

Penn State **Extension**

Water's Journey Through the Shale Gas Drilling and Production Processes in the Mid-Atlantic Region



The Mid-Atlantic Water Program is a coordinated effort among Delaware State University; University of Delaware; University of the District of Columbia; University of Maryland; University of Maryland, Eastern Shore; Penn State; Virginia State University; Virginia Tech; and West Virginia University.

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Robert Donnan

Gas pipeline being laid along a stream, Wetzel County, West Virginia.

Cover: Marcellus shale drilling in progress, Beaver Run Reservoir, Westmoreland County. Credit: Robert Donnan.

Introduction

Water is a critical ingredient for extracting gas from the Marcellus shale, which lies up to 9,000 feet underground beneath southern New York, northern and western Pennsylvania, the eastern half of Ohio, and most of West Virginia. In the Mid-Atlantic region the shale around most new gas wells has to be hydraulically fractured to release the trapped gas so that it can be brought to the surface. The drilling process itself can require more than 100,000 gallons of water, and the hydraulic fracturing (“fracing”) process can require 2.5 million to 8 million gallons per well. Fracing uses high-pressure water, sand, and chemicals to break up the gas-holding rock and create pathways for the flow of gas to the borehole.

Horizontal drilling is used to increase the well’s contact with the shale rock formation. After drilling several thousand feet into the earth, this technology allows the borehole to be gradually turned 90 degrees over several hundred feet and horizontal drilling to continue for about a mile. Fracing a horizontal well requires significantly more water than a traditional vertical well. For a more detailed introduction to water-related issues surrounding the development of Marcellus shale natural gas wells, see the Penn State Water Resources Extension publication “Introduction to Hydrofracturing” at extension.psu.edu/water/marcellus-shale/hydrofracturing/introduction-to-hydrofracturing-1.

Development of the Marcellus shale resource in Pennsylvania began in 2007 and has proceeded rapidly. As of November 2011, there were about 4,200 wells tapping natural gas in the Marcellus shale in Pennsylvania, and more than 3,000 additional wells had been permitted but not yet drilled. As of April 2011, there were about 1,400 completed Marcellus wells in West Virginia and 1,300 wells permitted but not yet drilled.

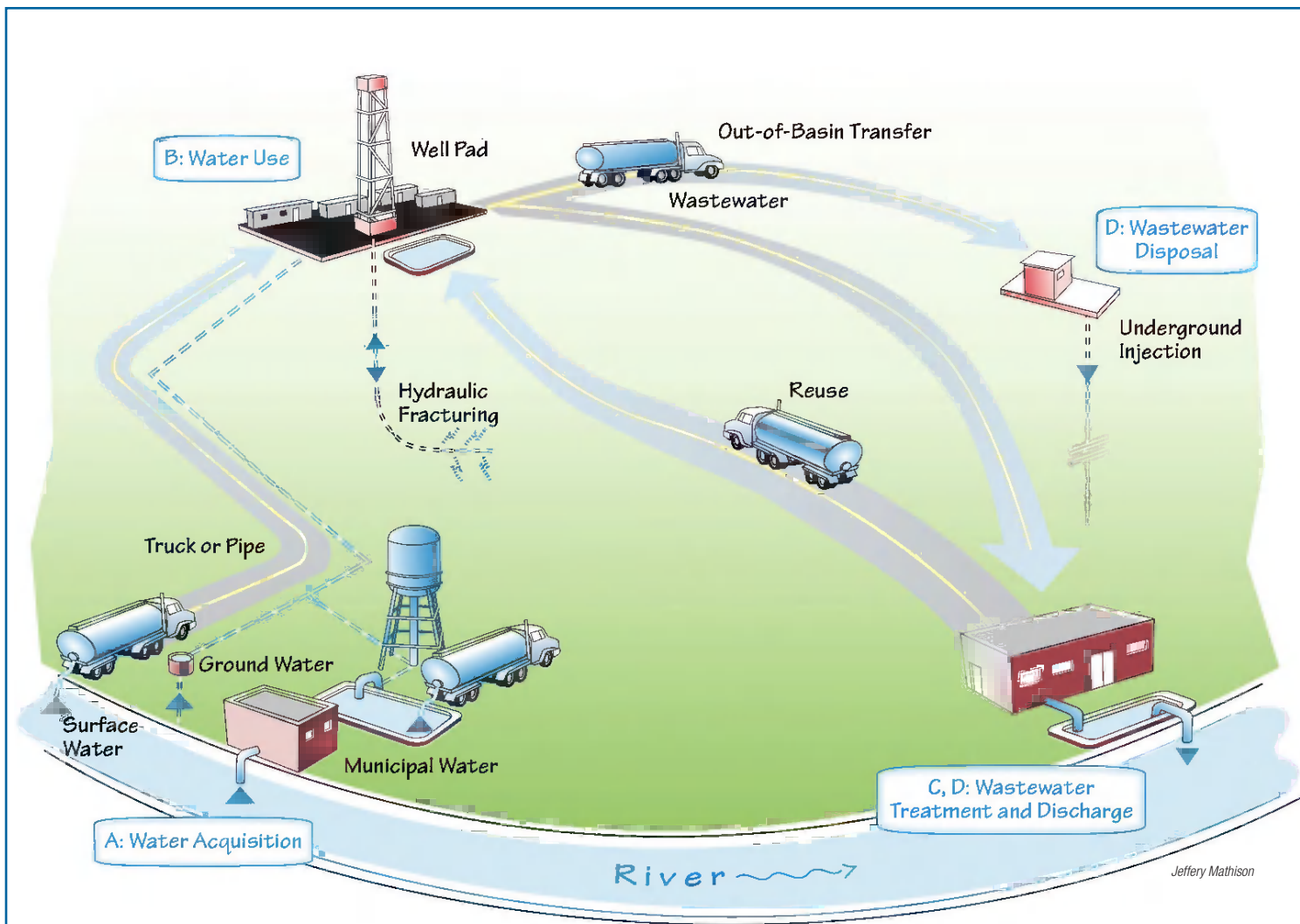
State and intrastate government agency resources are being challenged to keep up with the rapid pace of shale gas development. New technologies are being tried in both the resource development process and in managing environmental and water quality and quantity impacts. The regional river basin commissions, which exist largely in the eastern part of the Marcellus region, have been actively addressing Marcellus water management issues by developing regulations to address the industry’s demands on water resources and potential quantity and quality issues. For more detail on river basin commission roles in Mar-

cellus development, see the Penn State Extension publication “River Basin Approaches to Water Management in the Mid-Atlantic States” at extension.psu.edu/water/marcellus-shale/regulations/river-basin-approaches-to-water-management-in-the-mid-atlantic-states.

This publication illustrates the various paths for a water droplet used in the Marcellus shale natural gas industry in the Mid-Atlantic region. Using publicly available information, we attempt to track and quantify current water use through the stages of the gas well development process. This publication focuses mostly on Pennsylvania because it has the most Marcellus drilling activity of any state to date. All data reported are based on wells in Pennsylvania. Much of the data comes from the Susquehanna River Basin Commission (SRBC), which has been out in front in collecting water use data. We raise issues pertinent to most other Mid-Atlantic states with Marcellus shale, as well as Ohio. For the purposes of illustration we have simplified various steps in the process. Note also that other shale deposits, such as the Utica shale, underlie parts of these states. These may also eventually be drilled for gas, with the accompanying use of water and generation of wastewater.

Outside of the Susquehanna River basin, it is difficult to accurately assess the amounts and sources of water used in Marcellus well development and the amounts of wastewater being generated, treated, and disposed of through various paths. A system for tracking water flows has only recently been implemented in Pennsylvania and needs significant improvement. Additional errors may occur because of inconsistencies in how drilling companies self-reported water-related statistics. Numbers cited here give insight only about general trends, but they are useful for painting a big picture of the industry’s water use.

Challenges to safely disposing of Marcellus wastewater exist from its generation in many places that already have water quality problems due to acidic mine drainage from coal mining. This drainage impairs more than 3,000 miles of streams in Pennsylvania and about 5,000 miles in West Virginia. The presence of acidic mine drainage and, in some areas, pollutants from other industries, such as public wastewater treatment facilities and pharmaceutical and chemical manufacturers, reduces the ability of waterways to assimilate pollutants in treated Marcellus wastewater.



Jeffery Mathison

Fracing a horizontal Marcellus well may use 2.5 million to 8 million gallons of water, typically within about a week. This water may come from surface or groundwater or emerging alternate sources such as mine drainage. It is usually transported to the drilling site via truck, but in some cases water pipelines are used.

Currently, in the Marcellus region two to eight gas production wells typically extend underground in various directions from one 3- to 5-acre well pad. At the well pad water is mixed with sand and chemicals that may include oils, gels, acids, alcohols, and various manufactured organic chemicals. This solution, called “frac water,” is then forced under high pressure into the subsurface rock formation at the appropriate depth. Depending on the area within the Marcellus region, between 60 and 90 percent of this water remains underground, where it is trapped within the shale formation itself. The

water that returns to the surface (called “flowback water”) is the primary source of wastewater from shale gas drilling activities. Flowback water contains very high amounts of total dissolved solids (salts and metals) and may also contain naturally occurring radioactive materials originating from the shale.

Flowback water may be trucked to a treatment facility and treated, and then trucked to another well pad, where it is stored in lagoons or tanks until it is reused. Frac-related water treatment often occurs farther from the drill pad than does water acquisition.

Because only about 10 percent of the frac water is recaptured as flowback water, and some of that water is subsequently lost during the treatment process, additional water (termed “make-up water”) typically has to be added to the treated flowback water. Fresh water, or relatively clean water from another source (such as treated

municipal wastewater, abandoned mine drainage water, or nonpotable water sold by public water supply agencies) is usually used for make-up water. Treated water may be discharged into a river, creek, lake, or other surface water body only if it meets stringent state discharge standards. Some flowback water is disposed of without treatment via underground injection into suitable geologic formations very far below the lowest fresh groundwater zone, although this activity is extremely limited in Pennsylvania. In Pennsylvania, this process requires a permit from both the U.S. Environmental Protection Agency (EPA) and the Pennsylvania Department of Environmental Protection (PaDEP).

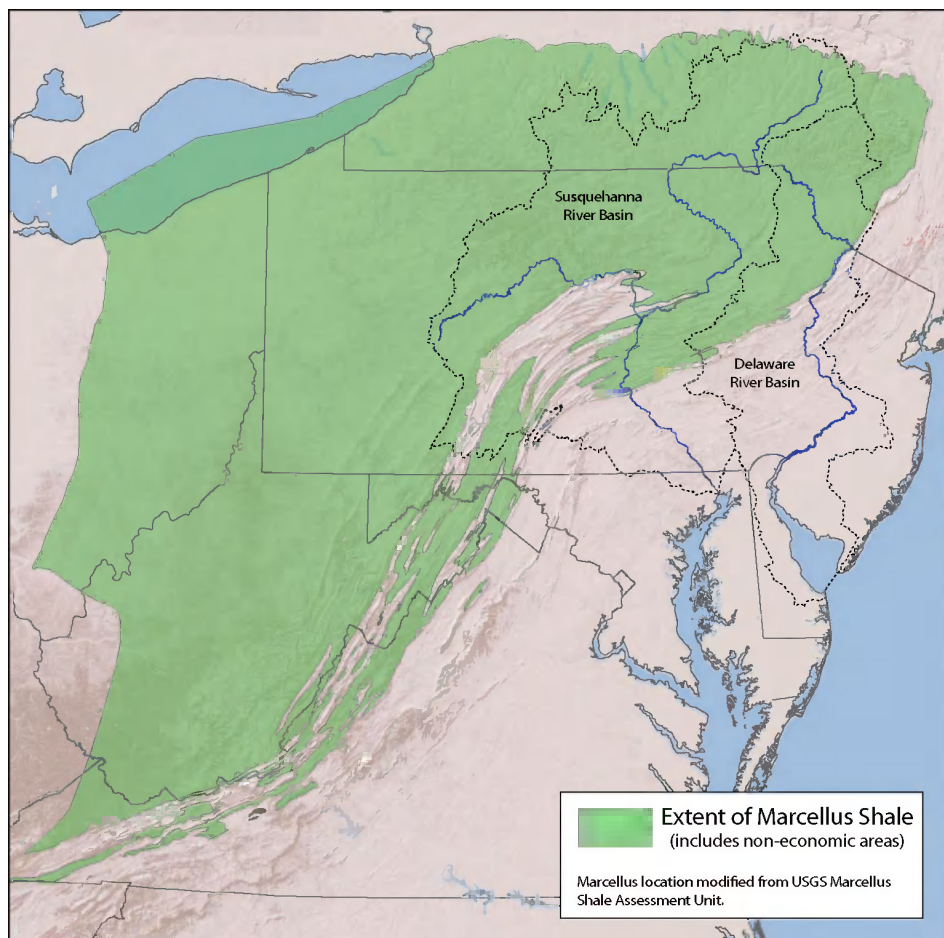
The well development process includes a number of points where accidents, spills, or leaks could occur due to mechanical failure or human error. More detail about each of these processes is included below.

A. Water Acquisition

About two-thirds of the fresh water used for fracing is withdrawn from permitted surface water sources and 30 percent is purchased from public water suppliers. The average amount of water used to hydraulically fracture a well is approximately 4.2 million gallons, 90 percent of which is fresh water and 10 percent is reused flow-back water from a previous well fracing. These numbers are based strictly on water withdrawal activity in the Susquehanna River basin in Pennsylvania from June 2008 to August 1, 2011 (831 wells reporting). Surface water is a primary source for hydraulic fracturing because it is accessible to most drilling sites and is therefore less costly to use. In some cases, discharges of pollutants, such as acidic mine drainage, from upstream sources can adversely affect the quality of the water that the gas industry wishes to use, necessitating treatment before use.

Regulatory requirements governing withdrawals for Marcellus drilling operations are in flux throughout the Mid-Atlantic region. Pennsylvania's regulatory climate is currently more settled than the others in the region, although some observers expect further revision of the state's oil and gas laws or regulations in the near future. Because of concerns with shale gas in various parts of the country, EPA is considering more oversight of state handling of environmental aspects of this industry.

The government institutions involved in water acquisition for Marcellus drilling and the process and approvals required differ by state and even within states (Table 1). For example, water withdrawals of any amount in the Susquehanna River watershed to develop gas wells in the Marcellus and other shale formations require approvals from the SRBC, a federal/interstate commission that seeks to protect and manage the water resources of the basin. Water withdrawals are also regulated by the PaDEP throughout Pennsylvania, including in areas of the state within the Ohio River basin. The Delaware River Basin Commission has the authority to regulate water withdrawals and discharges and is currently developing regulations specifically for the natural gas industry. Regardless of which river basin the water source is located in, an approved water management plan is required as a special condition of a well permit under the Oil and Gas Act throughout Pennsylvania.



Chuck Anderson

Table 1. Water withdrawal requirements and state of the industry in the Mid-Atlantic states.

<i>Jurisdiction</i>	<i>Activity</i>	<i>Water withdrawal requirement</i>
Pennsylvania	Active drilling and production	Water management plan required for Marcellus operations throughout state; Act 220 (Water Resources Planning Act) requirements must also be met if withdrawal meets Act 220 threshold
Susquehanna River basin	Active drilling and production	Above, plus SRBC approval required
Delaware River basin	Drilling suspended pending development of revised regulations by Delaware River Basin Commission (DRBC)	Water management plan, Act 220 requirements, plus DRBC approval required
New York	State government is taking steps to end effective moratorium on Marcellus drilling	New water withdrawal permitting law passed; applications for withdrawal of 2 million gallons a day or more will likely be due by Feb. 2015, while those for 0.5–1.99 MGD will not be due until Feb. 2016;* SRBC approval would also be required
West Virginia	Active drilling and production	Water management plan to West Virginia Department of Environmental Protection required for companies that withdraw more than 210,000 gallons of water per month
Maryland	Leasing activity; a few drilling permit applications; Department of the Environment proposed two-year drilling delay (Feb. 2011)	

*See "Draft Supplemental Generic Environmental Impact Statement," www.dec.ny.gov/energy/75370.html. The new law was signed on August 15, 2011.

Some water for fracking is withdrawn from pristine headwater streams, some of which may run low on water during seasonal droughts in summer and fall. This occurred a few times in Pennsylvania, mostly in the early years of Marcellus development. The SRBC considers cumulative flow impacts when regulating surface withdrawals to protect against loss of water for other beneficial uses by specifying that water withdrawal must be limited or stopped when certain low flow volumes are reached. In summer 2011, SRBC ordered gas companies to stop water withdrawals from about 40 permitted locations because of low flows.

In the Mid-Atlantic, water availability changes from season to season and year to year. If a drought occurs, some surface water sources become temporarily unavailable for Marcellus withdrawals. Pennsylvania, New York, and both of the river basin commissions have or are developing rules through which minimum “stream pass-by flows” will be established and incorporated into water withdrawal permits. Stream pass-by flows are meant to ensure that enough water remains within the waterway to protect the aquatic habitat and indigenous species as well as any downstream water quantity needs.

Water quantity and quality are closely linked. At low flow, streams are more sensitive to the addition of potential contaminants because less water is available for diluting pollutants.

Many areas of the Mid-Atlantic, both within and outside the Marcellus shale field, have no river basin commission focused on water quantity. This has raised a number of issues about equity and uniform permit requirements. In Pennsylvania, for example, PaDEP is applying SRBC’s low-flow guidelines in the area of the state outside SRBC’s and DRBC’s oversight to ensure a consistent regulatory approach statewide.



Kathy Pike, Altoona Water Authority

A bulk water filling station operated by Altoona Water Authority, Pa.

B. Water Use

Of the water used to frac a well, about 90 percent is fresh and 10 percent is reused from a previous frac job. These numbers are based strictly on withdrawals in the Susquehanna River basin in Pennsylvania from June 2008 to August 1, 2011 (831 wells reporting). After the fracking, about 10 percent (for these 831 wells) of the water injected into the ground returns to the land surface within 30 days (this portion is called flowback water), and the rest remains underground, absorbed by the relatively dry shale bed. Wider ranges of flowback water amounts may be experienced outside the Susquehanna River basin in Pennsylvania.

Once the well is in production, water generated is called produced water or production water. Produced water is removed from the gas at the top of the wellhead before the gas goes into the pipeline. This water is stored onsite and periodically removed for treatment or disposal. It is generated at lower volumes than flowback throughout the operational life of the well.

Some laypeople and water management professionals have raised concerns about the large amounts of water that remain below ground after fracking—that this water may be permanently (or at least in the very long term) removed from the water cycle. At this time it is premature to conclude this because data for produced water are limited. The shale may absorb the water. In addition to the flowback and produced water that returns to the earth’s surface to rejoin the water cycle once treated, water vapor is released back

into the atmosphere when the natural gas is combusted.

There is no publicly available evidence to date that groundwater contamination with fluids used in hydraulic fracturing has occurred as a direct result of the fracking process in the Marcellus. A typical Marcellus gas well extends 4,000 to 8,500 feet into the earth. In Pennsylvania, groundwater-bearing rock layers tapped for private water wells typically extend only 20 to 500 feet below the surface. Because of the large distances between the Marcellus shale layer and the much shallower “fresh” groundwater tapped by drinking water wells, there is little chance that the water used to frac the Marcellus shale layer could later contaminate these private water wells. Except under pressure, water does not run up hill. Stricter state regulations that went into effect in Pennsylvania in early 2011 require more protective well casing and cementing practices through the groundwater-bearing rock layers to help prevent this problem.

There have been incidents of stray or migrating methane gas that has affected private water wells located near Marcellus wells in some areas of Pennsylvania. Methane migration has typically been traced to faulty well casings or inadequate cement seals on the wells. The stricter well construction and casing regulations in Pennsylvania should reduce the potential for this problem to occur in the future. These regulations were strengthened in response to these methane migration incidents.



Craig McKibben

A Marcellus site in Bradford County, Pa. The red tanks hold water.

C. Wastewater Treatment

Of the water used in fracking that returns to the land surface as flowback water, some of it may be reused in another frac job. This practice has been increasing in Pennsylvania over the last several years. The average percentage of flowback water now reused in Pennsylvania is uncertain, but it is estimated to be about 75 percent. Nearly all of this flowback water is treated prior to reuse. Only about 5 percent is disposed of without treatment via underground injection (data from PaDEP for July to December 2011).

Flowback water presents treatment challenges because it contains extremely high amounts of total dissolved solids (TDS). The longer frac water remains below ground in contact with the shale, the more TDS, metals, and naturally occurring radioactivity it picks up from the rock. Produced water also contains these pollutants, and at higher concentrations than in flowback.

In Pennsylvania in 2010 new regulations affecting discharges of natural gas wastewater (including both flowback and produced water) high in TDS took effect to protect water bodies and public drinking water. The regulations limit the amount of TDS and other pollutants that can be discharged into waterways. The regulations established effluent standards for natural gas wastewater of 500 milligrams per liter (mg/L) for TDS, 250 mg/L for chlorides, and 10 mg/L for barium and strontium for new and expanding facilities treating natural gas wastewater. These four standards are based on monthly averages. Discharges of water containing elevated levels of TDS existing prior to August 21, 2010, are exempt from the regulation unless or until they expand. The May 2011 PaDEP request to the industry to cease disposal of Marcellus wastewater at publicly owned treatment plants virtually shut down this type of treatment, although drilling wastewater from traditional shallow wells is still going to these plants.

Current options for treatment of flowback water include onsite or offsite dedicated treatment facilities, a few of which are already operational, but many more of which are proposed and/or under construction; reuse with or without pretreatment on or offsite; advanced facili-



Close-up of Marcellus impoundment, Clearfield County, Pa.

Patrick Drohan

ties; or underground injection. These are discussed in more detail below.

Most municipal wastewater treatment plants, which use a biological treatment system, are not set up to adequately treat the high-TDS flowback water. All they can do is dilute the TDS, which is insufficient given the large volume of flowback water generated in some localities. PaDEP asked gas drilling operators to voluntarily stop using these plants for Marcellus wastewater disposal by May 2011 because of mounting water quality concerns downstream of municipal wastewater discharge points. Agency data from 2011 indicate that statewide use of municipal wastewater treatment plants accounts for less than 1 percent of the volume of Marcellus wastewater disposed of in the state. The discharge of high volumes of treated Marcellus wastewater from a biological treatment system could be of particular concern for waterways that have limited ability to assimilate additional salt loadings. Bromide was of special concern to state regulators because it combines with chlorine added during public water supply treatment to form trihalomethanes, which can cause cancer in humans over the long term if in high enough concentration in sources of drinking water.

Many industrial treatment plants treat high-TDS wastewater by combining traditional physical/chemical processes with thermal distillation and end up with concentrated brine that is typically disposed of in permitted deep injection disposal wells. Crystallizers have been proposed to create salt, but this wastewater treatment by-product would then have to be landfilled, triggering another set of regulatory requirements. Other advanced wastewater treatment techniques under development involve membranes and ultrafiltration, but these systems also produce a concentrated brine solution as a waste by-product, which must be properly disposed of.

Only a few advanced treatment systems are already operational in Pennsylvania, but dozens of other technologies were in the permit application process in mid-2011.

Underground injection is discussed in the next section because no treatment is performed before injection.

D. Wastewater Discharge/Return

Reuse

Many drilling companies aim to reuse 100 percent of the flowback water. With the publicly available reporting system currently in place, it is difficult to ascertain whether the companies are able to reach these very high levels of reuse. Reuse reduces the total amount of fresh water needed and wastewater generated as well as associated truck trips.

It is difficult to accurately assess the amounts of Marcellus wastewater being treated and disposed of via the various paths because a system for tracking this wastewater has only recently been developed in Pennsylvania and it needs to be refined to capture the true amount of wastewater recycling. Further confusion may result from inconsistencies in how drilling companies self-reported wastewater statistics, how to define “wastewater,” and how to classify landfilled wastes that contain water. Given these caveats, according to the PaDEP data, industry reported that about 65 percent of the waste fluid went to “brine or industrial” treatment facilities during the last six months of 2010. However, during the first six

months of 2011, this value decreased to about 35 percent. At least some of these facilities are explicitly set up to treat water and return it to the operators (the water trucks are full in both directions). In 2011, this process of treatment and return of wastewater has been reported as “reuse” rather than “brine or industrial” treatment, partially explaining the large difference in values between the two time periods. Likewise, reported reuse accounted for about 25 percent of tracked wastewater during the last six months of 2010 but increased to about 55 percent during the first six months of 2011. As noted above, statistics cited here may indicate trends and are useful for getting a big-picture sense of the industry’s water use. It is unclear from the 2011 PaDEP database how about 5 percent of the Marcellus wastewater is treated and/or disposed of, but the 5 percent could be lost in sludge or evaporate, or is within the measurement error of the various flow meters used.

No state in the region other than Pennsylvania has yet reported data on Marcellus wastewater management, so it

is not clear if these numbers reflect current or future water flows across the region.

West Virginia has had a wastewater reporting system since April 2010, and the first report is expected in November 2011. New York has proposed such a system.

Underground Injection

In underground injection, untreated Marcellus wastewater is forced below ground out into rocks bounded above by an impermeable rock layer(s). This injection is regulated under the federal Safe Drinking Water Act and requires an underground injection control (UIC) permit. EPA is responsible for permitting these wells in Pennsylvania (about 8 wells) and New York (6 wells). The state environmental agencies administer EPA’s Underground Injection Control Program in West Virginia (74 wells), Ohio (~170 wells), and Maryland (no wells). Pennsylvania’s wells have little or no available capacity, so most Marcellus wastewater disposed of via this route is trucked to West Virginia or Ohio. In addition, some experts believe that much of the geology of Pennsylvania may not be suitable for these wells, but several proposed wells are under review by EPA. Underground injection is commonly used in other shale gas fields, such as the Barnett shale in Texas, where the geology is more suitable.

PaDEP data show that about 400 million gallons of Marcellus wastewater were generated in the first six months of 2011 in Pennsylvania. Twenty-one million gallons were disposed of in Ohio underground injection wells and a very small amount—about 5,000 gallons—in West Virginia underground injection wells during the same period. These data are imperfect, as discussed above. Still, the information is the best currently available. At this point it appears that out-of-state disposal accounts for relatively little in the bigger picture of the industry’s overall wastewater disposal.



Robert Dornan

Residual wastewater tanker headed south on I-79 near Washington, Pa.

Accidents, Spills, and Leaks

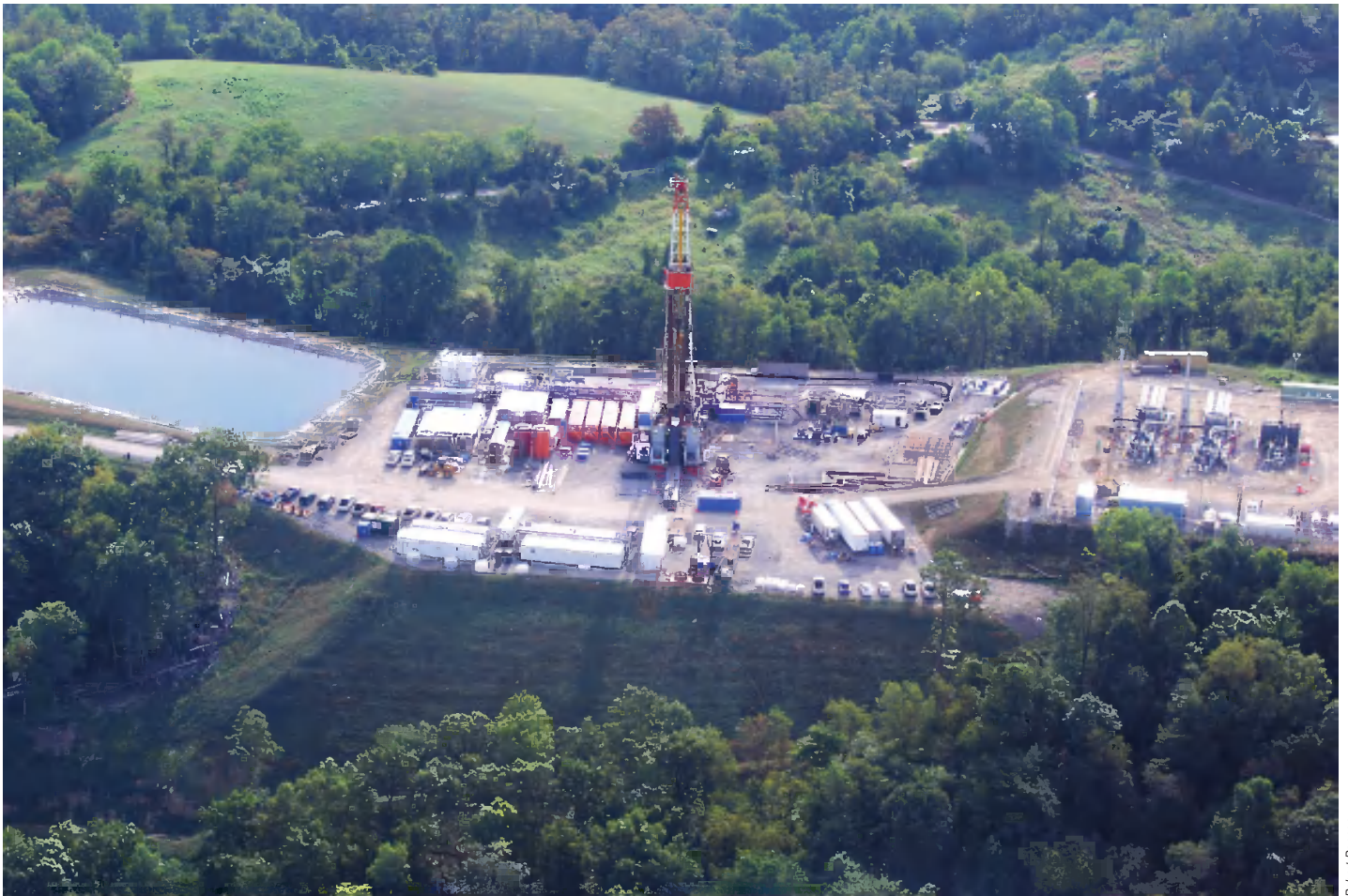
The chemicals used in fracking may include oils, gels, acids, alcohols, and various manufactured organic chemicals, which are often transported to drill pads on rural roads. The storage, treatment, and return of these waste fluids to the environment are water quality concerns. SRBC and DRBC require disclosure of the chemicals used in well development, although the exact ratios are proprietary. PaDEP regulations that took effect in 2011 also require that the chemicals used to frac wells be submitted as part of the well completion report. Under an emergency order issued by the governor in July 2011, West Virginia Department of

Environmental Protection requires such disclosure for companies that withdraw more than 210,000 gallons of water per month in the state.

The overall drilling process includes numerous points where accidents, spills, or leaks could occur, potentially affecting surface and/or groundwater. These releases could result from mechanical failure or human error. Water resources could be affected by a well blowout; spill of fracking chemicals or flowback water, including tanker truck accident; tank rupture; equipment failure; vandalism; or fire. As a condition of their stormwater management permits, gas companies are required

to meet the state's best management practice requirements, which are intended to protect against environmental damage in case of an accident, spill, or leak. Most operators now use closed-loop drilling mud systems, steel tanks, secondary containment, and lined well pads to minimize the potential for a release of any fluids and to capture it should a release occur.

States and river basin commissions are reviewing their regulatory requirements to identify ways to further protect waterways and other natural resources in the face of accidents, spills, and leaks related to Marcellus drilling.



Active Marcellus drilling site and impoundment, Greene County, Pa.

Conclusion

Water's journey through the Marcellus shale drilling and production processes is complex and roundabout. Some water no longer cycles because it is trapped in the shale as a consequence of hydraulic fracturing. We need to understand where the water from this industry comes from, how it is handled and what the industry adds to it, how it is treated, and how much of it returns to the water cycle. We also need to know about places where water essentially leaves the water cycle or is moved across watershed boundaries. Having this knowledge helps us identify points of concern about water quality and/or quantity.

This publication discusses water use by the industry at multiple levels—regional, local, and the drilling pad itself. At each level different issues are important. For example, at a regional level, some water managers are concerned about tracking out-of-basin transfers of water for fracing and wastewater treatment. At the local level, we want to be sure that streams are not dewatered (pass-by flow requirements would prevent this), especially during drought. At the drilling pad level, concerns often center around what chemicals are added to the frac water and the potential for damage to local water resources due to accidents, spills, and leaks.

Water acquisition and water discharge/return illustrate how the decisions made within one state, such as Pennsylvania's recent call to the natural gas industry to stop sending Marcellus wastewater to municipal wastewater treatment plants, affect other states—in this case by transportation of wastewater to Ohio and West Virginia treatment facilities and underground injection wells. The transport of water or wastewater across state and/or river basin lines interrupts the water cycle, although the amount of interbasin transfers currently occurring is a relatively small volume of water.

Aside from the land area within the Delaware River basin, the Marcellus area is not covered by one river basin commission with both water quantity and quality regulatory authority. Because of this, there may be a lack of consideration for the broader watershed picture. Water doesn't stop flowing at state boundaries. More interstate and possibly federal cooperation and coordination may be needed to ensure that gas exploration

activities in states in the Marcellus region can meet the applicable standards to protect water resources.

Throughout the region the ramifications of the different states' policy responses to the recent boom in gas industry exploration and development in the Marcellus region remain unclear. As of December 2011, New York, Maryland, West Virginia, and the Delaware River Basin Commission have yet to establish clear policies and administrative rules for permitting well drilling and water withdrawals. The evolving nature of water resources policy is a source of great uncertainty influencing development of the Marcellus shale gas play. The pace of institutional change is rapid, but the pace of industrial change is even faster. Check the resources below for updated information.

The other source of uncertainty related to water in the Marcellus industry is how and where its wastewater will be treated and discharged or disposed in the future. There is a rush to develop new treatment technologies and permit and build new treatment plants, but capacity is still lacking within Pennsylvania. Only a small percentage of Marcellus wastewater leaves Pennsylvania, but it's unclear what would happen if Pennsylvania was forced to handle all wastes that are now disposed of via underground injection, landfills, and treatment facilities in other states.

Note again that some of the data presented here are preliminary and are based on the industry's self-reporting to a new database that has acknowledged weaknesses and is currently under revision. The data presented are for Pennsylvania only because the industry's development is farthest along there and that is where data are available. Numbers will likely vary for other states based on local conditions. This publication points out deficiencies in our knowledge about water's journey through the Marcellus shale natural gas drilling and production process.

The caveats about the data also point out the need for better Marcellus water and wastewater data systems in Pennsylvania. Ideally, data systems should be developed collaboratively among states in the region so that valid data comparisons could be made across states and out-of-basin transfers of water could be tracked.

States that are now or will develop databases could learn from the revisions to Pennsylvania's database.

Future developments to watch for include new regulations and legislation in Pennsylvania, Maryland, Ohio, New York, and West Virginia; the potential for a greater role for the U.S. EPA in management and oversight of gas well wastewater reuse and disposal; river basin commission rulemaking; out-of-basin and out-of-state flows of fresh water and wastewater; radioactivity in wastewater; potential innovation in wastewater treatment technologies; increased reuse of wastewater; and improved systems for tracking Marcellus freshwater and wastewater flows.

Resources

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