate the relative impacts of different extraction techniques. A well that requires larger volumes of water may also produce significantly more energy over the life of the well. To assess water impacts it is important to look at water use and gas production over the life of a well because a large portion of water use comes in the first year, while the bulk of gas production occurs over longer time horizons (Lutz et al. 2013; Lewis 2012). Accurately assessing water impacts across shale basins or per well site requires normalizing water use and impact by unit of energy produced. It is therefore important to know the gas and oil production values per well. The normalization based on energy production is a key concept in the life cycle water footprint.

There are several ways to estimate water use per unit energy. The first is to estimate the majority of gas production, which occurs in the first four years of production (Lutz et al. 2013). While Lutz et al. (2013) did not focus on water use, it is instructive to understand how they normalize wastewater per unit energy. Lutz et al. (2013) found that Marcellus wells produce approximately ten times more wastewater per well than conventional wells. Yet they point out that compared with conventional wells, Marcellus wells also produce over 28 times more gas in four years, on average (Lutz et al. 2013). Thus Marcellus wells produce less wastewater per unit energy. However, they point out that, "[d]espite 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" (Lutz et al. 2013, p. 6).

[23] Reporting water withdrawals in terms of electricity requires careful consideration because it assumes a certain efficiency of combustion to generate electricity.

A second approach is to consider a much longer time horizon for gas production. Dale et al. (2013) estimated water use per unit energy in a life cycle analysis that also evaluated energy use and greenhouse gas emissions from extracting natural gas from the Marcellus Shale in Pennsylvania. They used a subset of the water use and waste data reported to Pennsylvania regulators, and they normalized these water data over a 30-year production interval to produce the data set for gas production shown in Table 24. They distinguished 728 wells started from 2008 to 2010 from wells started in 2011. They found that wells started in 2011 required 0.677 gallons/Mcf, a 2% reduction in water use compared to wells started from 2007–10.

Table 24: Thirty-year production estimates and water use per unit energy for shale gas

	Gas production		Water use per unit
Well start	**mcm**	**Mcf**	**energy (gallons/Mcf)**
2008–10	72	2,754,237	0.694
2011	108	3,813,559	0.677

Source: Dale et al. (2013).

The Dale et al. (2013) study addresses the question of whether the industry is getting better at lowering the overall water impacts from shale gas extraction. They conclude, "although improved fracturing processes have reduced the amount of water on a per-stage basis, longer laterals and additional fracturing stages nullify these improvements in our results. However, changes to flow-back management mean more water is reused and less is permanently disposed of in injection wells" (Dale et al. 2013, p. 5463). There have been improvements in water use efficiency per unit of energy produced, but the overall exploitation of the Marcellus play is swamping any efficiency or conservation gains. In other words, the per-well reductions in water use are far outpaced by the overall water use.

Dale et al. (2013) also conclude that, "with the rise of large-scale reuse of wastewater and more robust water pipeline and storage networks, high-level concerns over water consumption, at least in the relatively water-rich states that overlie the Marcellus, should be focused on excessive water withdrawals from specific bodies of water or during specific times rather than overall water quantity used for fracking" (p. 5465). In other words, some water bodies may leave communities or ecosystems more vulnerable than others during times of water stress, and efforts should focus on these areas instead of overall water use.

Other studies also focus on the lifetime production of the well, but do not specify the number of years of gas production. Mielke et al. (2010) compiled findings from the US Geological Survey (USGS) (Soeder and Kappel 2009) and estimated the volume of water consumed per unit energy for Marcellus Shale gas extraction is 1.2 gallons/Mcf. Using values from Chesapeake Energy, Mantell (2011) estimates the water use efficiency from the fracking process to be 1.07 gallons/Mcf. The values are collectively reported in Table 25 below, which shows a range from 0.677 gallons/Mcf (Dale et al. 2013) to 1.2 (Mielke et al. 2010). Such a variation might be anticipated, as there is no conclusive information about the lifetime production of a shale gas well.

Table 25: Estimates for volumes of water consumed per unit of energy

Water Use (gallons/Mcf)	Timeframe evaluated	Source
1.2	Not specified, life of well assumed	Mielke et al. 2010
0.677–0.694	30 years (assumes no re-stimulation)	Dale et al. 2013
1.07	Not specified, life of well assumed	Mantell 2011

6.3 Blue water footprint

6.3.1 *West Virginia*

To understand the water footprint results it was important to establish the production of natural gas per well. Water use per well for natural gas from shale is significantly more than in conventional wells, but natural gas production is also much higher. Our goal was to use published estimates and their assumptions to characterize the gas production from Marcellus Shale gas wells.[24] Wells are most productive early in their lifetime unless re-stimulated, so the wells' most productive years are the first four years (Lutz et al. 2013). King (2010; cited in Lewis 2012) suggests that well production declines exponentially over time, with five to ten years of viable production. These considerations helped justify using four-year production estimates to normalize the water use per well.

There are no published data showing actual lifetime gas production from West Virginia horizontal Marcellus wells on a per-well basis. This is understandable, given that horizontal drilling began so recently. Per-well estimates of natural gas production from the Marcellus Shale do exist for Pennsylvania, but may have significant uncertainties because of the way the data were extrapolated. Lewis (2012) estimates that, in its first four years, a single Marcellus well will on average produce 1,030,910 Mcf (See Table 26). Based on the four-year annual production and decline estimate shown in Table 26, approximately 40% of the four-year production total occurs in the first year. Lewis (2012) did not correct for the fact that the first year is typically not a full calendar year, and notes that this first year of production may be an underestimate. Nonetheless, this estimate of annual production and decline over four years were the most appropriate estimates to apply to West Virginia wells.[25]

Table 26: One estimate of annual production and decline over four years for Pennsylvania Marcellus wells (Mcf)

	First year	Second year	Third Year	Fourth year	Total
Mean	396,100	439,600	138,700	56,510	**1,030,910**
Confidence interval[26]	25,900	35,100	17,900	14,600	--

Source: Lewis (2012).

Even though these values were produced for Pennsylvania wells, we assumed that the shale formations across the Marcellus have similar declines in gas production over four years and applied this first-year percentage to actual production data from West Virginia to estimate production for a given well. From Table 26, also note that the fourth year production is only approximately 5% of cumulative four-year production.

Monthly production data were available for all wells that produced natural gas in West Virginia for each of the years of interest: 2010, 2011, and 2012. Only those 174 wells with both complete water

[24] Our approach did not consider any shale oil co-produced with natural gas. Many Marcellus Shale wells report oil production in addition to natural gas production, but these volumes are orders of magnitude smaller on a unit energy basis. The ISO 14040 (2006) framework and principles for life cycle analysis aim to prevent allocating impacts to co-products when they are not the primary economic driver of activities that cause the impacts. For this reason, we excluded any energy from oil from our normalization. Oil only constitutes a small fraction of the overall energy produced from these activities. A displacement approach could be used to credit natural gas production with the avoided burden of producing that volume of oil. But since other oil extraction techniques use far less water, it is not clear that these burdens could be avoided. In other words, any oil that is co-produced with natural gas does not displace any water use from oil extraction elsewhere.

[25] Another estimate of natural gas production over time demonstrated similar results. Duman (2012) estimated 10-year and 20-year production horizons, and this work suggested that 40.5% of the four-year production occurs in the first year.

[26] The confidence interval is used to estimate the uncertainty in the reported mean. The confidence intervals in Table 26 were estimated by Lewis (2012) because that study aimed to compare shale gas production to conventional gas production. Estimating confidence intervals allows one to ensure that any difference in the mean are not a result of uncertainty. Because we were not comparing this production curve to any other production curve, estimating an overall confidence interval was not necessary.

and natural gas production data were analyzed. Ideally, natural gas production would be summed for an annual production rate. However, the data revealed that wells were not operating for the entire calendar year, with each beginning production during different months during the given year. Once a well started producing, it typically continued to produce through the end of the calendar year.

To approximate a first-year production value, we took the reported monthly production in West Virginia for all wells with active production in our sample and estimated a monthly production average using all months with non-zero production. We summed the gas production for a given year and divided by the number of months. This monthly production average was extrapolated to approximate a value for 12 months of production. In other words, we aimed to estimate how much gas the well would have produced had it started producing gas on January 1st and continued through the end of the year. This was repeated for each year 2010, 2011, and 2012 and used as a first-year production proxy for all wells (See Table 27). An average per well was later obtained by dividing by the well count.

Table 27: Derivation of first-year production proxy for West Virginia wells (2010-2012)

Year	Well count	Production from all sample wells (Mcf)	First-year production proxy for all sample wells (Mcf)
2010	39	14,385,934	33,000,000
2011	93	35,158,685	77,000,000
2012	42	35,762,095	60,000,000

These proxy first-year production volumes were used in a model that projects a four-year production estimate. We chose a four-year total because Lutz et al. (2013) determined that the first four years are when the majority of gas is produced. As described above, approximately 40% of the well's four-year gas production occurs in the first year. Taking the annual estimates made above for each year, Table 28 provides the four-year production volumes. It is not clear what is driving the trend, but the 2012 wells in our sample are projected to be significantly more productive per well.

In the event that the 40% value underestimates gas production, we performed sensitivity analyses that assumed wells produced more gas than in the four-year period from the same water withdrawal. As described in Table 26, only about 5% of the cumulative gas production over four years occurs in that fourth year. For our sensitivity analysis we assumed that wells produce at the fourth year production rate for an additional two years (the six-year scenario) and six additional years (the ten-year scenario) before new water additions are required to re-stimulate production. In other words, we estimate that production over six years would be approximately 110% of the four-year production estimate, and production over ten years would be approximately 130% of the four-year production estimate. These per-well production values appear in Table 28 and were used to normalize the blue and grey water footprints.

Table 28: West Virginia production volumes (Mcf, 2010-2012)

	All sample wells	Per well		
Year wells started	4 years of production	4 years of production	6 years of production	ten years of production
2010	82,500,000	2,100,000	2,310,000	2,730,000
2011	192,500,000	2,100,000	2,310,000	2,730,000
2012	150,000,000	3,600,000	3,960,000	4,680,000

Note: These calculations are based on annual production and the four-year production curve estimated by Lewis 2012, as well as sensitivity analyses based on six- and ten-years of production before need for additional water injection. Lutz et al. (2013) suggest that additional water withdrawals are required every five to ten years.

We also used a longer-range production value as a sensitivity. Dale et al. (2013) estimate that a single Marcellus well will produce 3,813,559 Mcf over 30 years. They used samples from PADEP production data collected in six-month periods, which contained both total production and days of production. A regression was performed on each well based on production per day to estimate a total production over 30 years. Well production may extend 30 years and perhaps even beyond; however, Marcellus well production begins to decline significantly after the first or second year and requires re-stimulation with new water injections after five to ten years (King 2010). This increase in water use would be accompanied by an increase in gas production. Currently, there are no studies that estimate the relationship between well stimulation, water use, and gas production. Hence, if water use is normalized by the 30-year estimate of natural gas production, it is very likely underestimating water use—perhaps even significantly so.

As illustrated in Table 29, the volume of water removed from the hydrologic cycle was divided by the amount of natural gas produced to provide a water footprint for shale gas extracted in West Virginia normalized by energy production. The "four years of gas production" scenario is based on the West Virginia production data as suggested above. The "30 years of gas production" scenario is based on values from Dale et al. (2013), which is likely an overestimate for gas production per water injection given the need to re-stimulate a well via water injection after five to ten years, though technological advances (so-called zipper frac technology, for example) may eliminate the need for re-stimulation. Hence, we interpret the 30-year scenario as the high range sensitivity to the analysis. Dale et al. (2013) found that wells started in 2010 would produce 2,754,237 Mcf and those started in 2011 would produce 3,813,559 Mcf. The 2012 well-starts were assumed to have a similar profile as the wells started in 2011, but 2012 was not evaluated by Dale et al. (2013).[27]

Table 29: Blue water footprint for Marcellus wells in West Virginia (gallons/Mcf)

Basis	2010	2011	2012
Four years of gas production	2.2	2.2	1.6
Sensitivity to gas production estimates			
Six years of gas production	2.0	2.0	1.4
Ten years of gas production	1.7	1.7	1.2
30 years of gas production	1.7	1.2	1.5

As Table 29 shows, the blue water footprint—the volume of surface and groundwater consumed—ranges from 1.6 to 2.2 gallons of water per Mcf on a four-year production basis. If we assume the well will continue to produce gas at the rate found in year four for two additional years (six years total) the range is from 1.4 to 2.0 gallons of water per Mcf, and if we extend this rate out to ten years, the range is from 1.2 to 1.7 gallons of water per Mcf. On a 30-year basis, assuming no additional water injections, the blue water footprint ranges from 1.2 to 1.7 gallons of water per Mcf.

These values are higher than the only other peer-reviewed estimate of water use per unit energy on the Marcellus Shale by Dale et al. (2013), which suggested that gas production from Marcellus Shale is only 0.7 gallons per Mcf. It is likely that this discrepancy is because Dale et al. (2013) used the 30-year production horizon, but did not consider the volume of water that would be required to re-stimulate the well several times over the 30-year life of a well. Considering the four-year production scenario, and the sensitivity analyses, the range of 1.2 to 2.2 gallons of water per Mcf of natural gas is narrow enough to suggest that these values are consistent.

[27] We applied the same Dale 30-year production estimates to both West Virginia (Table 29) and Pennsylvania (Table 31). Even though our data suggests different production estimates for West Virginia and Pennsylvania wells, we wanted a conservative estimate for gas production per water injection in our sensitivity analysis.

6.3.2 *Pennsylvania*

For Pennsylvania, we aimed to take a similar approach to the one used for West Virginia; however, there is a major difference in the way that the states report production. In Pennsylvania, production has been reported in six-month intervals since 2010, while West Virginia requires monthly production totals be reported. Therefore, the method of estimating gas production used for West Virginia could not be used for Pennsylvania. A lack of data for 2012 also meant we looked at a different time period for Pennsylvania (2009 to 2011) than West Virginia (2010 to 2012).

Therefore, for Pennsylvania, we used per-well production values described by Lutz et al. (2013) that put per well production values at 1,062,000 Mcf over four years. Our preference would have been to modify these results based on the average increase is gas production per well as companies improve their extraction techniques, but our West Virginia sample of gas production show no significant change in gas production from 2010 to 2011 and a 44% increase from 2011 to 2012. Since 2012 was not in our Pennsylvania timeframe for analysis, we decided that the Lutz et al. (2013) estimate was most appropriate.

The results below were normalized by natural gas production to give the total water removed from the hydrologic cycle per unit of natural gas produced. The total water removed from the hydrologic cycle by Marcellus wells in Pennsylvania was divided by the average production from a Marcellus gas well in Pennsylvania over a four-year period to provide the blue water footprint, which ranges from 3.2 to 4.2 gallons per Mcf of natural gas production from Marcellus Shale. This is significantly higher than the results for West Virginia reported in Table 29, which suggested a range of 1.2 to 2.2 gallons of water per Mcf.

Table 30: Initial blue water footprint calculations for Marcellus wells in Pennsylvania (2009-2011)

Well start year	Four-year gas production per average Marcellus well (Mcf)	Water removed from the hydrologic cycle (gallons)	Blue water footprint (gallons/Mcf)
2009	1,062,000	3,352,802	3.2
2010	1,062,000	4,071,156	3.8
2011	1,062,000	4,417,035	4.2

Sources: Gas production from Lutz et al. (2013). Water removed from the hydrologic cycle are un-rounded values from Table 23 of this report.

One explanation for the difference between the Pennsylvania and West Virginia results may be related to the waste reporting practices. In West Virginia, only flowback fluid is reported—not all of the waste produced. However, the major driver appears to be that the data used for average gas production per well is much lower in Pennsylvania, as compared with West Virginia.

Using a similar approach to the water use data for West Virginia, we estimated the sensitivity of the water footprint per unit energy to overall gas production. We used the production estimates in Table 26 and assumed that wells produce two additional years at the fourth year rate (the six year scenario), and an additional six years at the fourth year rate (the ten year scenario). We also estimated the sensitivity of the blue water footprint to the amount of gas produced by using the Dale et al. (2013) estimates for a 30-year time horizon. The Dale et al. (2013) analysis lumped 2008 through 2010 into one average estimate, so we applied the same value to 2009 and 2010. The sensitivity of the blue water footprint to gas production is reported in Table 31.

Table 31: Blue water footprint for Marcellus wells in Pennsylvania (gallons/Mcf)

Basis	2009	2010	2011
Four years of gas production	3.2	3.8	4.2
Sensitivity to gas production estimates			
Six years of gas production	2.9	3.6	3.9
Ten years of gas production	2.4	3.0	3.2
30 years of gas production	1.2	1.5	1.2

The results in Table 31 show a range of 3.2 to 4.2 gallons of water per Mcf from 2009 to 2011. This is in line with the 30-year blue water footprint in West Virginia, which ranged from 1.2 to 1.9 gallons per Mcf for the three years of analysis. These values are higher than the 0.7 gallons per Mcf estimate provided by Dale et al. (2013). As we describe above, the values used by Dale et al. (2013) appear to ignore water use associated with re-stimulating the well several times over the 30-year life of the well. While we do not question the Dale et al. (2013) methodology to estimate gas production over 30-year life of the well, we do question the assumption that water withdrawals only occur once.

These blue water footprint metrics allow for a rough assessment of how much water is removed from the hydrologic cycle per unit of energy. In addition, coupled with the grey water footprint described in the following section, these blue water footprints serve as a basis for representing the cumulative impacts to water resources.

6.4 Grey water footprint

The grey water footprint of a product or process is “an indicator of the severity of water pollution, expressed in terms of the freshwater volume required to assimilate the existing load of pollutants” (Hoekstra et al. 2011). The dilution factor in a grey water footprint represents the number of times the effluent volume should be diluted to meet acceptable concentration thresholds. The basic premise behind the grey water footprint has been to understand how much water would be required to dilute polluted wastewater to some specified water quality standard. Research by Falkenmark and Lindh (1974) was one of the first attempts to make water pollution commensurate with water quantity, suggesting that a dilution factor of ten to fifty times the volume of wastewater flow is an adequate representation of pollution impacts on water resources. Research by Chapagain (2006) later distinguished dilution factors by type of pollutant and categories of emissions. This allowed for a better representation of impacts in the circumstances where the results would be sensitive to pollutants that are far above regulatory thresholds relative to other pollutants. Hoekstra and Chapagain (2008) introduced and linked the term grey water footprint to this approach.

The purpose of integrating this grey water footprint into the study is to understand the relative impacts of water pollution versus water consumption. Fracking can have impacts for both, but it becomes important to understand the relative magnitude of impacts to water quantity versus water quality. This may help policy makers and regulators focus on whether they should emphasize stronger rules on water use versus disposal, or both. Grey water footprints also can increase understanding of how pollutants are assimilated into the environment as well as the extent to which they stress existing municipal and industrial treatment plants. So long as grey water volumes remain below the surface and groundwater flows, any pollutants will be assimilated at concentrations below the selected standards. There are many caveats and assumptions that limit the applicability of these results, but a grey water footprint can provide an order-of-magnitude characterization of water pollution.

For this project we estimated the volumes of flowback water from natural gas wells and used published estimates for average concentrations of contaminants found in these waste streams. For thresholds, we used federal drinking water standards established by USEPA (2013b). These include the Maximum Contaminant Level Goal (the concentration at which there is no anticipated risk to health), the Maximum Contaminant Level (the highest permitted level for drinking water), and the Secondary Drinking Water Standard (a non-enforceable guideline). We also used contaminant thresholds developed by a special rule adopted in Pennsylvania that specified treatment standards for water treatment facilities receiving waste from oil and gas operations. It is also important to note that some contaminants do not have regulatory standards or recommended best practices. The absence of these thresholds does not necessarily imply absence of a water quality issue.

The contaminants chosen for evaluation in the grey water footprint were ones that were both present in previous studies of the composition of flowback fluid and those that had drinking water standards or discharge standards particular to waste from shale gas operations. Table 32 lists these contaminants and the standards. Of all the standards in this table, we chose the most stringent to benchmark the dilution factor. Where standards are zero, such as the case with some metals such as lead, the threshold chosen was the actionable level (USEPA 2013c). The dilution factor is the amount of water required to dilute the average concentration found in flowback water to the most stringent threshold. Because the average concentrations as well as the regulatory thresholds differ by pollutant, this approach helps identify which contaminants have the largest relative potential impacts on water pollution.

Table 32: Contaminants and thresholds screened in this research (mg/L)

Contaminant	USEPA Maximum Contaminant Level Goal	USEPA Maximum Contaminant Level	USEPA Secondary Standard	Pennsylvania rule adopted in 2010
Barium	2	2		
Chloride			250	250
Bromide[28]	0.1	0.1		
Sodium			20[29]	
Sulfate			250	
Lead	0	0.015		
Iron		0.3		
Manganese		0.05		
Benzene	0	0.005		
Toluene	1	1		
Strontium			4[30]	
Alpha particles	0	15		
Nitrate	10	10		
TDS				500

Sources: Drinking water standards from USEPA (2013b). The supplemental information for Olmstead et al. 2013 describes the Pennsylvania rule adopted in 2010. Many of the contaminants in Table 33 did not have standards or recommended best practices that could be applied to this analysis.

Table 33 shows estimates of contaminant concentrations found in flowback water. Flowback water data came from various sources, including the permitting manual for oil and gas development in New York (BOGM 2011) and a more recent draft environmental impact statement for revised permitting (NYSDEC 2001), which were reported as upper and lower ranges for effluent concentrations, as well as median and maximum discharges. Another important source was Hayes (2009), who provided a

[28] There is no standard for bromide, but USEPA says that pristine groundwater has a concentration of 0.1 mg/L.
[29] There is no standard for sodium, but concentrations above this level can be of concern to those on low sodium diets (USEPA 2013d; Penn State Extension 2013).
[30] There is no standard for strontium, but USEPA has developed a lifetime health advisory aiming to keep strontium below 4 mg/L (ATSDR 2013).

more extensive list of contaminants found in wastewater. Hayes (2009) reported upper and lower ranges from both five days post-hydraulic fracturing and 14 days post-hydraulic fracturing based on five samples of flowback water collected at each of 19 well sites. These two sources listed 28 contaminants and water quality criteria.[31] But not all contaminants or water quality parameters known to be present in flowback fluid were surveyed because they did not all have drinking water standards or specific discharge standards for facilities treating flowback fluid.

Table 33: Marcellus flowback water data used to calculate grey water footprint (mg/L unless otherwise specified)

	Averages			5 days post hydraulic fracturing		14 days post hydraulic fracturing	
Contaminant	Lower Estimate	Upper Estimate	Median Estimate	Lower Estimate	Upper Estimate	Lower Estimate	Upper Estimate
Barium	0.553	15,700	1,450	21.4	13,900	43.9	13,600
Chloride	287	228,000	56,900	26,400	148,000	1,670	181,000
Bromide				185	1,190	15.8	1,600
Sodium				10,700	65,100	26,900	95,500
Sulfate				2.4	106	< 10	89.3
Lead				Non-detect	0.606	Non-detect	0.349
Iron	0	810	29.2	21.4	180	13.8	242
Manganese				0.881	7.04	1.76	18.6
BTEX[32]						Non-detect	5.46
Strontium	0.501	5,841	1,115	345	4,830	163	3,580 J
Nitrate				< 0.1	1.2	< 0.1	0.92
TDS	1,530	337,000	63,800	38,500	238,000	3,010	261,000

Sources: Averages are from BOGM (2001) and NYSDEC (2011); The 5 days and 14 days post hydraulic fracturing estimates are from Hayes (2009). There are a number of contaminants here that did not have published values in the Marcellus Shale, but are believed to be constituent contaminants of waste. Unlike the rest of the parameters in his study, Hayes (2009) reported Alpha particles from a range of non-detect to an upper range, but also a median (Non-detect – 18,000 pCi/L; median 2,460 pCi/L).

The grey water footprint approach suggests representing the degree of water pollution as the volume of water required to assimilate the pollution to meet selected water standards. To estimate this grey water footprint, we chose the most stringent of the low and high ranges where multiple values were available. Using the contaminant concentration at each of the upper, median, and lower values and dividing by the relevant threshold, we produced a dilution factor. The equation for the volume required to dilute the contaminant to the chosen threshold is:

Dilution Factor = Contaminant Concentration / Water Quality Threshold

We did this separately for each contaminant with water quality parameters listed in Table 32. The dilution factor was multiplied by the total volume of water disposed to produce the grey water footprint. These data were from the same per well data used in the blue water footprint analysis where we aimed to use only wells with complete gas production and water use and disposal. The grey water footprint aims to understand the indicator for water quality per unit energy, so the product of flowback water disposed per well and the dilution factor were divided by natural gas production per well.

$$\text{Grey Water Footprint} = \frac{\text{Water Disposed x Dilution Factor}}{\text{Natural Gas Production}}$$

[31] Water quality criteria reported for flowback fluid in BOGM (2011), NYSDEC (2001), and Hayes (2009), but not used in the grey water footprint include oil and grease, pH, alkalinity, acidity, hardness, total Kjeldahl Nitrogen, ammonia, volatile and semi-volatile organic compounds, total organic carbon, dissolved organic carbon, chemical oxygen demand, biological oxygen demand, turbidity, and TSS.

[32] Benzene, toluene, ethylbenzene, and xylene (BTEX) was used as the proxy for the toluene and benzene dilution estimates.

Table 34: Primary contaminants, thresholds, and volume ranges for grey water footprint

	Upper (mg/L)	Median (mg/L)	Lower (mg/L)	Water quality threshold (mg/L)	Source for threshold	Dilution factor range
Barium	15,700	1,450	0.553	2.00	USEPA	7,850–0.3
Chloride	228,000	56,900	287	250.0	PA 2010 rule	912–1.1
Bromide	1,600	-	15.8	0.1	USEPA	16,000–158
Sodium	95,500	-	10,700	20.0	USEPA	4,775–535
Iron	810	29.2	non-detect	0.3	USEPA	2,700–0
Manganese	18.6	-	0.881	0.05	USEPA	372–17.6
Lead	0.606	-	non-detect	0.0015	USEPA	404–0
Benzene	5.46	-	non-detect	0.005	USEPA	1,092–0
Toluene	5.46	-	non-detect	1.0	USEPA	5.5–0
Strontium	5,841	1,115	0.501	4.0	USEPA	1,460–0.1
TDS	337,000	63,800	1,530	500.0	PA 2010 rule	674–3.1

Sources: Upper, median, and lower concentrations from Table 33. Thresholds from Table 32.

6.4.1 *West Virginia*

The grey water footprint for West Virginia was based on the per-well data with complete gas production and flowback water disposal data. The flowback water was multiplied this maximum dilution factor. This volume required to dilute the flowback water was normalized per Mcf of natural gas production. The results are in Table 35, which also shows which contaminant drives the grey water footprint at the upper, median, and lower limits. These results suggest a declining grey water footprint from 2010 to 2012, which is due to a smaller volume of flowback fluid per unit energy.

Table 35: Grey water footprint for Marcellus wells in West Virginia (2010-2012)

Well year	Contaminant	Upper (gallons/Mcf)	Contaminant	Median (gallons/Mcf)	Contaminant	Lower (gallons/Mcf)
2010	Bromide	1,000	Barium	50	Sodium	40
2011	Bromide	600	Barium	30	Sodium	20
2012	Bromide	500	Barium	20	Sodium	20

6.4.2 *Pennsylvania*

A similar approach was used to estimate the grey water footprint for Pennsylvania wells. These estimates were based on wells with full flowback water and natural gas production data. As Table 36 suggests, there is no significant decline in the grey water footprint from 2009 to 2011, as there is in West Virginia. The same water quality data and thresholds were used for Pennsylvania, so the same contaminants drove the upper, median, and lower thresholds.

Table 36: Grey water footprint for Marcellus wells in Pennsylvania (2009-2011)

Well year	Contaminant	Upper (gallons/Mcf)	Contaminant	Median (gallons/Mcf)	Contaminant	Lower (gallons/Mcf)
2009	Bromide	900	Barium	40	Sodium	30
2010	Bromide	800	Barium	40	Sodium	30
2011	Bromide	1,000	Barium	40	Sodium	30

6.4.3 *Summary of grey water footprint results*

The results of the grey water footprints from West Virginia and Pennsylvania suggest a few trends. The contaminant in the upper thresholds that requires the largest volume of water to dilute is bromide, followed by barium, sodium, and iron. Sodium is the primary driver in the least contaminated water and the difference between the high and low thresholds for sodium are only one order of magnitude as opposed to two, three, or four orders of magnitude for the other contaminants. If not for the high levels of sodium in the lower range of representative samples, it would be much easier to dilute pollution from the “cleanest” flowback fluid.

Compared to the blue water footprints, the grey water footprints can be significant because of very high concentrations of contaminants. Even at the lower bound of contamination, the difference is two orders of magnitude, meaning that one-hundred times more water would be required to dilute the water pollution per Mcf than is removed from the hydrologic cycle. At the upper bounds the difference is four orders of magnitude per Mcf compared to water removed from the hydrologic cycle.

The grey water footprint estimates here are used as an indicator to understand the relative magnitude of water pollution versus water use estimates. It is not a direct measure of water use. There are obvious limitations to grey water indicators, because water pollution is not being diluted in the way the indicator suggests. Most flowback fluid is being recycled or disposed of in UIC wells or at wastewater treatment facilities. However, at two orders of magnitude difference, we can get a better sense for how flowback water destined for disposal might stress water treatment facilities. In cases where there is illegal or improper disposal, we can also gain an order of magnitude assessment of how much this water pollution will impair freshwater sources. In sum, the grey water footprints represented here show that the water resource implications for hydraulic fracturing for natural gas are both an issue of water quantity and water quality, not one or the other as is often suggested.

7. CONCLUSIONS AND RECOMMENDATIONS

Several teams of researchers are studying whether, and how, horizontally drilled, hydraulically fractured Marcellus wells impact water resources. In this report, we add to this body of literature by analyzing the self-reporting data collected in West Virginia and Pennsylvania related to water withdrawals and fluid injection, recovery, and disposal. We also calculate blue and grey water footprints and consider improvements to the data collection and reporting requirements that would facilitate even better data analysis in the future.

7.1 West Virginia

7.1.1 *Water and fluid flows*

As shown on the following page, our analysis of self-reporting data has resulted in a variety of estimates of water withdrawals and fluid injection, recovery, and disposal in recent years in West Virginia. Figure 18 summarizes several key results.

On average, in recent years, approximately 5 million gallons of fracturing fluid has been injected per well. Surface water, by far, is the largest source of water, although reused flowback fluid has accounted for approximately 8% of total withdrawals.

Of the fluid injected underground, only 8%, on average, returns to the surface in the time frame captured by West Virginia reporting requirements; the rest remains underground. The water contained in the fracturing fluid that remains underground, together with that disposed of in UIC wells, is removed from the hydrologic cycle and is included in our blue water footprint calculations.

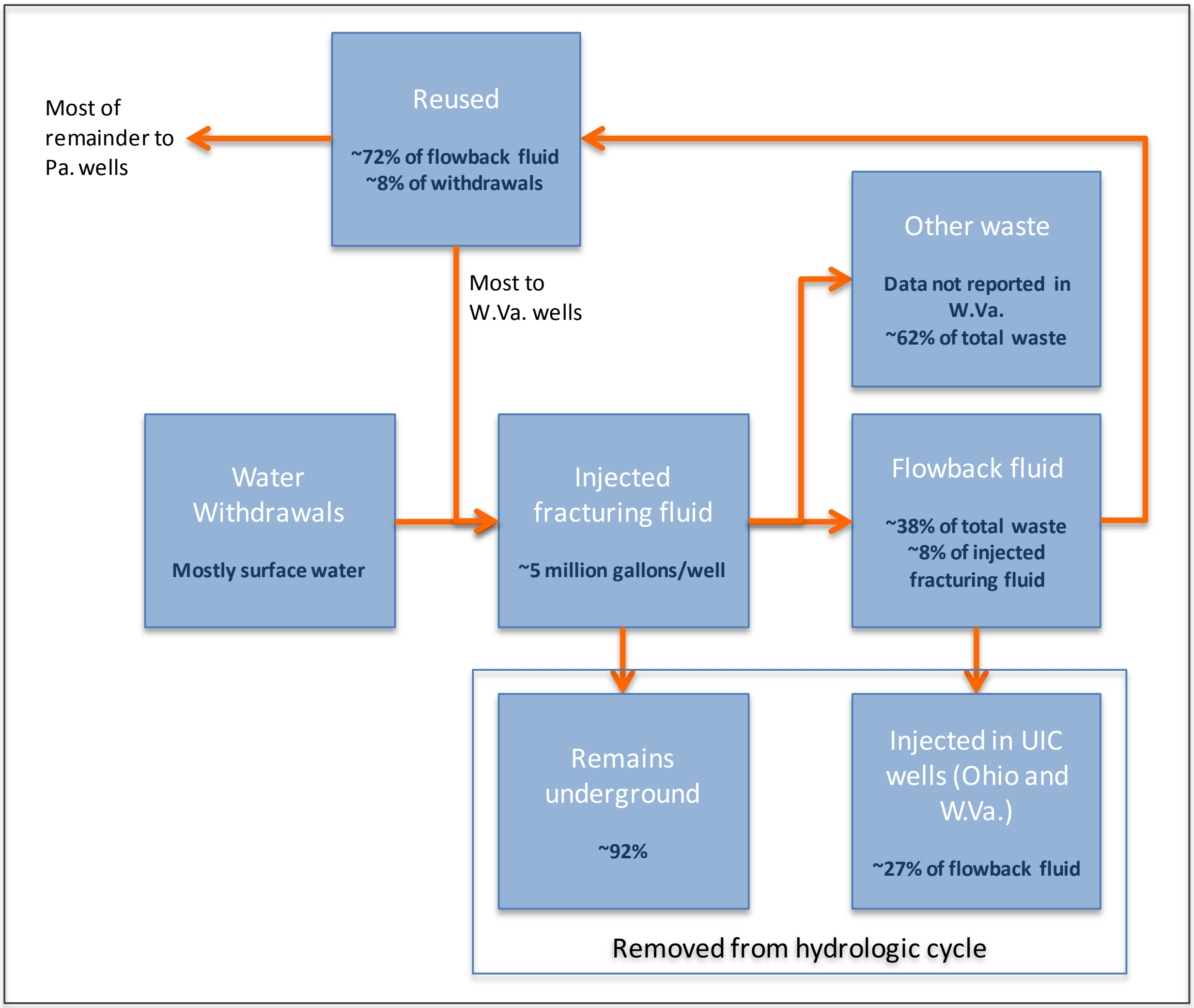
The flowback fluid reported as waste in West Virginia represents only approximately 38% of the total volume of Marcellus waste. This is because West Virginia only requires operators to report flowback fluid volumes once, in comparison to the Pennsylvania requirements to report of all types of waste every six months into the future.

Almost one-half of flowback fluid recovered in West Virginia is transported out of state. Between 2010 and 2012, 22% of recovered flowback fluid was sent to Pennsylvania, primarily to be reused in other Marcellus operations, and 21% was sent to Ohio, primarily for injection in UIC wells.

Potential impacts to West Virginia's surface waters are most likely to occur from water withdrawals, and not from waste disposal. Very little flowback fluid from West Virginia is sent to treatment plants that discharge to surface waters; however, most water used in Marcellus operations is withdrawn from surface waters. If these withdrawals are not timed appropriately, especially on small streams, aquatic life can be harmed if dewatering occurs. Pursuant to new rules, operators must now demonstrate that sufficient in-stream flow will be available immediately downstream from surface water withdrawal locations. Effective enforcement of these rules will be critical to protect the state's surface waters.

The three-state region—which includes West Virginia, Pennsylvania, and Ohio—is tightly connected in terms of waste disposal. Flowback fluid from West Virginia wells is recycled and shipped to Marcellus wells in Pennsylvania, and flowback fluid is also shipped to UIC wells in Ohio for disposal.

Figure 18: Summary of key West Virginia water and fluid flows



Source: All figures calculated in this report.

KEY WEST VIRGINIA RESULTS

- From 2010 through 2012, approximately 2 billion gallons of water was withdrawn from surface and groundwater, purchased from public or private water suppliers, or obtained from other wells for use in Marcellus gas production in West Virginia (See Table 7).
- Surface water was the most widely utilized source of water used in Marcellus well development. Approximately 1.6 billion gallons of water have been withdrawn from West Virginia's surface waters for injection in horizontal wells in the Marcellus, representing 81% of all withdrawals (See Table 7).
- Reuse as a percentage of total withdrawals has increased somewhat in West Virginia, but still only totaled 10% of withdrawals in 2012 (See Table 7).
- In West Virginia, an estimated 3.9 billion gallons of fluid have been injected into horizontal wells in the Marcellus since 2010. Horizontal Marcellus wells injected an average of approximately 5 million gallons during this period (See Table 10).
- Most fluid injected into Marcellus wells in West Virginia never returns to the surface (Figure 6). Between 2010 and 2012, only 8% of injected fluid was recovered in the time frame captured by the reporting requirements.
- On average, horizontal Marcellus wells in West Virginia disposed of approximately 0.4 million gallons of fluid per well (Table 11).
- Between 2010 and 2012, 78% of recovered flowback fluid was reused; however, the percentage of recovered flowback fluid that is reused has dropped in recent years, from 88% in 2010 to 73% in 2011 and 65% in 2012 (Table 11). While most recovered fluid is reused, the reused fluid still represents only a small percentage of total withdrawals used to service Marcellus wells in West Virginia.
- The percentage of flowback fluid disposed of at UIC wells increased from 12% in 2010 to 26% in 2011 and 35% in 2012 (Table 11).
- From 2010 through 2012, only 57% of recovered flowback fluid from horizontal Marcellus wells in West Virginia actually stayed in West Virginia, while 21% was shipped to Ohio (primarily to UIC wells) and 22% was shipped to Pennsylvania (primarily for reuse at other Marcellus wells) (Table 13).
- On average, about 4.7 million gallons per well were removed from the hydrologic cycle by horizontal Marcellus wells in West Virginia between 2010 and 2012 (Table 14). This totaled an estimated 3.7 billion gallons.
- In West Virginia, the blue water footprint, which represents the volume of water removed from the hydrologic cycle per unit of gas produced, ranged from 1.6 to 2.2 gallons per Mcf. When considering the sensitivity of these results to higher natural gas estimates, the range dropped to 1.2 to 2.0 (Table 29).

7.1.2 *Data collection and reporting*

In the face of an unprecedented growth in the number of Marcellus wells that have been permitted, drilled, and hydraulically fractured in recent years, the West Virginia Legislature and WVDEP have taken steps to improve data collection and reporting. As summarized in Table 37, current West Virginia laws and regulations require operators to compile and report key information related to withdrawals, injections, recovery, and disposal. Although these data are not compiled into a formal database that is accessible online, Microsoft Excel spreadsheets with all submitted data are compiled by WVDEP and provided freely upon request.

Table 37: West Virginia data reporting

Category of data	Form where data is reported	Required or voluntary?	Data reported by operators?	Reported data compiled into searchable database?	Searchable database publicly available?
Water withdrawals	Frac Water Reporting Form	Required	Incomplete	Yes	Upon request
Fluid injection volume	Frac Water Reporting Form	Required	Incomplete	Yes	Upon request
Chemicals in fluid	Well completion report and FracFocus	Required starting July 1, 2013	Unknown	FracFocus data searchable via SkyTruth	FracFocus data available via SkyTruth
Waste recovery	Frac Water Reporting Form	Required for flowback only	Incomplete	Yes	Upon request
Waste disposal	Frac Water Reporting Form	Required for flowback only	Incomplete	Yes	Upon request

Note: West Virginia operators have a one-year reporting deadline to report water withdrawals, fluid injection, waste recovery, and waste disposal volumes; however, it is not specified when the timeline begins, and this deadline is not enforced. Research presented in this report suggests that data reported to WVDEP for wells permitted in 2010 and 2011 is incomplete. The searchable databases referred to in this table are Excel spreadsheets available upon request from WVDEP.

However, additional steps can be taken to fine-tune these systems to make sure that regulators, the public, and researchers have accurate information that is provided in a convenient form and in a timely manner.

Two separate units within WVDEP—the Water Use Section and the Office of Oil and Gas—oversee different reporting requirements. The Water Use Section of the Division of Water and Waste Management oversees reporting of water volumes. The Office of Oil and Gas, however, handles permits and associated water management plans, the reporting of chemical additives, and other duties such as inspections and enforcement. This division of responsibility creates situations in which staff at one office may not be fully cognizant of other aspects of reporting requirements, and it may also lead to inconsistencies between databases that are being maintained for the same gas wells. It would be ideal if all Marcellus-related water reporting were managed within a single unit at WVDEP; however, absent such a reorganization, the Water Use Section and Office of Oil and Gas should closely integrate their data collection and reporting requirements and databases.

Withdrawal, injection, recovery, and waste disposal databases are not available online. WVDEP staff provided water-related data upon request, but these databases were actually copies of portions of Microsoft Excel databases. In addition, periodic requests were required in order to ensure that the most up-to-date data were provided. WVDEP already posts a considerable amount of data in searchable online databases, such as natural gas production data. WVDEP should implement an online database that provides free public access to its withdrawal, injection, recovery, and waste disposal data. This should be performed expeditiously to inform management decisions affecting environmental consequences as the rate of development increases.

Withdrawal, injection, recovery, and waste disposal datasets are incomplete. Based on the analysis conducted in this report, the Frac Water Reporting Database is only approximately 35% complete (See Table 9). While timelines are in place for certain types of reporting, it does not appear that WVDEP is monitoring the completeness of the data or enforcing the reporting of data within specified timelines. WVDEP should audit each database to determine what percentage of wells have reported. Methods similar to those used in this report could be employed, or WVDEP might have access to comparable or better methods. In addition, WVDEP should enforce its timelines to ensure that operators report on time.[33] If necessary, the West Virginia Legislature should revise its laws and/or rules to set strict timelines and penalties for the reporting of water quality and quantity information. In the meantime, WVDEP should use all available resources to compel operators to report information required by West Virginia laws and regulations, even if this reporting is technically voluntary.

Withdrawal data are not available for individual wells. WVDEP requires water withdrawals to be reported by well site, and not by well. This makes it impossible to track withdrawals by well, because each well site may have multiple wells and because well sites may be used to stockpile water for use elsewhere. In contrast, the water management plans submitted with each well permit application include estimates of future withdrawals by well. WVDEP should implement a system whereby water withdrawals are reported for individual wells, and not by well site. This would allow better tracking of sources of water for each well, and it would also allow comparisons against the estimates of future withdrawals by well that are submitted in each water management plan.

Large quantities of waste remain unreported in West Virginia. In contrast to Pennsylvania, where waste disposal is reported for a wide variety of waste types (including, for example, drilling waste, brine, and spent lubricants), disposal data are only reported for flowback fluid in West Virginia. In addition to excluding these other categories of waste, the West Virginia system also misses flowback fluid that returns to the surface more than 30 days after fracking. This missing data can be quite substantial. According to Pennsylvania's waste disposal data (See Section 5.4), flowback fluid constitutes approximately 38% of the total volume of waste generated by Marcellus wells in Pennsylvania. WVDEP should expand the scope of the recovery and disposal data reporting to include all waste types that are generated over time, and not just flowback generated in the first 30 days. Rather than reporting data once, it should be reported periodically over time. This may require legislative changes to the relevant laws and/or rules.

Duplicate injection, recovery, and waste disposal volumes are often submitted. In the Frac Water Reporting Form, operators have often entered the same injection, recovery, and waste disposal volumes for multiple wells on the same pad or for multiple waste disposal events. This raises the question of whether the operator divided the volume before reporting or whether the volumes have been double- or triple-counted. WVDEP should ensure that the Frac Water Reporting Form clearly asks for well-by-well information. In addition, should an operator enter duplicate information for multiple wells on a single form, the Frac Water Reporting Form should automatically flag this and explain to the operator that well-by-well information should be entered.

Inconsistent waste and disposal data have been submitted. When processing the West Virginia data for this report, many wells were removed from the analysis due to questions about data consistency. Wells were removed because recovery exceeds injection, a field had missing data, the recovery volume was negative, or disposal and recovery volumes differed by more than 10%. WVDEP should implement procedures to automatically check submitted data to ensure that it meets basic standards

[33] For example, just before completion of this report, it became apparent that the Frac Water Reporting Database provided by WVDEP (2013a) omitted 30 wells that began injection in 2011 but that had not reported until 2013. These wells were left out of our analysis; however, the discovery of these wells further underscores the importance of ensuring that operators report on time.

for data quality. At a minimum, this system should check for the types of questionable data documented here.

Well status data are missing. WVDEP provides an online Oil and Gas well search tool. Many entries in this database have a blank entry for “well status” field; therefore, it is not known whether these wells are active. WVDEP should institute a quality control procedure when data are reported to ensure that all necessary fields are filled in, before combining submitted data into its database.

No single data source provides the number of Marcellus wells drilled, fracked, and entering production in a given year. Despite the fact that operators must submit a variety of reports related to water, waste, and production volumes, none of the existing databases provide year-by-year accounting of the number of Marcellus wells drilled, fracked, and entering production in a given year. This is basic information that is known to WVDEP and is necessary to track the progress of the development of the Marcellus Shale; it should be easily and publicly available.

7.2 Pennsylvania

7.2.1 *Water and fluid flows*

As shown on the following page, our analysis of self-reporting data has resulted in a variety of estimates of water withdrawals and fluid injection, recovery, and disposal in recent years in Pennsylvania. Figure 19 summarizes the key results. On average, in recent years, approximately 4.3 million gallons of fracturing fluid has been injected per well. This is comparable to, but less than, the 5 million gallons reported in West Virginia.

Of the fluid injected underground, only approximately 6%, on average, returns to the surface; the rest remains underground. This percentage is also comparable to the 8% estimated for West Virginia. It is important to note that this figure represents the percentage of ***injected fracturing fluid*** that returns to the surface; the total amount of waste reported to PADEP is much higher. The water contained in the fracturing fluid that remains underground, together with that disposed of in UIC wells, is removed from the hydrologic cycle and is included in our blue water footprint calculations.

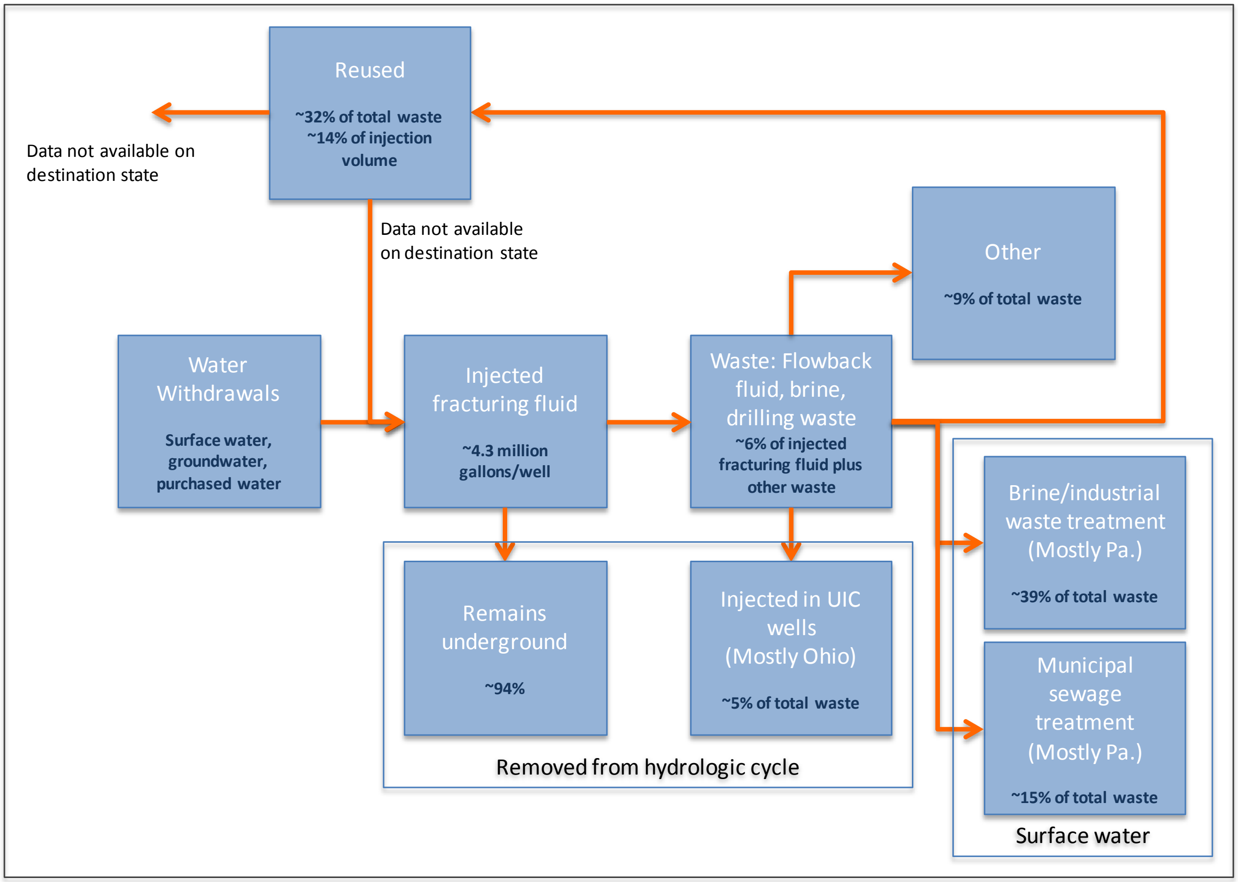
In Pennsylvania, three primary waste categories are tracked: flowback fluid, brine, and drilling waste, with flowback fluid representing approximately 38% of the total.

In recent years, more than one-half of the waste generated by Marcellus wells in Pennsylvania is treated and discharged to surface waters—either through brine/industrial waste treatment plants or municipal sewage treatment plants. This stands in stark contrast to West Virginia, where virtually no flowback fluid is reported to be discharged to surface waters. In Pennsylvania, approximately one-third of total waste is reused, although data are not available to determine whether it is reused in Pennsylvania or elsewhere. Only approximately 5% of total waste is injected in UIC wells—mostly in Ohio.

In contrast to West Virginia, there is significant potential for Marcellus development in Pennsylvania to impact its surface waters, because such a large percentage of waste is ultimately shipped to treatment plants that discharge to the state’s rivers and streams. While National Pollutant Discharge Elimination System (NPDES) permits are required for these sites, impacts could occur via spills, exceedances of permit limitations, or a lack of appropriate limitations for pollutants of concern.

The Pennsylvania data also confirm that the three-state region is tightly connected in terms of waste disposal. While most Pennsylvania waste remains in-state, a significant amount of waste is shipped to UIC wells in Ohio.

Figure 19: Summary of key Pennsylvania water and fluid flows



Source: All figures calculated in this report.

KEY PENNSYLVANIA RESULTS

- In Pennsylvania, no single database is available to document withdrawals by Marcellus wells statewide. SRBC data, however, documents that in the SRB, approximately 8.3 billion gallons of water were withdrawn for Marcellus wells from 2009 through 2012 (Table 16).
- Of the total withdrawals for Marcellus wells in the SRB, about 6 billion gallons, or 72%, was withdrawn directly from surface and groundwater (Table 16). This figure provides a minimum percentage, because additional surface and groundwater is provided to Marcellus wells via public water systems, which are accounted for separately.
- Reused flowback fluid as a percentage of total injection volume is not available statewide; however, in the SRB, reused flowback fluid increased to 18% of total injection volume for Marcellus wells by 2012 (Table 19).
- According to data reported to FracFocus, Pennsylvania Marcellus wells injected approximately 10 billion gallons between 2009 and 2012; however, the reporting rate to FracFocus was only approximately 41% in this time period, so the true statewide injection volume was an estimated 24 billion gallons. An average of 4.3 million gallons have been injected into Marcellus wells during this time period (Table 17 and Table 18).
- According to data from SRBC, approximately 9.4 billion gallons of fluid were injected into Marcellus wells in the SRB—a subset of those in Pennsylvania—between 2009 and 2012 and averaged 4.3 million gallons per well—the same as the statewide average for wells that reported to FracFocus (Table 18 and Table 19).
- During 2009 through 2012, an average of 6% of the fluid injected into Marcellus wells in the SRB was recovered (Table 20).
- Flowback fluid makes up only 38% of the total waste reported from Marcellus wells in Pennsylvania (Figure 13).
- The percentage of waste reused has increased substantially and reached 56% of total waste in 2012 (Table 21).
- From 2008 through 2011, 88% of waste from horizontal Marcellus wells in Pennsylvania stayed in Pennsylvania, 9% was shipped to Ohio, and 2% was shipped to West Virginia (Table 22).
- Most of the waste generated in 2008 through 2011 was kept in-state for treatment and discharge to surface waters: 38% was sent to brine or industrial waste treatment plants located in Pennsylvania and an additional 15% was sent to municipal sewage treatment plants in Pennsylvania (Table 22).
- Horizontal Marcellus wells in Pennsylvania, on average, removed about 4.1 million gallons from the hydrologic cycle between 2009 and 2011 (Table 23). This totaled an estimated 17.8 billion gallons.
- In Pennsylvania, the blue water footprint, which represents the volume of water removed from the hydrologic cycle per unit of gas produced, ranges from 3.2 to 4.2 gallons per Mcf from 2009 to 2011 on a 4-year production basis. When considering the sensitivity of these results to higher natural gas estimates, the range dropped to 1.2 to 3.9 (Table 31). The discrepancy appears to be because of different estimates for natural gas production.

7.2.2 *Data collection and reporting*

As summarized in Table 38, current Pennsylvania laws and regulations require operators to compile and report key information related to withdrawals, injections, recovery, and disposal. However, water withdrawal data are only available in a format convenient for researchers within the SRB.

In addition, because fluid injection volumes and the chemicals in the fracking fluid are reported via FracFocus, they are not directly available in a searchable database that is available to the public, except via SkyTruth.

Waste recovery and disposal data, however, are compiled into Microsoft Excel spreadsheets and posted online for public use.

Table 38: Pennsylvania data reporting

Stage	Form where data is reported	Required or voluntary?	Data reported by operators?	Reported data compiled into searchable database?	Searchable database publicly available?
Water withdrawals	Completion report	Required	Yes	No	No
Fluid injection volume	FracFocus	Required via FracFocus starting in 2012	Incomplete	FracFocus data searchable via SkyTruth	FracFocus data available via SkyTruth
Chemicals in fluid	Chemical disclosure form, completion report, FracFocus	Required via FracFocus starting in 2012	Incomplete	FracFocus data searchable via SkyTruth	FracFocus data available via SkyTruth
Waste recovery	Production (and waste) report	Required	Yes	Yes	Yes
Waste disposal	Well site restoration report, production (and waste) report	Required	Yes	Yes	Yes

Note: Water withdrawals reported to Pennsylvania's water acquisition database cannot be filtered for withdrawals for drilling and fracturing in the Marcellus formation; therefore, it is not considered to fulfill the criteria in this table. Completion reports are only available as paper copies and are not compiled into a searchable or publicly available database.

FracFocus is not searchable for multiple wells. The chemical disclosure data submitted to FracFocus is not searchable except for individual wells. If not for SkyTruth, the data would not be useable except on a well-by-well basis. Act 13 also provides that, by January 1, 2013, PADEP shall make a determination whether the registry allows the department and the public to search by various fields. As of mid-2013, PADEP had not made such a determination. PADEP should therefore create a web-based interface so that the public can search FracFocus by state, county, operator, year, or other useful search terms. This would obviate the need for a nonprofit organization such as SkyTruth to compile a separate database based on the contents of FracFocus. It would also allow such a search to use up-to-date entries in FracFocus. Now, SkyTruth only updates its datasets monthly.

Only summary data are available from SRBC without paying exorbitant fees. SRBC compiles informative data about water withdrawals, injections, and recovery, and these data are available online. However, this database is only available for a fee of $250 per quarter of data. Downloading data from 2010 to 2012 would then cost $3,000. For this report, free summary data were used because of the expense of accessing SRBC's database. SRBC is a public entity and, therefore, should make these data freely available to the public. Marcellus data from PADEP and WVDEP are all freely available. If fees are necessary, then they should be greatly reduced.

In Pennsylvania, Marcellus-specific water withdrawal data are not available outside of the Susquehanna River Basin. PADEP maintains a database of all water acquisitions by water users that withdraw greater than 10,000 gallons per day in any given 30-day period in all Pennsylvania river basins except the SRB. It is possible to filter this database to acquisitions for use by the oil and gas industry, but it is not possible to filter for withdrawals for drilling and fracturing in the Marcellus formation. While it is laudable that PADEP's water withdrawal database is freely available online, it should include fields such that data can be retrieved specifically for Marcellus wells.

Withdrawal data are not available for individual wells. Outside of the SRB, PADEP's water acquisition database tracks water withdrawals by individual withdrawal points and purchases. It is not possible to relate this data to individual wells or well pads. Within the SRB, SRBC's withdrawal data also cannot be tracked to individual wells. PADEP and SRBC should implement systems whereby water withdrawals are reported for individual wells. This would allow better tracking of sources of water for each well, and it would also allow comparisons against the estimates of future withdrawals by well that are submitted in each water management plan.

Pennsylvania completion reports are only available as paper copies. These reports include data that well operators now report to FracFocus such as chemical additives in the stimulation fluids, but they also include information not reported to FracFocus, such as the total volume of recycled water used. All information submitted via completion reports should be publicly available in electronic form—not just the information that is submitted to FracFocus. This may require action by PADEP and/or the Pennsylvania Legislature.

Duplicate waste disposal volumes are often submitted. The same waste volume was reported for multiple waste disposal events for many wells in Pennsylvania. This raises the question of whether the operator divided the volume before reporting or whether the volumes have been double- or triple-counted. PADEP should ensure that its reporting system clearly asks for well-by-well information. In addition, if an operator enters duplicate information for multiple wells on a single form, the system should automatically flag this and explain to the operator that well-by-well information should be entered.

7.3 Summary

Recent laws and regulations in West Virginia and Pennsylvania have set in motion a significant amount of new data collection and reporting regarding the burgeoning Marcellus Shale industry. Today, publicly available information quantifies the volumes of water withdrawn; fluid injected; and waste recovered, disposed of, and recycled. However, as documented in this report, reporting is not complete, operators have entered inconsistent and erroneous data, and some data are not freely and publicly available.

Given the holes in these datasets, it is likely that much more water is being withdrawn and more waste is being generated than is reported. In short, the true scale of water impacts can still only be estimated.

A considerable amount of flowback fluid is now being reused and recycled. This is commendable, and maximizing the amount of fluid recycled should continue to be a focus of the industry. However, the data suggest that even as more waste is recycled, it is only displacing a small percentage of freshwater withdrawals. Therefore, as Marcellus development continues at a rapid pace, recycling and reuse cannot be the single solution to protect the region's water resources from withdrawals.

The data suggest that, in recent years, approximately 4.7 million gallons per well in West Virginia and 4.1 million gallons per well in Pennsylvania have been removed from the hydrologic cycle in recent years. While West Virginia and Pennsylvania are generally water-rich states, these results have potential impacts as similar horizontal drilling and hydraulic fracturing operations are developed in shale plays in more arid areas. The specific volumes of fluid injected and waste recovered will certainly vary in different plays based on the depth and thickness of the shale and other factors; however, these data suggest that the removal of water from the hydrologic cycle is an impact worth considering and mitigating.

A final key observation is that, as Marcellus development proceeds, waste generation is increasing. In Pennsylvania, operators reported an almost 70% increase in waste generated from 2010 to 2011—rising to a reported 613 million gallons of waste in 2011. The question of how to appropriately handle this growing volume of waste will continue to loom large until the pace of well development slows.

As these databases become more complete and accurate, we expect the estimates in this report to be refined. However, the estimates in this report represent the best available results that correspond to the data self-reported by Marcellus operators.

Overall, our findings suggest that the volumes of water used to fracture Marcellus Shale gas wells are quite substantial, the quantities of waste generated are significant, and continual improvement and enforcement of data collection and reporting requirements will be necessary to minimize the potential impacts to water resources in West Virginia, Pennsylvania, and Ohio.

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APPENDIX A: DETAILED DATA COLLECTION AND REPORTING REQUIREMENTS IN WEST VIRGINIA

Water management plan

According to the Natural Gas Horizontal Well Control Act, a water management plan must be submitted along with a well work permit application for any well requiring the use of greater than 210,000 gallons of water obtained by withdrawals from state waters during any 30-day period. This plan may be submitted on an individual well or watershed basis, and must include the following information:

- Type of water source, the county of each source to be used by the operation for water withdrawals, and the latitude and longitude of each anticipated withdrawal location;
- Anticipated volume of each water withdrawal;
- Anticipated months when water withdrawals will be made;
- Planned management and disposition of wastewater after completion from fracturing, refracturing, stimulation and production activities; and
- A listing of the anticipated additives that may be used in water utilized for fracturing or stimulating the well.[34]

For all surface water withdrawals, the water management plan must also include an identification of the current designated and existing water uses, including any public water intakes within 1 mile of the withdrawal location. The operator must also demonstrate that sufficient in-stream flow will be available immediately downstream of the withdrawal location, and include methods to be used to minimize adverse impacts to aquatic life.

A well work permit will not be issued without a water management plan that has been approved by the Secretary.[35]

Large quantity water user registration

The Water Resources Protection and Management Act governs water use by large quantity water consumers—including Marcellus wells, other water-intensive industries, and public water supplies. Any entity that withdraws greater than 750,000 gallons of water during one calendar month is required to register with the WVDEP Water Use Section. These large-quantity users must update the WVDEP annually on their water use. If water use falls below this threshold, further reporting is not required.

Frac Water Reporting Form

All well operators who use greater than 750,000 gallons of water to fracture a well must register as a large-quantity user and report their water use and disposal through the online Frac Water Reporting Form. While the Act specifies that reporting is required for ***withdrawals*** of 750,000 gallons or more, instructions provided with the Frac Water Reporting Form requires reporting if a well ***uses*** 750,000 gallons or more to frack a well (WVDEP 2013b). This form includes a variety of information related to withdrawals, injection, recovery, and disposal.

Withdrawal information is entered for each ***well site,*** and not by well. For example, six wells might be drilled from a single well pad; in this case, withdrawal information for all six wells would be

34 W.Va. Code §22-6A-7.
35 W.Va. Code §22-6A-8.

reported for a single "site." Sometimes, a centralized impoundment is used as an intermediate holding pond for water that will be used at numerous well pads. Because water withdrawals are reported by site, situations where there are multiple wells at the site of withdrawal delivery, complicate efforts to use this database to track the volumes of withdrawals used at specific wells.

For each well site, the Frac Water Reporting Form requires operators to enter the following information:

- type and name of each water source,
- latitude and longitude of each source,
- total amount withdrawn from each source, and
- begin and end date of each withdrawal.

In contrast, water injection, recovery, and disposal volumes are reported for each ***well***. Information reported includes:[36]

- API number;
- well location coordinates;
- producing formation and drill depth;
- amount of water injected and begin and end dates of injection;
- total amount of fluid recovered during the 30 days following injection or until half of the total volume injected is recovered, whichever occurs first;
- volume of waste water reused at another well and the API number of the well where the waste was reused;
- volume of water disposed of at a UIC well, permit number of the UIC well, begin and end date of disposal at the UIC well, and location coordinates of the UIC well; and
- volume of water disposed of at a POTW, permit number of the POTW, begin and end date of disposal, and location coordinates of the POTW.

Well operators are directed to complete a Frac Water Reporting Form within one year following fracturing. No system is currently in place for enforcing reporting compliance. As shown previously in Table 9, only approximately 35% of 2010 and 2011 wells have reported water use to the Frac Water Reporting database.

For this report, flowback fluid in West Virginia is defined as the fluid that returns to the surface within 30 days of injection, or 50% of the total volume injected, because this is the fluid required to be reported by WVDEP. Brine continues to return to the surface for the duration of the life of the well. This fluid must be collected and disposed of by well operators; however, it is not reported in West Virginia.[37]

Based on an analysis of Pennsylvania waste disposal data (See Section 5.4), flowback fluid constitutes approximately 38% of the total volume of waste generated by Marcellus wells in Pennsylvania (Figure 12 and Figure 13). Thus, because well operators in West Virginia are only required to report flowback fluid, large quantities of waste—perhaps as much as 62%—remain unreported in West Virginia. This unreported waste is virtually entirely made up of brine and drilling waste (see Figure 13).

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[36] The Natural Gas Horizontal Well Control Act requires operators to keep records of the information reported on the Frac Water Reporting Form onsite for three years, but does not mandate that operators report this data. Operators are also required to document the following information related to transportation of fluids to be used in hydraulic fracturing and recovered from wells: quantity of water transported, collection and delivery or disposal locations, and the name of the water hauling company.

[37] This requirement is inconsistent with Pennsylvania, in which a wide variety of waste types are reported: basic sediment, produced fluid, drill cuttings, flowback fluid, drilling fluid, flowback fracturing sand, servicing fluid, and spent lubricant.(PADEP 2013f).

Well completion report

Operators are required to submit a well completion report to WVDEP and the West Virginia Geological and Economic Survey within 90 days following completion of well work. This report includes geological, drilling, and cementing information.[38] The Natural Gas Horizontal Well Control Act and the Rules Governing Horizontal Well Development[39] mandate that a list of all additives used during hydraulic fracturing and stimulation must be included in this report. Information required includes the following:

- the trade name, supplier, and purpose of each additive used in the hydraulic fracturing and stimulation process;
- a list of chemicals and additives intentionally added to a base fluid for the purpose of preparing a fracturing fluid;
- the Chemical Abstracts Service (CAS) registry number of each chemical;
- the maximum concentration of each chemical in the additive;
- the maximum concentration as added to the base fluid; and
- the volume of the base fluid to be used.

The operator may designate this information as a trade secret not to be disclosed to the agency; however, this information must be disclosed to health care professionals for use in treatment and diagnosis in the case of a medical emergency or to WVDEP in the case of an investigation by the agency.

Since July 1, 2013, the effective date of amendments to the Rules Governing Horizontal Well Development,[40] the chemical additives reporting requirement may be fulfilled by reporting to WVDEP and to the FracFocus Chemical Disclosure Registry.[41]

Other requirements

In addition to the well completion report, the Natural Gas Horizontal Well Control Act includes a number of other provisions to address the large quantities of water required for fracking, including:

- identification of uses of surface waters from which withdrawals will be made,
- prior notification of WVDEP of the source of water from which withdrawals will be made,
- receipt of verification from WVDEP before withdrawal commences that streamflow is sufficient to protect uses, and
- appropriate signage at withdrawal points.

Production reports

Production reports,[42] which include the quantity of oil and gas produced at each well for each month, must be submitted annually for the duration of production of a well. Data for the preceding year must be submitted by March 31 each year.[43]

[38] 35 CSR 4-12.
[39] 35 CSR 8.
[40] 35 CSR 8.
[41] 35 CSR 8-10.
[42] Form WR-39E.
[43] 35 CSR 4-15.

APPENDIX B: DETAILED DATA COLLECTION AND REPORTING REQUIREMENTS IN PENNSYLVANIA

Water management plan

Operators cannot withdraw or use water for drilling or hydraulic fracturing of Marcellus wells except in accordance with an approved water management plan. Compliance with approved water management plans is a condition of well permits issued for drilling and hydraulic fracturing of Marcellus wells.[44]

Water management plans are submitted to PADEP for review and approval…"based upon a determination that the proposed withdrawal, when operated in accordance with the proposed withdrawal operating conditions set forth in the plan, including conditions relating to quantity, withdrawal rate and timing and any passby flow conditions, will:

- not adversely affect the quantity or quality of water available to other users of the same water sources;
- protect and maintain the designated and existing uses of water sources;
- not cause adverse impact to water quality in the watershed considered as a whole; and
- include a reuse plan for fluids that will be used to hydraulically fracture wells."[45]

For withdrawals within the SRB, these criteria are presumed to be achieved if the proposed water withdrawal has been approved by and is operated in accordance with conditions established by the SRBC. A similar presumption is included for withdrawals within the jurisdiction of the Delaware River Basin Commission or the Great Lakes Commission. However, PADEP still may establish additional requirements as necessary to comply with the laws of this Commonwealth.[46]

Well record

Although not used for this analysis, well records, which must be submitted to PADEP within 30 calendar days of cessation of drilling or altering a well, include a variety of information such as contact information for the permittee, locational information for the well, the dates that drilling started and ended, the drilling method, information about casings and cement, elevation and depth of the well, drillers logs, and other information.[47]

Chemical disclosure form

A chemical disclosure form must be filed within 60 days following conclusion of hydraulic fracturing. According to Act 13, the form must be completed and posted on the chemical disclosure registry: FracFocus.[48]

Provisions are made for trade secrets and confidentiality; however, all information not determined to be a trade secret or confidential is available to the public.

Act 13 also provides that, by January 1, 2013, PADEP shall make a determination whether the registry allows the department and the public to search by various fields. If not, PADEP is to

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[44] Act 13 Section 3211(m).
[45] Act 13 Section 3211(m)(2).
[46] Act 13 Section 3211(m)(3).
[47] 25 PA §78.122(a).
[48] Act 13 Section 3222.1.b.2.

investigate the feasibility of making the chemical disclosure information available on its Web site. As of mid-2013, PADEP had not made such a determination (Hanger 2013; Konschnik et al. 2013).

Completion report

Completion reports must be filed within 30 days after completion of a well (30 days after the well is capable of production). Completion reports must include a variety of information related to water quality and quantity:

- a descriptive list of the chemical additives in the stimulation fluids;
- the trade name, vendor and a brief descriptor of the intended use or function of each chemical additive in the stimulation fluid;
- a list of the chemicals intentionally added to the stimulation fluid, by name and chemical abstract service number;
- the maximum concentration of each chemical intentionally added to the stimulation fluid;
- the total volume of the base fluid;
- a list of water sources used under the approved water management plan and the volume of water used;
- the pump rates and pressure used in the well; and
- the total volume of recycled water used.[49]

These completion reports are only available in paper copies (Lutz 2013b).

Well site restoration report

Well site restoration reports must be submitted within 60 days after restoration of the well site.[50] This report includes information about:

- land application of tophole water;
- the amount of off-site waste disposal of drilling fluid, fracking fluid, or other waste amounts;
- the locations to which this waste is transferred (disposal well, landfill, sewage treatment plant, brine disposal plant, or other location, including permit number and hauler information);
- on-site disposal of drill cuttings or waste;
- pit disposal;
- land application; and
- site restoration.

Information related to off-site waste disposal is a fundamental data source for this report. The well site restoration report is submitted only once and only reflects disposal of waste encountered soon after restoration of the well site. The production (and waste) reports described below are submitted every six months into the future and are our source for disposal data analysis.

[49] Act 13 Section 3222.b.1.
[50] 25 Pa. Code §78.65(3).

Production (and waste) reports

Production (and waste) reports must be filed twice per year for Marcellus wells: on or before February 15 and August 15 of each year.[51] Each report must include gas production for the previous six-month period. For example, reports filed by February 15 provide six-month production figures for July through December of the previous year.[52] PADEP posts production reports online as spreadsheets (PADEP 2013b).

In addition to gas production, these reports must also include information on the amount and type of waste produced and the method of waste disposal or reuse.[53] While the well site restoration report includes similar waste information, it is submitted only once, soon after restoration of the well site. The production (and waste) reports described in this section are submitted every six months into the future.

[51] When this six-month reporting period was instituted, some Marcellus production data were reported twice (Lutz et al. 2013).
[52] Act 13 Section 3222.a.1.
[53] 25 PA §78.121.

APPENDIX C: QUALITY CONTROL FOR WEST VIRGINIA DATA

Any wells with missing total injection, total recovery, or total disposal volumes were removed. In one case, a well had a negative value entered for recovery volume; this well was removed from our dataset. Next, recovery amount and disposal amount (which includes reuse) for each well were compared. Because all recovered fluid should be disposed of or reused, wells with more than a 10% difference between amount disposed and amount recovered were removed from the dataset.

In some instances, an identical volume of fluid injected was reported for two or more wells located at the same well site within the same year. We assumed that the total volume injected at a well site was reported for each well. Therefore, to avoid overestimating the total volume injected, the volume reported was divided by the number of times that it was reported, and this resulting volume was used in further analyses.

In addition, for some wells, identical volumes were reported for disposal of one well's waste at multiple facilities. Lutz et al. (2013) performed an extensive analysis of waste generated by Pennsylvania Marcellus gas wells (See Section 5.4). The PADEP data used in this analysis also contained numerous instances where the same waste volume was entered for multiple disposal events. The authors discussed this issue with PADEP employees familiar with the reporting system and determined that it was highly likely that identical volumes were errors and that the total volume was entered for each disposal event. Thus, to avoid over-estimation of fluid volumes, each identical volume was divided by the number of times that it occurred. We followed this method for the WVDEP data analyzed here to maintain consistency with the Pennsylvania method. It is possible that some of these identical volumes are true values; if so, we would be reporting conservative estimates for water use and disposal in West Virginia.

APPENDIX D: QUALITY CONTROL FOR PENNSYLVANIA DATA

One issue with the PADEP wastewater data was that it showed that identical volumes of a given wastewater type were being taken from the same well to multiple treatment facilities within a given year. Through conversations with PADEP, it became clear that there was a problem with the way that the data was entered into the system. In reality, only a portion of the total was being delivered to each disposal facility. To remedy this issue, the total volume that was replicated was divided by the number of times that it was entered (Lutz et al. 2013).

Some wells lacked values for drilling fluid and for flowback fluid. As both fluids are essential for hydraulic fracturing, it was assumed that missing values resulted from a lack of reporting by well operators. Only wells with nonzero values for drilling fluid and flowback fluid were included in the dataset used for analysis (Lutz et al. 2013).

Wells generate brine for multiple years during production. In many instances, brine was not reported consistently for each year of production. Zero brine production values were assumed to be reporting errors, and these wells were removed from the dataset (Lutz et al. 2013).

Problems were also identified related to the geography of wastewater disposal facilities. Many of the names of wastewater treatment plants contained typos and were entered inconsistently by different operators. Typos were corrected by matching names to NPDES permits and using internet research. In addition, some disposal facilities were missing geographic coordinates. These data were also filled in. UICs with missing information were matched to a list of wells obtained from the Ohio Department of Natural Resources (Lutz et al. 2013).