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In Fracking's Wake: New Rules are Needed to Protect Our Health and Environment from Contaminated Wastewater

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This report combines an evaluation of federal and state laws regulating fracking wastewater with a thorough review, compiled for NRDC by an independent scientist, of the health and environmental risks posed by this high-volume waste stream and the currently available treatment and disposal methods. It finds that the currently available options are inadequate to protect human health and the environment, but that stronger safeguards at the state and federal levels could better protect against the risks associated with this waste. The most significant of the policy changes needed now are (a) closing the loophole in federal law that exempts hazardous oil and gas waste from treatment, storage, and disposal requirements applicable to other hazardous waste, and (b) improving regulatory standards for wastewater treatment facilities and the level of treatment required before discharge to water bodies.

In examining a number of different fracking wastewater disposal methods that are being used in the Marcellus Shale region, the report finds that although all are problematic, with better regulation some could be preferable while others should not be allowed at all. NRDC opposes expanded fracking without effective safeguards. States such as New York that are considering fracking should not move forward until the available wastewater disposal options are fully evaluated and safeguards are in place to address the risks and impacts identified in this report. Where fracking is already taking place, the federal government and states must move forward swiftly to adopt the policy recommendations in this report to better protect people and the environment.

About NRDC

NRDC (Natural Resources Defense Council) is a national nonprofit environmental organization with more than 1.3 million members and online activists. Since 1970, our lawyers, scientists, and other environmental specialists have worked to protect the world's natural resources, public health, and the environment. NRDC has offices in New York City, Washington, D.C., Los Angeles, San Francisco, Chicago, Montana, and Beijing. Visit us at www.nrdc.org.

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EXECUTIVE SUMMARY

This paper analyzes the problem of wastewater generated from the hydraulic fracturing process of producing natural gas, particularly with regard to production in the Marcellus Shale.* It shows that, while hydraulic fracturing (often called "hydrofracking" or "fracking") generates massive amounts of polluted wastewater that threaten the health of our drinking water supplies, rivers, streams, and groundwater, federal and state regulations have not kept up with the dramatic growth in the practice and must be significantly strengthened to reduce the risks of fracking throughout the Marcellus region and elsewhere.**

Hydrofracking and the production of natural gas from fracked wells yield by-products that must be managed carefully to avoid significant harms to human health and the environment. These wastewater by-products are known as "flowback" (fracturing fluid injected into a gas well that returns to the surface when drilling pressure is released) and "produced water" (all wastewater emerging from the well after production begins, much of which is salty water contained within the shale formation).

Both types of wastewater contain potentially harmful pollutants, including salts, organic hydrocarbons (sometimes referred to simply as oil and grease), inorganic and organic additives, and naturally occurring radioactive material (NORM). These pollutants can be dangerous if they are released into the environment or if people are exposed to them. They can be toxic to humans and aquatic life, radioactive, or corrosive. They can damage ecosystem health by depleting oxygen or causing algal blooms, or they can interact with disinfectants at drinking water plants to form cancer-causing chemicals.

* This paper focuses primarily on hydraulic fracturing in the Marcellus Shale, although the issues raised herein are relevant anywhere fracking occurs. Thanks to the knowledge gained from years of experience with fracking in the Marcellus, highlighting that region can provide insight for other regions undergoing new or expanded fracking.

** Due to the breadth and depth of this topic, there are certain issues relating to the management of shale gas wastewater that we do not attempt to address in this paper, although they can present important environmental concerns in their own right. These include stormwater issues, accidental spills, waste generated before fracking fluid is injected, and impacts of wastewater management that are not water-related. Also not addressed in this paper are the impacts of water withdrawals for use in the hydraulic fracturing process or impacts from well drilling and development (including contamination of groundwater during hydraulic fracturing).

Table 1. Chemical Constituents in Produced Water from Marcellus Shale Development[1,*]			
Chemical constituent or surrogate parameter	**Unit of measure**	**Range reported in produced water from wells drilled in Marcellus Shale at 5 days post hydraulic fracturing**	**Range reported in produced water from wells drilled in Marcellus Shale at 14 days post hydraulic fracturing**
Total Suspended Solids (TSS)	mg/L	10.8–3,220	17–1,150
Turbidity	NTU	2.3–1,540	10.5–1,090
Total Dissolved Solids (TDS)	mg/L	38,500–238,000	3,010–261,000
Specific Conductance	umhos/cm	79,500–470,000	6,800–710,000
Total Organic Carbon (TOC)	mg/L	3.7–388	1.2–509
Dissolved Organic Carbon (DOC)	mg/L	30.7–501	5–695
Chemical Oxygen Demand (COD)	mg/L	195–17,700	228–21,900
Biochemical Oxygen Demand (BOD)	mg/L	37.1–1,950	2.8–2,070
BOD/COD Ratio (% biodegradable)			0.1 (10%)
Alkalinity	mg/L	48.8–327	26.1–121
Acidity	mg/L	<5–447	<5–473
Hardness (as $CaCO_3$)	mg/L	5,100–55,000	630–95,000
Total Kjeldahl Nitrogen (TKN)	mg/L as N	38–204	5.6–261
Ammonia Nitrogen	mg/L as N	29.4–199	3.7–359
Nitrate–N	mg/L as N	<0.1–1.2	<0.1–0.92
Chloride	mg/L	26,400–148,000	1,670–181,000
Bromide	mg/L	185–1,190	15.8–1,600
Sodium	mg/L	10,700–65,100	26,900–95,500
Sulfate	mg/L	2.4–106	<10–89.3
Oil and Grease	mg/L	4.6–655	<4.6–103
BTEX (benzene, toluene, ethylbenzene, xylene)	µg/L		Non-detect–5,460
VOC (volatile organic compounds)	µg/L		Non-detect–7,260
Naturally occurring radioactive materials (NORM)	pCi/L	Non-detect–18,000 pCi/L; median 2,460 pCi/L	
Barium	mg/L	21.4–13,900	43.9–13,600
Strontium	mg/L	345–4,830	163–3,580 J
Lead	mg/L	Non-detect–0.606	Non-detect–0.349
Iron	mg/L	21.4–180	13.8–242
Manganese	mg/L	0.881–7.04	1.76–18.6

1 T. Hayes, Gas Technology Institute, *Sampling and Analysis of Water Streams Associated with the Development of Marcellus Shale Gas*, report prepared for Marcellus Shale Coalition, December 2009, http://www.bucknell.edu/script/environmentalcenter/marcellus/default.aspx?articleid=14; E.L. Rowan et al., *Radium Content of Oil- and Gas-Field Produced Waters in the Northern Appalachian Basin (USA): Summary and Discussion of Data*, 2011, 31, http://pubs.usgs.gov/sir/2011/5135/pdf/sir2011-5135.pdf.

* These data are from a single source (Hayes, "Sampling and Analysis of Water Streams"), with the exception of NORM (from Rowan et al., "Radium Content of Oil- and Gas-Field Produced Waters"). NORM data did not specify how long after well completion the samples were taken, and thus cannot be associated with either 5 or 14 days post hydraulic fracturing. BTEX and VOC data provided here have significant uncertainty. Data marked J are estimated due to analytical limitations associated with very high concentrations. Extensive data on produced water quality throughout the United States are available (see energy.cr.usgs.gov/prov/prodwat/intro.htm). Additional data specific to Marcellus are available from a variety of sources (produced water treatment plants, PADEP, drilling companies), although they have not been collated into a single database, making summative analysis difficult.

Because of these risks, shale gas wastewater must be carefully managed. The most common management options currently in use are recycling for additional hydraulic fracturing, treatment and discharge to surface waters, underground injection, storage in impoundments and tanks, and land application (road spreading). All of these options present some risk of harm to health or the environment, so they are regulated by the federal government and the states. But many of the current regulatory programs are not adequate to keep people and ecosystems safe. Consequently, this paper concludes with policy recommendations regarding how the regulation of shale gas wastewater management should be strengthened and improved.

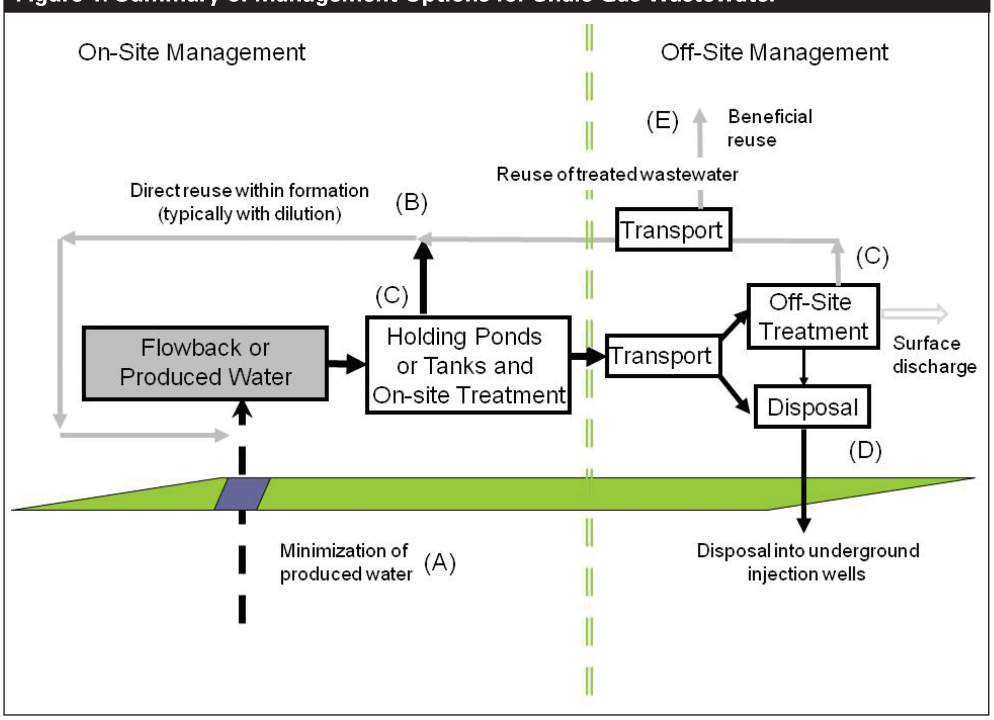
MANAGEMENT OPTIONS FOR SHALE GAS WASTEWATER

There are five basic options to manage wastewater generated during the production of natural gas from shale formations: minimization of produced water generation, recycling and reuse within gas drilling operations, treatment, disposal, and beneficial reuse outside of operations. On-site options associated with minimization, recycling, and reuse are used mostly for water during the flowback period; off-site treatment and disposal methods dominate the management of produced water.

Minimization and Recycling/Reuse. Minimization of wastewater generation and recycling/reuse within operations take place at the well site during drilling. While these have not been popular management choices in oil and gas drilling previously, they are increasingly being used in the Marcellus Shale because traditional off-site disposal methods are not often available in close proximity to wells. On-site recycling can have significant cost and environmental benefits as operators reduce their freshwater consumption and decrease the amount of wastewater destined for disposal. However, it can generate concentrated residual by-products (which must be properly managed) and can be energy-intensive.

Disposal. Direct discharge of wastewater from shale gas wells to surface waters is prohibited by federal law. Consequently, when operators want to dispose of wastewater with little or no treatment, they do so predominantly through underground injection. Disposal through underground injection requires less treatment than other management methods, and when done with appropriate safeguards, it creates the least risk of wastewater contaminants' being released into the environment. However, it does create a risk of earthquakes and can require transportation of wastewater over long distances if disposal wells are not located near the production well. Almost all onshore produced water in the U.S. (a category that includes natural gas produced water) is injected, either for disposal or to maintain formation

Figure 1. Summary of Management Options for Shale Gas Wastewater



pressure in oil fields. Marcellus wastewater is often transported to injection wells in Pennsylvania, Ohio, and West Virginia.

Treatment. Treatment is the most complex management option. It can occur on-site or off-site and in conjunction with recycling/reuse, discharge, and disposal. While treatment can be costly and energy-intensive, all methods of wastewater management generally involve some form of treatment—e.g., to prepare wastewater for subsequent reuse in gas development or for injection into disposal wells, or to generate clean water for discharge or partially treated water and/or residuals for beneficial reuse.

When wastewater is bound for subsequent reuse within hydraulic fracturing operations or for injection in disposal wells, treatment focuses on removing organic contaminants and inorganic constituents that can cause the fouling of wells. Treatment for other objectives—to produce a water clean enough for reuse or discharge, or to produce a brine or solid residual for subsequent reuse—may include additional, targeted removal of other constituents.

Shale gas operators in some regions, including the Marcellus, have sent wastewater to publicly owned treatment works (POTWs) for treatment, but this practice can have serious environmental consequences. With regard to salts, among the most prevalent contaminants in Marcellus wastewater, POTWs do not provide any meaningful treatment at all because they are not designed to remove dissolved solids; most salts that enter POTWs will be discharged directly to receiving water bodies. Additionally, high concentrations of salt, organics, and heavy metals in wastewater can disrupt the treatment process in POTWs. Consequently, sending wastewater to POTWs without pretreatment to remove salts is generally no longer permitted in Pennsylvania. (Some POTWs were exempted from state regulations requiring pretreatment, but they have been asked voluntarily to stop accepting shale gas wastewater.)

An alternative to POTW treatment for removal of suspended solids and organic constituents is treatment at dedicated brine or industrial wastewater facilities, also called centralized waste treatment (CWT) facilities. These plants use many of the same treatment processes that are found in POTWs but may also add coagulation and precipitation techniques to remove dissolved solids. However, while CWTs may be designed to remove more pollutants from wastewater than POTWs do, their discharges may still contain high levels of pollutants such as bromide. Brine treatment plants have been operating in the Marcellus production basin for many decades. After treatment at a CWT, water can be discharged to a surface water body or discharged to sewers for subsequent discharge from a POTW.

Beneficial Reuse. The beneficial reuse of oil and gas brines has a long history in many states. In many areas, produced water is used for dust control on unpaved roads and for deicing or ice control on roads in northern climates during the winter. Such application of Marcellus brines to roadways is permitted in Pennsylvania, provided the brines meet certain water quality requirements. Selling wastewater to local governments for this use allows gas operators to recover some of their treatment and management costs, but applying wastewater onto land surfaces increases the risk that pollutants will be washed into nearby water bodies or leach into groundwater.

Management Options for Residuals. In addition to the treated wastewater, all treatment methods produce residuals—waste materials, mostly in solid, sludge, or liquid form, that remain after treatment. In the Marcellus region and elsewhere, solids and sludges are managed through conventional processes: land application or landfill, depending on their characteristics. Highly concentrated liquid brine wastes (i.e., highly salty water) have the same disposal options as the original produced waters, at lower transportation costs. The most common disposal option for concentrated brines from desalination is deep well injection. If desalination brines are sent to treatment facilities that are not subject to discharge limits on dissolved solids (as is often the case with POTWs), the benefits of concentrating these wastewaters are completely lost.

Use of These Practices in Pennsylvania in 2011. Based on data from the Pennsylvania Department of Environmental Protection, in 2011, about half of all wastewater from shale gas production in Pennsylvania was treated at CWTs that are subject to the state's recently updated water pollution discharge limits, described below. (It is not possible to determine from the data what volumes of wastewater treated at CWTs were subsequently discharged to surface waters, reused, or disposed of in another way.) About one-third was recycled for use in additional hydraulic fracturing. Less than one-tenth was injected into disposal wells, and a similar amount was treated at CWTs not subject to updated treatment standards. Less than 1 percent was treated at POTWs. The remainder (less than 1 percent) was reported as in storage pending treatment or disposal.

From the first half to the second half of 2011, total reported wastewater volumes more than doubled. Treatment at CWTs increased nearly four-fold, even as wastewater volumes directed to "exempt" CWTs decreased by 98 percent. Deep-well injection more than tripled, and re-use in fracking operations increased by about 10 percent. Treatment at POTWs was virtually eliminated.

Figure 2. Technologies for Removing Oil, Grease, and Organics from Produced Water

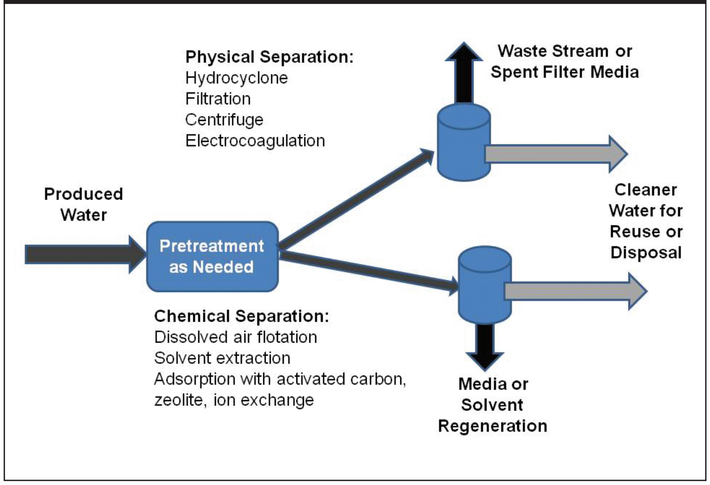
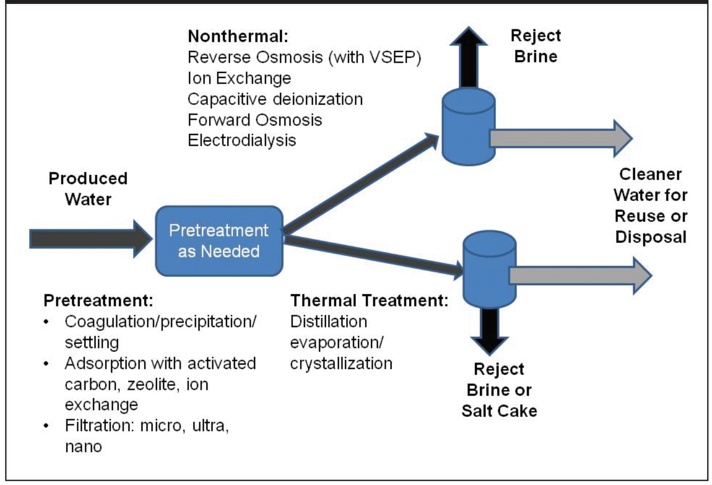


Figure 3. Technologies for Removing Dissolved Ionic Constituents from Produced Water



TECHNICAL ANALYSIS OF TREATMENT METHODS

Many technologies are available for treating shale gas wastewater. Regardless of the ultimate fate of the wastewater, some degree of treatment is typically necessary. The choice of a specific treatment method will depend on the nature and concentration of the contaminants in the wastewater as well as the intended disposition of the treated water, which determines the necessary levels of pollutant reduction.

Discharge to surface waters requires extensive treatment to protect drinking water supplies and aquatic ecosystems. Reuse may require partial treatment to avoid reintroducing into the next well contaminants that will affect production. Wastewater used in road spreading may also require treatment to reduce pollutant concentrations in runoff. Similarly, when wastewater is injected into disposal wells, partial treatment is often done to minimize the risk of clogging the well.

For any given drilling operation, once the wastewater is characterized and the necessary water quality is known, a treatment system made up of different components can be selected. Treatment begins with removal of suspended solids, inorganic or organic, and then removal of dissolved organics and potentially scale-forming constituents. When all that remains is simple dissolved salts, desalination can be done, as would often be necessary for discharge to surface waters. Additionally, high levels of NORM will require special handling.

Other factors can also influence the selection of appropriate treatment methods, such as the energy intensity of a treatment method and the nature of the residuals generated by treatment. For all types of treatment, the separation of the contaminant from the water will generally require significant chemical and energy inputs, depending upon the process, the quality of the influent wastewater, and the desired quality of the effluent finished water. Likewise, all treatment methods generate a residual waste that contains the contaminants that have been removed or the by-products of their transformation. This residual can be a liquid stream, a solid or sludge product, or a gaseous stream, and it must be managed appropriately to avoid environmental harms. For example, brines and sludges created through treatment processes can be disposed of as solid waste or sent to disposal wells.

Applicable treatment technologies involve chemical, physical, and/or biological processes. These include settling, filtration, coagulation, centrifugation, sorption, precipitation, and desalination. Desalination can be achieved through thermal methods (like vapor compression, distillation, multi-stage flash, dew vaporization, freeze-thaw, evaporation, and crystallization) or non-thermal methods (like reverse osmosis, nanofiltration, electrodialysis, electrodeionization, capacitative deionization, membrane distillation, and forward osmosis). In Pennsylvania, treatment plants use a wide range of technologies like these; however, because desalination is the most energy intensive, many facilities treat only up to the point at which desalination would occur and then repurpose the water for additional activities in oil and gas development.

POTENTIAL WATER IMPACTS OF SHALE GAS WASTEWATER MANAGEMENT

Wastewater associated with hydraulic fracturing itself and, later, with the production of gas from a fractured well must be managed to avoid environmental harms. However, many of the available management techniques may directly cause environmental harm due to the release of pollutants to surface waters, soil, and groundwater.

On-Site Impoundments and Tanks. As with any liquid material in storage, accidental spills and mismanagement can cause releases to the environment that could contaminate nearby waters and soils. Open impoundments, also called pits, are typically subject to requirements designed to minimize the risk of contamination, though the adequacy of those requirements varies from place to place. Closed tanks are also sometimes used for collection of produced water during the flowback period, sometimes with secondary containment, a best management practice where the tank sits within a traylike structure with raised sides, such that materials released during a tank rupture would be contained and not leach into soil or travel to nearby waterways.

Impacts Away from the Well Site. The most significant potential for water impacts from shale gas wastewater is associated with the long-term production of water from the well and occurs away from the well site. Produced water is generally shipped off-site for management and disposal, at which point pollutants in wastewater can be intentionally released directly to the environment, either with or without appropriate treatment and safeguards to limit pollution discharges. Additionally, at any of the locations where produced water is handled, accidental releases can occur, and best practices and good management are necessary to avoid accidents, as are contingency plans to reduce the impact of accidental releases.

Deep Well Injection. Underground injection of wastewater is designed to isolate materials that could cause harm if released to the biosphere. A U.S. Environmental Protection Agency (EPA) risk analysis determined that injection via strictly regulated Class I hazardous waste wells is a safe and effective technology that presents a low risk to human health and the environment. Additional studies have confirmed this assessment. However, oil and gas wastes are currently injected into Class II disposal wells, which are subject to fewer safety requirements and therefore pose a greater risk of contaminating groundwater and triggering earthquakes. Partial treatment of produced water, either prior to injection or at the injection well facility, is often used to reduce the likelihood of well clogging.

Surface Water Discharge. Inadequate treatment at a CWT or POTW followed by discharge of treated water can pollute surface waters—including drinking water sources—downstream of the discharge. If quantities or concentrations of contaminants in the discharge are too high, or if the receiving water lacks adequate assimilative capacity, the pollution can seriously harm ecosystems and human health. Some contaminants (e.g., benzene, toluene, ethylbenzene, and xylenes) are directly toxic to ecosystems or people; others interact in the environment to produce unwanted effects (e.g., nutrients like ammonia that can encourage harmful algal blooms). Some are a concern because they can affect the beneficial use of the water downstream (e.g., sulfate, which can make drinking water taste bad), and still others can disrupt ecosystems (e.g., chloride, which alters fish reproduction).

Land Application. Application of produced water to roads for dust control has several potential impacts. Rainfall and snowmelt wash salts and other chemicals off roadways, which can result in stream or groundwater contamination. The potential for such harm increases when application rates are high or take place in close proximity to rainfall events. Moreover, when produced waters are used for road spreading, they may replace equally effective dust suppressant and deicing agents while resulting in higher levels of chloride pollution to surface water and groundwater (due to higher concentrations or more frequent application).

Residuals Management. Regardless of the treatment option selected, residuals—the concentrated brines and solids containing the chemicals removed from the produced water—will be created as a by-product. Since chemicals in these residual wastes are present at higher concentrations than in the original produced waters, careful management is essential to avoid undermining the value of the treatment process through release of residuals to the environment. For example, in light of the high pollutant concentrations, surface water discharge of residual brines or land or road application of brines or solid salts produced through treatment can result in watershed impacts equal to, or greater than, the potential impact of the original produced water.

REGULATORY FRAMEWORK FOR SHALE GAS WASTEWATER

A number of federal and state statutes and regulations govern the treatment, disposal, and reuse of shale gas wastewater. These regulations are intended to minimize or eliminate the risk of harm from exposure to wastewater pollutants, but many regulatory programs are not adequately protective, and several even have complete exemptions for shale gas wastewater (or exemptions for oil and gas wastewater of all kinds, including Marcellus Shale wastewater).

Treatment and Discharge to Water Bodies. The Federal Water Pollution Control Act, more commonly called the Clean Water Act, regulates the treatment and discharge of shale gas wastewater into surface water bodies. Under the Act, facilities must obtain permits if they intend to discharge shale gas wastewater, or any by-product resulting from treatment of that wastewater, into a surface water body. These permits contain limitations on pollutants that may be discharged in the wastewater.

Federal regulations completely prohibit the direct discharge of wastewater pollutants from point sources associated with natural gas production. Instead of discharging wastewater directly to surface waters, then, many hydraulic fracturing operators send wastewater to treatment facilities that are authorized to discharge under Clean Water Act permits issued (typically) by the states under authority delegated by the EPA. These facilities include POTWs and CWTs. EPA regulations set pretreatment requirements for the introduction of industrial wastewater to POTWs (known in EPA regulations as "indirect discharge") and for the discharge of industrial wastewater from CWTs. However, the Clean Water Act regulatory program is not comprehensive; for example, there are no pretreatment requirements specifically for shale gas wastewater, and discharge standards for CWTs are out of date.

States may also establish requirements for these discharges that are stricter than the federal standards. For example, the Pennsylvania Department of Environmental Protection (PADEP) has issued regulations implementing the Clean Water Act and the state's Clean Streams Law with industrial waste discharge standards. In 2010 PADEP finalized revisions to state regulations addressing the discharge to surface waters of wastewater from natural gas operations. The regulations prohibit the discharge of "new and expanding" discharges of shale gas wastewater unless the discharge is authorized by a state-issued permit. Such discharges may be authorized only from CWTs; POTWs may be authorized to discharge new or increased amounts of shale gas wastewater only if the wastewater has been treated at a CWT first.

Underground Injection. The federal Safe Drinking Water Act (SDWA) regulates the underground injection of wastewater. SDWA establishes the Underground Injection Control (UIC) program. This program is designed to prevent the injection of liquid wastes into underground sources of drinking water by setting standards for safe wastewater injection practices and banning certain types of injection altogether. All underground injections are prohibited unless authorized under this program.

Under the UIC program, the EPA groups underground injection wells into five classes, with each class subject to distinct requirements and standards. Because of a regulatory determination by the EPA not to classify shale gas wastewater as "hazardous" (discussed below), it is not required to be injected into Class I wells for hazardous waste. Rather, shale gas wastewater may be injected into Class II wells for fluids associated with oil and gas production. Class II wells are subject to less stringent requirements than Class I hazardous waste wells.

In the Marcellus region, Maryland, Ohio, and West Virginia have assumed primacy and implement the UIC program. New York, Virginia, and Pennsylvania have not assumed primacy, so the EPA directly implements the UIC program in those states.

Reuse for Additional Hydraulic Fracturing. In contrast to the injection of shale gas wastewater as a disposal practice, the injection of fluids (which may include recycled wastewater) for the hydraulic fracturing process itself is exempted from regulation under the federal Safe Drinking Water Act. As a result, if shale gas wastewater is managed or treated for the sole purpose of reuse for further hydraulic fracturing, it is not subject to federal regulation.

However, states can have their own regulations that apply to the reuse of shale gas wastewater. In Pennsylvania, facilities that process wastewater for beneficial reuse may be authorized under PADEP-issued general permits, which establish generally applicable standards. Operations authorized under these general permits do not require individualized permits for wastewater processing.

Impoundments. Because of an exemption from federal law (discussed below), the storage and disposal of shale gas wastewater in impoundments is regulated solely by the states. In Pennsylvania, facilities that store and dispose of shale gas wastewater in impoundments must obtain permits under PADEP solid waste regulations, which contain construction and design specifications and operating requirements for those impoundments. Pennsylvania has also enacted a law that limits the ability of municipalities to regulate the siting of impoundments; several municipalities are challenging this law in court.

Land Application. Because of an exemption from federal law (discussed below), the land application of shale gas wastewater is regulated primarily at the state level. While Pennsylvania's oil and gas well regulations generally prohibit operators of oil and gas wells from discharging brine and other produced fluids onto the ground, the state's solid waste management regulations state that PADEP may issue permits authorizing land application of waste. Using this authority, PADEP has issued a general permit authorizing the application of natural gas well brines specifically for roadway prewetting, anti-icing, and deicing purposes as long as the brines meet certain pollutant concentration limits. In some other states, however, the road spreading of shale gas wastewater is prohibited.

Handling, Storage, and Transport Prior to Disposal. State regulations govern the handling, storage, and transport of shale gas wastewater prior to its ultimate disposal. Oil and gas wastes are currently exempt from the federal Resource Conservation and Recovery Act (RCRA), which generally regulates the handling and disposal of waste. A 1980 amendment to the statute exempted oil and gas wastes from coverage under RCRA for two years. In the meantime, it directed the EPA to determine whether regulation of those wastes under RCRA was warranted. In 1988, the EPA made a determination that such regulation was not warranted. Consequently, oil and gas wastes remain exempt from the hazardous waste provisions of RCRA. This means that natural gas operators transporting shale gas wastewater, along with the POTWs, CWTs, and any other facilities receiving it, are not transporting or receiving "hazardous" wastes and thus do not need to meet the cradle-to-grave safeguards established by RCRA regulations.

In the absence of federal regulations, states regulate the handling, storage, and transport of shale gas wastewater. In Pennsylvania, wastewater from industrial operations is classified as nonhazardous, and it must be managed and disposed of in accordance with the state's Solid Waste Management Act.

Residual Waste. Residual wastes are subject to various regulations depending on their composition (liquid or solid) and method of disposal (surface water discharge, injection, land application, etc.). Many of the regulatory issues described above arise with residuals as well.

POLICY RECOMMENDATIONS

The current regulation of shale gas wastewater management, treatment, and disposal is inadequate because it fails to safeguard against foreseeable risks of harm to human health and the environment. Government oversight of wastewater treatment and disposal must be improved at both the federal and the state level.

Treatment and Discharge to Water Bodies. Currently, discharge of pollutants in shale gas wastewater is allowed in amounts and concentrations inadequate to protect water quality. The EPA and the states must develop limits both on the discharge of shale gas wastewater from POTWs and CWTs and on the amount of pollution allowable in surface water bodies.

- The EPA and the states should ban or more strictly regulate the discharge of shale gas wastewater to POTWs.
- The EPA and the states should update pollution control standards for CWTs that accept shale gas wastewater.
- The EPA and the states should develop water quality criteria for all chemicals in shale gas wastewater. Water quality criteria are numeric limitations on pollutants in a particular water body that are adequate to support the water body's designated uses.
- The EPA and the states should identify water bodies impaired by pollutants in shale gas wastewater, or with the reasonable potential to become impaired, and should require reductions in pollution loads to those waters.
- The EPA and the states should protect water bodies not yet impaired by shale gas wastewater.

Handling, Storage, and Transport Prior to Disposal. Improper handling, storage, or transport of shale gas wastewater can lead to spills and other releases of pollutants that contaminate land and water with toxic or radioactive material.

- Congress or the EPA should eliminate the RCRA hazardous waste exemption for shale gas wastewater and subject such wastewater to regulation as "hazardous waste" in cases where it does, in fact, display physical and chemical characteristics that qualify as hazardous.
- Regardless of whether the federal RCRA exemption is eliminated, states can and should classify shale gas wastewater as hazardous when it meets relevant technical criteria and should regulate it accordingly.
- States should require regular testing of shale gas wastewater to assess whether wastewater from any given source, at any given time, possesses hazardous characteristics.

Underground Injection. Injection into wells creates a risk that injection fluids will migrate into sources of drinking water, as well as a risk of triggering earthquakes. These unnecessary risks should be minimized.

- Wastewater with hazardous characteristics should be injected into Class I hazardous waste wells, which are subject to regulations more stringent than those governing Class II wells. This can be achieved if Congress or the EPA eliminates the RCRA hazardous waste exemption for oil and gas wastes, or if the EPA amends UIC program regulations.
- In the interim, states should use their authority to more strictly regulate Class II wells for oil and gas wastewater.

Reuse for Additional Hydraulic Fracturing. The hydraulic fracturing process itself should be federally regulated. However, when fracking occurs, reuse of wastewater for additional hydraulic fracturing can offer many benefits (although these benefits can in some cases be offset by energy use and the generation of concentrated residuals). Where appropriate, states should encourage or even require the reuse and recycling of shale gas wastewater.

- Congress should eliminate the Safe Drinking Water Act exemption for hydraulic fracturing to ensure that injection of fracturing fluid will not endanger drinking water sources.
- When the benefits of recycling outweigh disadvantages, states should encourage or require reuse of shale gas wastewater in the hydraulic fracturing process.

Impoundments and Tanks. States should prohibit or strictly regulate impoundments to minimize the risk of spills or leakage.

- States should not allow the storage or disposal of shale gas wastewater in open impoundments. Flowback and produced water should be collected at the well and either recycled or directly routed to disposal. In the event that storage of wastewater is necessary, it should be done in closed tanks.
- If states do not prohibit impoundments, they should regulate them more strictly with regard to location, construction, operation, and remediation.
- States should also regulate closed storage tanks more strictly; this regulation should require, among other things, secondary containment.

Land Application. Because application of shale gas wastewater to land and roadways can lead to environmental contamination through runoff of toxic pollutants into surface waters, it should be prohibited, or at minimum strictly regulated.

- States should prohibit the land application or road spreading of shale gas wastewater. Other available substances are equally effective but have less environmental impact, and these should be used on roads for dust suppression and de-icing.
- If land application and road spreading are not prohibited, they should only be authorized subject to strict limits on pollutant concentrations and required preventive measures to limit runoff.
- The EPA and states should enforce existing Clean Water Act requirements for controlling polluted runoff from municipal storm sewer systems to ensure that any road spreading does not violate those requirements. The EPA should also complete its ongoing development of new rules to strengthen the CWA stormwater regulatory program.

Residual Waste. Just as shale gas wastewater should not be categorically exempt from RCRA hazardous waste regulations, residual waste derived from the treatment of that wastewater should not be exempt from regulation if it displays the characteristics of a hazardous waste.

- Shale gas wastewater treatment residuals should be subject to RCRA's hazardous waste regulations. Congress or the EPA should require that residual waste with hazardous characteristics be regulated as hazardous by eliminating the RCRA hazardous waste exemption for oil and gas wastes.

Public Disclosure. Regardless of which treatment or disposal method an operator uses to manage its shale gas wastewater, it should be required to publicly disclose the final destination of the waste.

Model Regulations. The federal Bureau of Land Management (BLM) regulations now under development for hydraulic fracturing activities on federal lands should be as protective of health and environment as possible and should include at minimum (to the extent BLM has regulatory jurisdiction) all recommendations set forth in this paper. Since BLM has expansive authority over development of federal oil and gas resources and other activities on federal lands, strong BLM rules could serve as model regulations on which states could base their own.

NRDC supports establishing a fully effective system of safeguards to ensure that natural gas is produced, processed, stored, and distributed in a way that helps protect our water, air, land, climate, human health, and sensitive ecosystems. NRDC opposes expanded fracking until effective safeguards are in place. For more information on NRDC's position on natural gas and fracking, go to http://www.nrdc.org/energy/gasdrilling/.

Introduction

Natural gas development has exploded at breakneck speed in recent years, fueled by advances in an extraction technique known as hydraulic fracturing (or "fracking"), which has allowed the oil and gas industry to access previously out-of-reach reserves. Unfortunately, federal and state safeguards to protect people and the environment from the hazards of fracking have not kept pace. As a result, this development has proved dangerous, destructive, and polluting.

This paper describes the health and environmental risks from one aspect of fracking: polluted wastewater generated by the fracturing process. It evaluates the available methods for management of those wastes, identifies the shortcomings of the existing regulatory regime, and offers recommendations for improving regulations to protect public health and the environment. Ultimately, the problem of managing this wastewater is one for which there are no easy answers, and one that many regulators are not adequately prepared to address.

Overview of Hydraulic Fracturing and Wastewater Generation

Natural gas is found in underground layers of rock referred to as formations. Shale gas formations are generally tighter and much less permeable than other formations, causing the gas to be much less free-flowing.[1] The Marcellus Shale, of particular focus in this paper, is one such formation. The Marcellus is the largest shale gas play in the United States by geographic area—it spans six states: New York, Pennsylvania, Ohio, Maryland, Virginia, and West Virginia—and contains the greatest total quantity of technically recoverable gas.[2]

Shale gas is often referred to as "unconventional" gas. Whereas "conventional" sources of oil and gas are generally produced using traditional methods of drilling and pumping, unconventional oil and gas sources generally require more complex and expensive technologies for production.[3] Along with shale, other sources of unconventional gas include coal seams and impermeable sandstone formations.[4] As of 2008, unconventional production accounted for 46 percent of total U.S. natural gas production.[5]

In the case of shale gas, the technology used for production is known as hydraulic fracturing. Hydraulic fracturing involves the injection of liquid under pressure to fracture the rock formation and prop open the fractures, allowing natural gas to flow more freely from the formation into the well for collection.[6] The development of hydraulic fracturing technology, along with advances that allow the horizontal drilling of wells, has facilitated the expansion of shale gas development over the past 20 years. Prior to these innovations, shale gas development was not viewed as economically feasible, but recently such development has exploded.[7] The first economically producing wells in the Marcellus were drilled in 2003; in 2010, 1,386 Marcellus wells were drilled in Pennsylvania alone (up from 763 drilled in 2009).[8]

The liquids used in the hydraulic fracturing process consist primarily of water, either fresh or recycled, along with chemicals used to modify the water's characteristics (for example, to reduce friction or corrosion) and sand or other agents, referred to as "proppants," that hold open the fractures in the formation.[9]

The process of producing natural gas via this process yields by-products that must be managed as part of the operation's waste stream, and these by-products present significant risks to human health and the environment if not managed properly. This paper focuses on the wastewater that returns to the surface of the well after the fracturing process.

When the pressure used to inject the fracturing fluid into the well is released, some of the fluid returns to the surface during what is known as the “flowback” period. This period lasts approximately 10 to 14 days, or until the well begins natural gas production. Water that returns to the surface during the flowback period is usually called “flowback water” or just “flowback.” Its characteristics are defined by the chemicals added to it and the chemicals present in the shale that are released into the water during contact. Flowback volumes in shale formations range from 10 to 25 percent of the fracturing fluid originally injected into the well, or approximately 10,000 to 60,000 barrels (420,000 to 2,520,000 gallons) per well for each hydraulic fracture, depending on the characteristics of the formation.[10,a]

Once gas production begins at the well, all wastewater emerging from the well is called “produced water” or “production phase water.” The characteristics of produced water are generally less related to the chemicals used in the fracturing operation and more related to the geochemistry of the formation. Concentrations of formation-derived chemicals in produced water generally increase over the lifetime of the well, while the overall volume of produced water may remain stable or decline with time. Long-term produced water volumes range from 200 to 1,000 gallons per million cubic feet of gas produced, depending on the formation, typically at a rate of 2 to 10 barrels (84 to 420 gallons) per day.[11] Because the lifetime of a shale gas well can extend to 40 years, the total amount of produced water generated can reach into the millions of gallons.[12] However, each shale formation yields different volumes of produced water. The Marcellus Shale is a relatively dry formation, generating less produced water than other formations around the country (though the amount generated is still significant).[13]

Both types of wastewater—flowback and production phase water—contain potentially harmful constituents. These constituents can be broadly grouped into several principal categories: salts (often expressed as total dissolved solids, or TDS), organic hydrocarbons (sometimes referred to as “oil and grease”), metals, chemical additives (from the fracturing fluid), and naturally occurring radioactive material (NORM). Because of these constituents, shale gas wastewater must be carefully managed to prevent harm to human health and the environment. If wastewater is accidentally spilled onto nearby lands or into local waters, or if it is intentionally released into the environment without adequate treatment, exposure to the pollutants it contains can be dangerous to people and ecosystems.

The same types of management practices are generally used for the two types of wastewater, so this paper discusses the two separately only when differences in their chemical composition or spatiotemporal availability make their management options distinct. Throughout the paper (and particularly in its technical chapters), the inclusive term “produced water” is often used to refer to both flowback and production phase water without distinction, as flowback is technically considered a subset of produced water. The generic term “wastewater” is also intended to refer to both types without differentiating between them.

[a] An individual shale gas well is typically fractured 10 to 16 times. One barrel is equal to 42 gallons.

Topics Addressed in this Paper

This paper consists of two main parts. Chapters 1 through 3 detail the technical considerations relating to management of shale gas wastewater. Chapters 4 and 5 describe the current regulatory regime and offer recommendations for improving those regulations to protect human health and the environment.

Specifically, Chapter 1 broadly describes the various management options available for wastewater produced during shale gas development. These management options include the recycling of wastewater for additional hydraulic fracturing, disposal in injection wells, discharge to surface waters, and land application. Chapter 2 presents a more detailed technical overview of specific wastewater treatment methods and how those methods are selected for specific wastewaters. As the chapter describes, the quality of the wastewater and the desired destination or use of the wastewater dictate the options for treatment. Chapter 3 presents a description of potential water-related environmental and health impacts that can result from the various management options. This overview considers both the effects of current management practices on water resources and the impacts that could be mitigated through changes in those practices.

Chapter 4 summarizes the current regulatory framework governing shale gas wastewater management options. This chapter describes relevant statutes and regulations at the federal level and the state level in Pennsylvania and identifies some of their key limitations. Finally, Chapter 5 presents policy recommendations regarding how the current regulatory approach—which is inadequate in many ways—should be improved to prevent harmful impacts to health and the environment.

Topics Not Addressed in this Paper

Due to the breadth and depth of this topic, there are certain issues relating to the management of shale gas wastewater that we do not attempt to address in this paper, although they can present important environmental concerns in their own right. These include:

- Non-water-related impacts of wastewater management (with limited exceptions). Such impacts include air emissions from open wastewater storage pits and trucks used to haul wastewater, noise and traffic impacts from those trucks, soil contamination, land disturbance impacts from the construction of wastewater management facilities, and energy demand associated with wastewater treatment processes.
- Impacts of spills during off-site transport of wastewater. Such spills may result from accidents, from inadequate management or training, or from illicit dumping. Major spills from trucks carrying shale gas wastewater have occurred in Pennsylvania; indeed, spills and leaks account for many of the environmental violations cited in connection with shale gas development by the Pennsylvania Department of Environmental Protection.[14]
- Waste generated while a well is being drilled (before fracturing fluid is injected). Waste generation during drilling consists of drilling muds and cuttings. This waste is stored on-site; drilling muds are often recycled, and cuttings are dewatered and disposed of as solid waste in landfills.

Additionally, there are many other major impacts of hydraulic fracturing on water resources, which are beyond the scope of this paper. These include:

- Stormwater discharges from well sites. In order to create an area for drilling a new well, operators clear and grade an area that can accommodate the wellhead(s); pits for holding water, drill cuttings, and used drilling fluids; and space for trucks used to transport equipment and wastes. Typically, this space ranges from 3 to 5 acres.[15] During rain events, stormwater runoff can carry sediment from this cleared area into nearby water bodies. Large volumes of runoff also erode stream banks and riverbanks. Oil and gas operations are exempt from stormwater permitting requirements under the Clean Water Act.[16]
- Impacts of water withdrawals for use in the hydraulic fracturing process. Because hydraulic fracturing requires large amounts of water—around 3,800,000 gallons of fracturing fluid per well in the Marcellus Shale, on average—this is a concern in areas of the country with water scarcity.[17] Even in areas with water abundance, withdrawals from smaller headwater streams can diminish streamflow enough to negatively affect aquatic life.[18]
- Impacts from well drilling and development (including contamination of groundwater during hydraulic fracturing). The process of developing a shale gas well—drilling through an overlying aquifer, stimulating the well via fracturing, completing the well, and producing the gas—creates a risk of contaminating groundwater.[19] For example, in December 2011 the U.S. Environmental Protection Agency released a draft report finding evidence that groundwater in Pavillion, Wyoming, was contaminated by chemicals consistent with constituents in hydraulic fracturing fluid.[20,b]
- Groundwater contamination may result from a failure of well integrity or the migration of hydraulic fracturing fluid chemicals from the target formation. Abandoned wells that are improperly sealed may also cause environmental contamination.

[b] In March 2012, the EPA agreed to retest Pavillion's water supplies to "clarify questions" about the initial report's monitoring results. See Timothy Gardner, "EPA to Retest Wyoming Water Said Tainted by Fracking," *Reuters*, March 9, 2012, reuters.com/article/2012/03/09/usa-epa-fracking-idUSL2E8E9ASA20120309.

Chapter 1. Management Options for Water Produced During Shale Gas Development

There are five basic options for managing water produced during the production of natural gas from unconventional formations: minimization of produced water generation; recycling and reuse within operations; treatment; disposal; and beneficial reuse outside of operations. Table 1 summarizes the options for on- and off-site management as well as the target type of water for different options; dot size indicates frequency of use. Figure 1 shows on-site options on the left and off-site options on the right. As Table 1 indicates, on-site options associated with minimization, recycling, and reuse are more frequently employed for water during the flowback period, while off-site treatment and disposal methods dominate the management of production phase water. As noted, “produced water” refers to all water that returns during the flowback and production periods. A distinction between early produced water (“flowback”) and later produced water will be made only when chemical constituents or management are different.

Table 1. Management of Water During Flowback and Production

	On-site	Off-site	Flow-back	Production
A. Minimization or reduction of generation	●		●	
B. Recycling or reuse in process	●	•	●	•
C. Treatment	•	●	•	●
D. Disposal	•	●	•	●
E. Beneficial reuse		•		•

Figure 1. Summary of Management Options for Shale Gas Wastewater

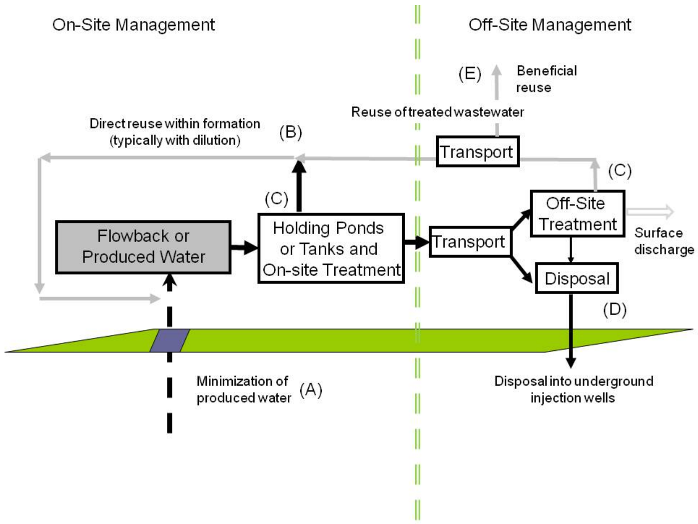


Table 2 provides a summary of the produced water management options being chosen in Pennsylvania for Marcellus Shale formation produced water in 2011. Data are from the Pennsylvania Department of Environmental Protection (PADEP).

Table 3. Wastewater Management from Marcellus Shale in Pennsylvania in 2011 (barrels)[c]

Method	Jan.-June 2011	July-Dec. 2011
Reuse within operations (not road spreading)	5,028,566	5,670,753
Disposal at injection well	521,983	1,718,410
Industrial treatment plants (CWT), exempt[d]	1,971,019	42,345
Industrial treatment plants (CWT), nonexempt[d]	1,691,171	13,920,901
Municipal sewage treatment plants (POTWs)	101,897	408
Storage pending disposal or reuse	228,618	6,884
Landfill (liquid waste only)	26,735	6,005
Other (not specified)		6,640
TOTAL[e]	**9,679,990**	**21,372,346**

[c] For purposes of these data, "wastewater" includes fracturing fluid, brine, and drilling wastewater. Spent lubricant, drill cuttings, and flowback fracturing sand are not included in wastewater.

[d] "The terms "exempt" and "nonexempt" refer to whether the waste treatment facility was exempt from, or subject to (i.e., nonexempt from), Pennsylvania's so-called "Chapter 95" requirements for wastewater treatment, which established maximum concentrations of total dissolved solids and chlorides permissible in surface water discharges from treatment facilities. Those requirements are discussed later in this Chapter as well as in Chapter 4.

The PADEP data used for Table 2 contain some misclassifications. For exempt CWTs and POTWs, specific analysis by permit number was used to ensure correct totals. For nonexempt CWTs and injection wells, DEP classifications were used, although some facilities listed as brine-treatment CWTs in January-June data are then listed as a disposal well in July-December data.

Despite these misclassifications, it is possible to draw some general conclusions about the approximate proportional breakdown of wastewater management methods. In 2011, approximately half of all Pennsylvania wastewater was treated at CWTs that are subject to the state's new water pollution discharge limitations (i.e., nonexempt). (It is not possible to determine from the data what volumes of wastewater treated at CWTs were subsequently discharged to surface waters, reused, or disposed of by another method.) About one-third of the wastewater was recycled for additional hydraulic fracturing. Less than one-tenth was injected into disposal wells. A similar amount was treated at CWTs that are exempt from the state's new discharge regulations, with most of that treatment occurring in the first half of the year, before the state asked operators to stop sending their wastewater to such facilities (as discussed below). Less than 1 percent was treated at POTWs. The remainder (less than 1 percent) was reported as in storage pending disposal or reuse.

From the first half to the second half of 2011, total reported wastewater volumes more than doubled. Treatment at CWTs increased nearly four-fold, even as wastewater volumes directed to exempt CWTs decreased by 98 percent. Deep-well injection more than tripled, and reuse in hydraulic fracturing operations increased by about 10 percent. Treatment at POTWs was virtually eliminated.

Minimization of Wastewater Generation & Reuse and Recycling Within Operations

Minimization of wastewater generation and recycling/reuse within operations take place on-site at the well during development. While these have not been popular management choices in oil and gas drilling previously, extensive development of these options has been undertaken in the Marcellus gas field due to low availability of traditional off-site disposal methods in close proximity to well development. *Reduced cost and significant environmental benefits accrue with reduction, reuse, and recycling, as reduced volumes of wastewater result in less trucking and less treatment and disposal.*

Minimization of produced water generation, especially in the early flowback period, is generally achieved either through completion techniques that require less water or through technologies applied within the well bore ("downwell"). For oil-producing wells, mechanical blocking devices and downwell oil/water separators are used; however, oil wells typically produce many times more water than gas wells, despite these technologies.[21] For hydraulically fractured natural gas wells, water use and wastewater minimization technologies are still being developed, and the effect they will have on long-term produced water quantities is uncertain.

Reuse of produced water for enhanced oil recovery has been practiced for decades, but reuse of produced water in gas development has only recently been explored. Challenges to reuse may include removing constituents that could affect well performance (salts, suspended solids including microorganisms, and scale-forming chemicals) and adjusting the stimulation chemistry with chemical additives that work in saltier waters,[22] although many producers in the Marcellus formation report use of produced water from the flowback period without treatment.[23] Recently, Pennsylvania issued a general permit (WMGR121) that covers the treatment of produced water for subsequent reuse in hydraulic fracturing.[f] A 2010 report listed two facilities that operate under the general permit.[24] This same report surveyed seven operators and reported that six were practicing recycling and reuse, with several attempting to reuse all produced water from their operations.[25,g]

The rapidity with which the industry has adopted resource conservation suggests that these techniques have the potential to be transferred to many existing gas fields to reduce water usage and wastewater generation. The opportunity for reuse and recycling is greater during the flowback period than during the production phase. After the pad is fully developed, with all wells producing, options for minimization and recycling/reuse decline. Produced water generated during the lifetime of the well can be collected and repurposed for operations at other wells, but this requires transport to new well pads, and this may be more costly than transport to disposal or treatment locations, depending upon the distances involved and the quality of the produced water. Logistics and economics control reuse opportunity.

Off-site reuse of untreated produced water is rare. Generally only very clean water, typical of some coal bed methane sites, can be directly reused. Wastewaters low in pollutants such as organics and dissolved solids can be used for irrigation, livestock watering, base flow augmentation in streams, injection into aquifers for recharge, and road application for dust suppression or deicing. Off-site reuse for industrial operations, including in hydroelectric power plant cooling and as a working fluid in geothermal energy production, are emerging options. Limited trials for cooling operations indicate that high TDS precludes this use.[26] Thus, reuse in the non-extractive energy sector is likely to be an option only for low-concentration wastewaters with little scaling potential. Due to the high concentration of salt in produced water from the Marcellus formation, none of these options are currently used. Reuse of partially treated wastewater, both on-site and off-site, will be discussed in the treatment section below.

Disposal

On-site management via disposal or discharge is permitted only under specific and limited conditions, and Marcellus gas operations do not qualify. Discharge of wastewater at the point of generation (direct discharge on-site) is not permitted at most onshore oil and gas wells. (Further discussion of the direct discharge prohibition can be found in Chapter 4.)

Direct disposal aboveground or to soils in the near-surface environment, on- or off-site, was routine in the early part of the 20th century, and on-site unlined ponds and nearby off-site land application were common disposal techniques.[27] Today on-site unlined ponds are no longer used because such ponds—percolation ponds in particular—can cause salt contamination in soils and

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[f] For more information on regulation of produced water recycling, see Chapter 4.

[g] The six operators reporting recycle and reuse were Chesapeake Energy, Range Resources, EQT, East Resources, BLX, and Norse Energy.

aquifers.[28] Land application of untreated water by spraying is generally not permitted or is allowable only for wastewater with a low salt content.

Off-site disposal is done predominantly via underground injection into a disposal well, and almost all onshore produced water in the United States is managed in this fashion.[29] Typically, oil and suspended solids are removed from the produced water at the disposal well prior to injection to reduce well plugging and formation clogging from scale-forming chemicals or microbial growth. Alternatively, if no treatment is undertaken, periodic downhole workovers may be performed to remove formation clogs.[h]

Injection wells are suitable in areas with porous sedimentary rock. Good potential for injection exists in the mid-continent and Great Plains; conditions are less favorable along the Atlantic Coast, in New England, and in the Appalachian Mountain area. In many regions, the permitting of a new injection well requires the plugging of old and orphan wells, due to extensive prior development of other gas formations.

Injection of wastewaters for disposal is regulated as part of the Underground Injection Control (UIC) section of the Safe Drinking Water Act of 1974; UIC Class II wells are specific to injection of *brines and other fluids associated with oil and gas production*. (Further discussion of the Underground Injection Control program can be found in Chapter 4.)

There are 1,855 Class II wells in Pennsylvania; however, only eight were licensed for disposal in 2010 (see Table 3). Two were subsequently closed, and two additional wells were approved in 2011.[i] The State Review of Oil and Natural Gas Environmental Regulations (STRONGER), an independent regulatory review for Pennsylvania, indicates that there are at least 20 well injectivity reviews (the first stage of application) pending for UIC wells in Pennsylvania.[30] In addition to current or future Pennsylvania disposal wells, oil and gas wastewater is transported to injection wells in Ohio and West Virginia. Prior to Marcellus development, West Virginia had only two Class II disposal wells operating. By January 2010, nine such wells had been approved in West Virginia, and seven were operating. In addition to these commercial wells, West Virginia has 62 private brine disposal injection wells. Ohio has 2,801 Class II wells; 177 are permitted for disposal. In 2011 Ohio reviewed its brine disposal regulations and increased the fees for out-of-state users. In early 2012, the Ohio Department of Natural Resources halted wastewater injection at a disposal well near the site of a series of earthquakes in northeastern Ohio. On March 9, 2012, Ohio DNR released a report linking the earthquakes to the injection well and a previously unknown fault in the area.[31] Seismic concerns related to underground injection have been raised in other parts of the country as well.[32,j]

Numerous surveys over the past few decades have documented the extensive use of disposal wells for oil and gas produced water disposal. Argonne National Laboratory reports that 98

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[h] A "workover" is the term for any repair or modification after a well is in operation. "Downhole" refers to repairs that take place within the well itself rather than at the surface.

[i] A brine disposal well in Greene County owned by CNX Gas was closed in August 2010. An XTO Energy well in Indiana County was closed in 2011. Two new wells were approved in Columbus Township (Warren County) in 2011 but as of early 2012 had not yet begun accepting wastewater.

[j] The Arkansas Oil and Gas Commission banned disposal wells in the state after they were linked to increased seismic activity.

percent of onshore produced water (a category that includes natural gas produced water) is injected, either to maintain formation pressure in oil fields or for disposal.[33] In 2010 four of seven surveyed gas companies indicated using disposal wells for produced water, with three identifying Ohio wells and one not disclosing the disposal well location.[34]

Table 3. Permitted Oil and Gas Brine Disposal Wells in Pennsylvania

Facility	**County**	**Formation**	**Pressure (psi)**	**Injection Volume (Barrels/Month)**
Columbia Gas	Beaver	Huntersville/ Oriskany	1,300	21,000
EXCO– North Coast	Clearfield	Oriskany	3,240	4,260
CNX Gas[a]	Greene	Mine Void	0	150,000
Great Lakes Energy (now Range Resources)[b]	Erie	Gatesburg	1,570	20,000
XTO Energy[c]	Indiana	Balltown	1,930	3,600
Cottonwood	Somerset	Oriskany	3,250	27,000
EXCO-North Coast	Clearfield	Oriskany	1,450	4,200
Dominion	Somerset	Huntersville / Oriskany	3,218	30,000

[a] Facility closed by EPA order, August 2010.
[b] Commercial facility
[c] Facility closed, well plugged.

Two injection wells in Pennsylvania were the subject of concern during the expansion of produced water generation and disposal concomitant with the rapid development of the Marcellus Shale in 2008 through 2010. The CNX Gas well (permit PAS2D210BGRE) involved disposal of coal bed methane produced water into the Morris Run Borehole, which was drilled into an inactive coal mine. Mine void disposal is not unusual for some kinds of wastewaters, especially those that are alkaline, which may reduce the acidity of the mine discharge.[k] Disposal of oil and gas produced water into this type of formation is not typical; however, coal bed methane water is relatively low in dissolved solids, and the permit specifically allowed only this type of wastewater. This facility was the site of violations from September 2007 to March 2009.[35] Violations related to poor security (unlocked gates), poor management (no flow meters operational), and poor recordkeeping (disposal records incomplete). PADEP requested that EPA revoke the permit. CNX stated its intention to close the well in early 2010 (by letter to EPA on March 12, 2010). EPA issued a fine and a final order to close the facility in August 2010.

Hydraulic connectivity between the CNX disposal well and a nearby mine discharging to surface waters had also been suspected, but not demonstrated.[36] Still, this concern highlights the fundamental issue associated with disposal into mine voids. Mine voids may be at or above the

[k] Such discharge to mine voids as a beneficial practice is legal when authorized by EPA in advance. See 40 CFR 144.24 and 144.84.

level of underground drinking-water reservoirs, and if hydraulically connected to active mine locations may be subject to pumping activities that cause fluids to flow back to the surface. For this reason, disposal into mine voids is typically limited to wastewaters that will have a beneficial effect on mine pool water quality.

Tunnelton Liquids Company ("TLC"; permit PA0091472) was in operation for many years, treating predominantly acid mine discharge. The operations included the receipt of produced water from oil and gas operations, which was mixed with the acid mine discharge and partially treated. Treated water was discharged to the Conemaugh River, and the residual sludge was disposed of into a mine void in the Marion mine. This operation was approved in a Consent Order and Agreement with PADEP in 1997, and a permit was issued for discharge in 1997 and renewed in 2002. Treatment was permitted for 100,000 gallons per day of oil- and gas-related wastes, as well as 900,000 gallons per day of acid mine drainage wastewater. In May 2011, the EPA issued a notice of violation, stating that TLC was operating an unlicensed UIC well.[37] EPA informed PADEP of this action and requested confirmation that no other mine void injection plans had been approved by PADEP.[38]

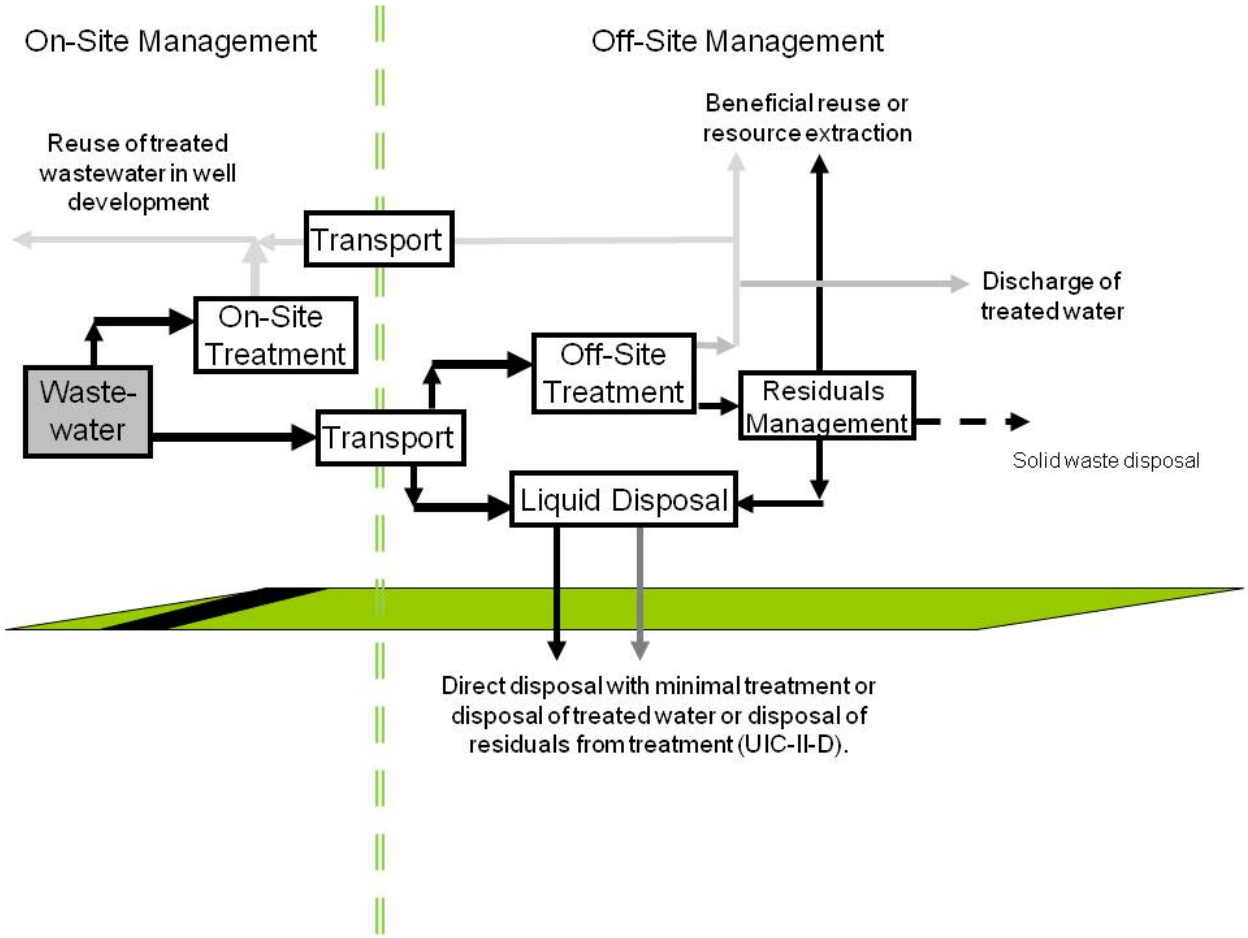
To the authors' knowledge, with the closure of the CNX well and the Tunnelton Liquids facility, produced water from oil and gas operations is no longer being disposed of in mine voids in southwestern Pennsylvania. Thus, the potential for these fluids to enter adjacent mines and find paths to groundwater or surface water is reduced.

Treatment

Treatment is the most complex management option. It can occur on-site or off-site and in conjunction with recycling, reuse, discharge, and disposal. It can be utilized to prepare wastewater for subsequent reuse in gas development or for disposal, or it can be used to generate clean water for discharge or distinct qualities of finished water or residuals for beneficial reuse. *The many potential outcomes of different treatment options will be discussed in Chapter 2.*

Figure 2 shows additional detail of the steps involved in treatment. On the left, on-site treatment is associated only with treatment for reuse at the well pad. Since no discharges are permitted from the well location, only an evaporative treatment with water discharged to the air would reduce the volume of produced water requiring off-site transport (though this could have other adverse impacts, including emissions of air pollutants and increased risk of spills or accidental overflows). Reuse (with or without dilution or treatment) is the dominant on-site management option (as discussed above). Most treatment associated with produced water takes place off-site and thus requires transport of the wastewater. Shown in the middle of Figure 2, transport is either to disposal wells, discussed above, or to treatment facilities. Treatment generates treated water, which may be discharged, shipped back to the well site for reuse, or diverted for beneficial reuse or resource extraction (top right). Finally, residuals generated during treatment, either concentrated liquid wastes (brines) or solid waste, can be sent to disposal (deep well or landfill) sites or diverted for beneficial reuse (bottom right).

Figure 2. Treated Water and Residual Product Flows



On-site and off-site treatment methods utilize very similar techniques. The choice of methods generally depends on the desired water products rather than the location of treatment. Treating wastewater for subsequent reuse within hydraulic fracturing, either on- or off-site, focuses on removal of organic contaminants and inorganic species known to induce fouling when reused. Treatment for other objectives—to produce a water clean enough for reuse or discharge, or to produce a brine or solid residual for subsequent reuse—may require more selective targeted removal technologies.

Contaminants to remove in treatment

For all kinds of wastewaters, treatment design begins with evaluation of the constituents to remove and assessment of methods to remove those targets. The major constituents of concern in produced water from natural gas development are (1) salt content, including metals, (2) organic hydrocarbons (sometimes referred to as "oil and grease"), (3) inorganic and organic additives, and (4) naturally occurring radioactive material (NORM).

Salts. Inorganic dissolved ionic components are usually measured by electrical conductivity or by gravimetric methods after water evaporation. They are expressed as salinity, conductivity, or total dissolved solids or reported as specific concentrations of soluble ions. Ionic constituents found in produced water include calcium, magnesium, sodium, potassium, carbonate, bicarbonate, sulfate, nitrate, chloride, and bromide. While the generic chemical term "salts" or "ions" is used for all dissolved inorganics, and the measurement techniques will provide a surrogate summary term, in practice some sources consider only monovalent ions in salts and create a separate category for other inorganic constituents (e.g., calcium, magnesium, sulfate), often called "scale-formers." Heavy metals (e.g., zinc, lead, manganese, iron, barium) are predominantly ionic salts and thus are part of this category as well, although they are often discussed separately. These distinctions are sometimes relevant for treatment technologies, but such differences can be evaluated only through complete chemical analysis of the water.

Organic compounds. These carbon-based compounds include oil and grease, which are sparingly soluble in water, as well as organics commonly found with petroleum and natural gas, including benzene, toluene, xylene, phenols, organic acids, and high-molecular-weight organics (e.g., polycyclic aromatic hydrocarbons, or PAHs). Again, this represents a large class of chemicals, which may be assessed broadly (e.g., as "petroleum hydrocarbons"). However, solubility is a critical characteristic affecting treatability, and therefore important differences in chemicals in this broad group must be considered.

Chemical additives. These compounds, while not a distinct chemical class, are often considered separately in produced water treatment. The exact chemical makeup of a hydraulic fracturing mixture varies, but the following classes of chemicals may be present:

- Proppants (sand)
- Clay stabilizers, which prevent the formation clay from swelling
- Acids to dissolve minerals and initiate cracks
- Gelling agents, which thicken the water to suspend the proppant
- Breakers, which allow a delayed breakdown of the gel
- Bactericides/antimicrobial agents to eliminate corrosion-enhancing bacteria
- Corrosion inhibitors, scale inhibitors, and iron controls to prevent corrosion and scaling
- Cross-linking agents, which maintain fluid viscosity as temperature increases
- Friction reducers
- Surfactants to increase viscosity

The makeup of hydraulic fracturing fluid is based on an evaluation of well conditions, the experience of the contractor handling the well completion, and evolving industry practices.

Significant concern has been raised regarding the nature of these additives, with 29 identified as of particular concern for human health and 13 identified as probable or known human carcinogens.[39] Among the most notable are 2-butoxyethanol (2BE), naphthalene, benzene, and polyacrylamide. At least one study notes that 2BE is being replaced in hydraulic fracturing with a less toxic product.[40] Table 4 summarizes the chemicals identified by a congressional study and their detection in produced water from the Marcellus formation.[41]

Table 4. Chemical Components of Particular Concern That May Be Present in Hydraulic Fluids Fracturing, as Identified in a Congressional Study[42]

Chemical component used 2005–2009	Chemical category[l]	Detected in at least one produced water sample (MSC report)
Methanol	HAP	Not tested
Ethylene glycol (1,2-ethanediol)	HAP	Yes
Diesel	Carcinogen, SDWA, HAP	Not tested
Naphthalene	Carcinogen, HAP, PC	Yes
Xylene	SDWA, HAP	Yes (total xylenes)
Hydrochloric acid	HAP	Not tested
Toluene	SDWA, HAP	Yes
Ethylbenzene	SDWA, HAP	Yes
Diethanolamine	HAP	Not tested
Formaldehyde	Carcinogen, HAP	Not tested
Sulfuric Acid	Carcinogen	Not tested
Thiourea	Carcinogen	Not tested
Benzyl chloride	Carcinogen, HAP	Not tested
Cumene	HAP	Not tested
Nitrilotriacetic acid (NTA)	Carcinogen	Not tested
Dimethyl formamide	HAP	Not tested
Phenol	HAP	Yes
Benzene	Carcinogen, SDWA, HAP	Yes
Di (2-ethylhexyl) phthalate	Carcinogen, SDWA, HAP	Not tested
Acrylamide	Carcinogen, SDWA, HAP	Not tested
Hydrofluoric acid	HAP	Not tested
Phthalic anhydride	HAP	Not tested
Acetaldehyde	Carcinogen, HAP	Not tested
Acetophenone	HAP	Yes
Copper	SDWA	Yes.
Ethylene oxide	Carcinogen, HAP	Not tested
Lead	Carcinogen, SDWA, HAP, PC	Yes
Propylene oxide	Carcinogen, HAP	Not tested
p-xylene	HAP	Yes (total xylenes)

Naturally occurring radioactive material (NORM). Shale gas produced water in the United States typically contains NORM at levels elevated from background,[43] and oil and gas development in other states has produced elevated NORM at levels of concern on production equipment and in wastewaters. This has generally not been the case in Pennsylvania, where

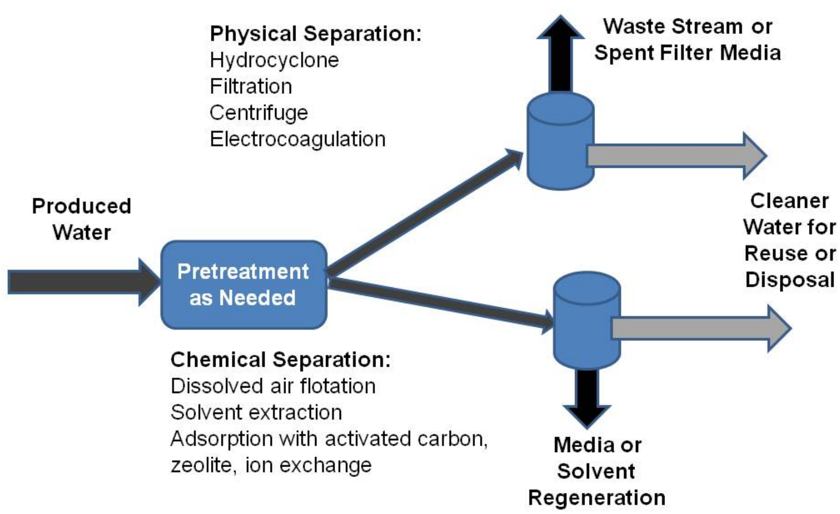
[l] HAP= Hazardous Air Pollutant. SDWA=Safe Drinking Water Act Regulated Chemical. PC=Priority Chemical.

routine surveys at oil and gas facilities producing hydrocarbons from conventional formations have rarely found levels above background.[44] Unlike more typical Pennsylvania sources, the Marcellus Shale is considered radioactive, as is common for organic rich shales.[45] The most abundant types of NORM in produced water from the Marcellus formation are radium-226 and radium-228, produced from radioactive decay of uranium and thorium present in the shale formation. Evaluation of drill cuttings and produced waters from Marcellus wells confirms that elevated levels of radioactivity are not uncommon for wastewaters associated with Marcellus Shale development.[46]

Treatment technologies

Produced water, including flowback, that is not reused generally requires treatment prior to disposal. As noted above, once contaminants of concern are evaluated, treatment options that target those constituents are considered.[m] For produced water, treatment options typically focus on removal of suspended solids, organics like oil and grease, and minerals (dissolved solids or salts). NORM is most often removed through treatments that target the three major constituents. Suspended solids are typically removed through settling (often in holding ponds or tanks) or filtration. Oil and grease treatment methods include physical separation processes, such as hydrocyclones, filtration, and centrifuge, and chemical separation processes, such as dissolved air flotation, solvent extraction, and adsorption (see Figure 3). When organics must be removed to very low levels (below the levels at which they become soluble in water), multistage treatment operations may be needed. For example, many soluble organics can be sorbed onto surfactant-modified zeolite (SMZ) and stripped to the air, and the off-gas subsequently mineralized in vapor phase bioreactors.[47]

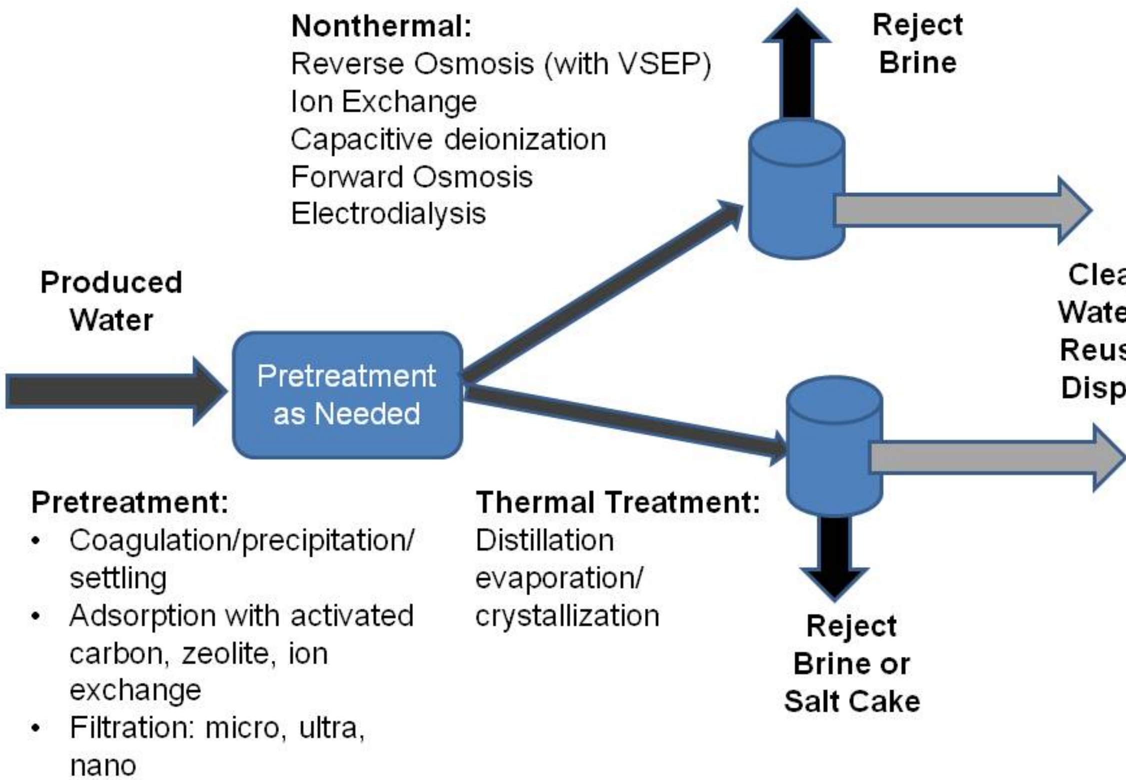
Figure 3. Technologies for Removing Oil, Grease, and Organics from Produced Water



[m] Treatment technologies are briefly introduced here but are covered in more detail in Chapter 2.

Treatment methods for removal of suspended solids and organics will rarely affect dissolved solids. When targeted salt removal is an objective, precipitation methods are generally effective only for multivalent ions (e.g., calcium, magnesium, iron, sulfate) and do not remove monovalent ions (e.g., sodium, chloride, bromide).[n] The removal of monovalent ions is commonly referred to as desalination or demineralization. Desalination treatment options include thermal methods, such as distillation, evaporation, and crystallization, and non-thermal methods, such as reverse osmosis (RO) with or without vibratory shear-enhanced processing (VSEP), ion exchange, capacitive deionization, forward osmosis, and electrodialysis (see Figure 4).

Figure 4. Technologies for Removing Dissolved Ionic Constituents from Produced Water



The simplest thermal desalination technique is evaporation from on-site holding ponds. Using energy from sunlight, evaporation reduces the volume of wastewater for disposal. It is widely practiced in arid areas, where evaporation exceeds precipitation. This method is unsuitable in the humid eastern part of the United States, particularly in areas of the Ohio River Basin where significant precipitation is evenly spaced throughout the year. On-site evaporation ponds are not utilized in the Marcellus production range. On-site holding ponds in precipitation-dominated regions *collect* water from rainfall, which dilutes the wastewater. Dilution can potentially increase the suitability of produced water for reuse (because it is less salty), but it clearly

[n] Valency refers to the charge on the ion, with monovalent being +1 or -1 as ions and multivalent being other values.

eliminates the evaporative potential to reduce volume for disposal. Open-pond evaporation may also contribute to air releases if volatile chemicals are present in the wastewater.

More complex desalination techniques use either thermal methods or membrane methods. Thermal methods involve heating the water to boiling and recapturing the steam as clean water. The salts that were in the produced water will be in the residual brine or salt cake left behind after the water has been boiled off. Other contaminants in the water will partition into the solid residual or the air, depending on their chemical characteristics, with metals and NORM in the residual. Membrane methods use small pores that allow only water to pass through while rejecting dissolved ions. Clean water comes out, and a more concentrated, lower-volume brine is left behind. Again, this brine will contain the contaminants that were removed from the water. Additional details of the methods for desalination and their challenges are provided in Chapter 2.

Treatment Facility Options for Produced Water

As noted, treatment processes are selected to remove specific constituents. Wastewaters that contain multiple contaminants of concern are generally treated in specially designed plants that have multiple unit operations to remove the targets. An example is a conventional wastewater treatment plant designed to treat municipal sewage. Wastewater generated by homes and businesses contains a wide variety of constituents (e.g., organic matter, nutrients, suspended solids). Consequently, a municipal wastewater plant, often called a publicly owned treatment works (POTW), has multiple steps designed to remove suspended solids, dissolved organic compounds that cause oxygen demand in receiving waters, and sometimes nutrients, like ammonia or nitrate. POTWs are not designed to remove salts, as the typical wastewater they receive does not contain high loads of dissolved inorganic chemicals like salt. POTWs have permits that allow discharge of treated water to surface waters. Treated wastewater is not pure water; it contains small amounts of the contaminants that were targeted for removal. Since salts are not targeted for removal, most salts that enter a POTW will be in the treated water and will be discharged to the receiving water.

Produced Water Disposal at Publicly Owned Treatment Works

Publicly owned treatment works (POTWs) can receive industrial wastewater in addition to municipal wastewater. Because POTWs are designed primarily to treat municipal sewage, industrial wastes are generally subject to pretreatment requirements to ensure that constituents in the industrial waste do not interfere with the conventional treatment processes in the POTW. High concentrations of salt in produced water can disrupt biological treatment in POTWs, although this is rarely observed, as permits often restrict POTWs to receiving oil and gas wastewater at less than 1 percent or 5 percent of total flow.[48] Heavy metals can disrupt nitrification in POTWs that include this nutrient removal process; however, this disruption is typically seen at higher concentrations of metals than are in produced waters.[49] Some organics that can be present in produced water (e.g., formaldehyde) have specific inhibitory effects on nitrification; again, this is seen at high concentrations.[50]

Treatment of produced waters at POTWs in systems that face capacity limitations is also a concern. POTWs are typically designed to treat a specific average flow rate of sewage. They have some additional capacity to manage short-term higher flows during storm events, but many systems do not have significant excess capacity under all conditions (e.g., during a period marked by multiple storm events). Systems with capacity limitations—due to inflow and infiltration associated with aging pipe systems or wet-weather flows that exceed pipe or plant capacity—could exacerbate uncontrolled overflow conditions if the volume or timing of produced water treatment is not adequately managed.

When needed to prevent disruption of the POTW or because they will not be removed in conventional processes, organics can be removed from produced water through several pre-treatment methods. For example, Kwon et al. reported on the use of a surfactant-modified zeolite absorption followed by a membrane bioreactor for removal of BTEX (benzene, toluene, ethylbenzene, xylene).[51] Yi et al. reported on the pretreatment of coke-plant wastewater to improve biodegradability in POTW processes.[52]

Treatment of oil and gas produced waters through POTWs, with or without pretreatment, is likely to remove suspended solids, some metals, and biodegradable organics. Suspended solids and some metals present in the produced water are likely to be removed through physical processes that will retain these contaminants in the sludge produced in conventional POTWs. The solids settle with other solids produced through treatment, and metals sorb onto these solids, ending up in the sludge.[53] Many organics, even those that are toxic, can be removed by the microbial species present in the treatment plant (e.g., phenol and NTA are biodegradable in POTWs).[54] Biodegradable organics are transformed by the bacteria into carbon dioxide and cell materials. Organic compounds that are resistant to microbial degradation will not be removed in POTWs, and dissolved ions (salts) will not be affected by treatment.

Nationally, POTW treatment followed by dilution in surface receiving waters is not frequently used as a produced water treatment/disposal option. However, it was a common practice in southwestern Pennsylvania during the long development of conventional fossil fuels and was initially practiced for disposal of produced waters from Marcellus development. In the Argonne National Laboratory survey, three of seven producers indicated sending produced water to POTWs at some time.[55]

As described in Chapter 4, in 2011 Pennsylvania updated Chapter 95 regulations setting maximum concentrations of total dissolved solids and chlorides permissible in discharges from POTWs (and other facilities, as discussed below). However, as of July 2011, 15 facilities in Pennsylvania were exempt from compliance with the regulations, meaning that they were allowed to continue discharging treated wastewater with concentrations exceeding the TDS and chlorides limits. Nine of these facilities are POTWs (listed in Table 5). Several of these, including Allegheny Valley Joint Sewage Authority and Altoona City Authority, stopped accepting oil and gas wastewaters in early 2011, and three listed in Table 5 declared their intention to stop receiving this wastewater in September 2011.[56] The remaining facilities may continue to receive produced water from oil and gas operations; however, PADEP requested in May 2011 that Marcellus drillers stop taking produced water to these facilities.[57] Data from PADEP indicate a 99.5 percent reduction in produced water from Marcellus operations going to exempt POTWs between the first half of 2011 and the second half (see Table 5).[58,o]

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[o] Note that the classifications of some facilities in the PADEP data exports are incorrect. Where this is the case, totals presented here will not match a cursory examination of PADEP data. However, the totals presented here are based on facility-level evaluation of the DEP database.

Table 5. POTW Facilities Permitted to Accept Produced Water from Oil and Gas Under Chapter 95 Exemption

Name	Permit Number	Receiving Stream	Total Flow (MGD)	Oil and Gas Flow (MGD)	Marcellus Produced Water?	Marcellus Produced Water Received Jan.–June 2011 (bbl)	Marcellus Produced Water Received July–Dec. 2011 (bbl)
Altoona City Authority, Water and Sewer Division	Not provided in PADEP database					21,822	
Williamsport Sanitary Authority	PA0027057	West Branch Susquehanna River	8.4	0.12	Indirect wastewater from CWT	3,030	
Punxsutawney Borough Municipal Authority	PA0020346	Mahoning Creek	2.2	0.02	Not in 2011	0	0
Municipal Authority City of McKeesport	PA0026913	Monongahela River	11.5[a]	0.102	None since May 19, 2011	22,525	0
Clariton Municipal Authority[b]	PA0026824	Peters Creek	6[a]	0.035	None since September 2011	309	0
Ridgway Borough Sewage Treatment Plant	PA0023213	Clarion River	2.2	0.02	None since May 19, 2011	30,702	0
Bockway Area Sewage Authority	PA0028428	Toby Creek	1.5	0.014	No (per letter to EPA March 31, 2011)	0	0

Reynoldsville Borough Authority	PA0028207	Sandy Lick Creek	0.8	0.011	Yes	6,928	80
New Castle City Sanitary Authority[d]	PA0027511	Mahoning River	17	0.55 (indirect)	Indirect wastewater from Advanced Waste Services	0[c]	0[c]
Johnstown Redevelopment Authority, Domick Point STP[b]	PA0026034	Conemaugh River	12[a]	0.076	None since September 2011	16,581.34	328
Kiski Valley[b]	PA0027626	Kiskiminetas River	7	0.09 (indirect)	Indirect wastewater from McCutcheon Enterprises	0[c]	0[c]
TOTAL						101,897.34[p]	408

[a] These POTWs may receive no more than 1 percent of their daily flow in oil and gas produced water.
[b] These POTWs stopped receiving oil and gas produced water as of September 30, 2011. Kiski Valley ordered McCutcheon to cease discharges to the plant May 19, 2011.
[c] See amounts in Table 6 from pretreatment facilities.
[d] In docket CWA-03-2011-0272DN, EPA ordered New Castle Sanitation Authority to discontinue its acceptance of oil and gas exploration and/or production wastewater as of September 28, 2011. Additional sampling was required.

[p] DEP spreadsheet with these data incorrectly lists Clariton Municipal Authority, Ridgway Borough Sewage Treatment Plant, Williamsport Sanitary Authority, and Altoona City Authority as CWTs and Castle Environmental as a POTW. Totals in these tables will not match a cursory analysis of the DEP spreadsheet data.

Produced Water Disposal at Centralized Waste Treatment Facilities

An alternative to POTW treatment for removal of suspended solids and organic constituents is treatment at dedicated brine or industrial wastewater facilities, also called centralized waste treatment (CWT) facilities. These treatment plants utilize many of the same unit operations that are found in POTWs but may also add coagulation and precipitation techniques to remove a select set of dissolved solids. For example, removal of iron or barium or radium salts can be achieved through pH control and addition of chemicals that facilitate precipitation. Brine treatment plants using conventional techniques have been operating in the Marcellus production basin for many decades. After treatment, water can be discharged to surface water under a discharge permit, discharged to sewers for subsequent treatment in a POTW with a pretreatment permit, or subjected to additional treatment for removal of salts.

There were 17 dedicated brine treatment plants in Pennsylvania operating prior to August 21, 2010, when new Chapter 95 discharge regulations took effect. As of July 2011, 6 of the 15 facilities in Pennsylvania that were exempt from the new regulations were dedicated brine treatment facilities (see Table 6).[q] Assessment of wastewater management from Marcellus drilling companies (provided to PADEP) indicates a 95 percent reduction in wastewater volumes going to Chapter 95-exempt CWT facilities between the first half of 2011 and the second half.[59]

There are also nonexempt brine treatment facilities that operate under the updated Chapter 95 regulations. These plants can process and return produced water for reuse or can discharge to surface water through permits, provided their treated water meets the new discharge limits (e.g., TDS must be less than 500 mg/L). Due to a significant increase in volumes of produced waters associated with gas development, additional treatment facilities have been proposed and sited in Pennsylvania in the past two years. In Pennsylvania, as of April 2011, 25 new dedicated brine treatment facilities had applied for DEP permits. As of October 2010, three permits had been issued, two in Lycoming County and one in Somerset County.[60] These plants are currently operating to provide partial treatment with return of water to the industry for reuse. Desalination stages are planned for many of the proposed plants; however, most plants recognize the significant cost differential to produce desalinated waters. Thus, treatment that includes full desalination is unlikely until reuse opportunities decline for their current product.

Five of seven drillers surveyed by Argonne National Laboratory reported sending some produced water to disposal companies in Pennsylvania or West Virginia.[61] CWTs received significant volumes of wastewater in 2011 (see Table 2, above). The exact nature of treatment at CWTs, as well as the ultimate disposition of wastewaters sent to these plants and treated waters generated at these plants, are beyond the scope of the present analysis. Chapter 2 provides general information on removal techniques and summarizes available data on effluent characteristics at a few brine treatment plants.

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[q] Note that there are 7 CWTs listed in Table 6. However, Advanced Waste Services discharges only to the New Castle City Sanitary Authority (a POTW listed in Table 5). This combination is considered a single facility since Advanced Waste Services does not have a permit for discharge.

Table 6. CWT Facilities Permitted to Receive Produced Water Under Chapter 95 Exemption

Name	Permit Number	Receiving Stream	Total Permitted Flow of Oil and Gas Wastewater (MGD)	Effluent Water Quality Data	Marcellus Produced Water Received Jan.–June 2011 (bbl)	Marcellus Produced Water Received July–Dec. 2011 (bbl)
PA Brine Josephine	PA0095273	Blacklick Creek	0.144	Quarterly data provided to EPA.[a] DMR data for November and December 2011 available.[b]	161,718.5	7,908.73
PA Brine Franklin	PA0101508	Allegheny River		Quarterly data provided to EPA.[a] DMR data for December 2011 available.[b]	584,524.86	8,410.79
Hart Resource Technologies	PA0095443	McKee Run	0.045 flowback; 0.018 gal/day produced water	Quarterly data provided to EPA.[a] Monthly DMR data available since March 2011.[b]	106,769	86
Tunnelton Liquids	PA0091472	Conemaugh River	0.1 oil and gas and 0.9 acid mine drainage	No DMR Data 2007–2010.[b] Limited data supplied to EPA.[a] Action by EPA pursuant to operation of an unlicensed UIC well for disposal of sludge from operations.[62]	275,845.78	0
Advanced Waste Services of PA (formerly Castle Environmental Inc.)	PAR00051 AWS and PAR00002 as CE	N/A. Discharges to New Castle City POTW	0.2	No DMR data.[b]	544,006.6 as AWS and 1,187 as CE	8,050
McCutcheon Enterprises	PAD013826847	N/A. Discharges to Kiski Valley		No DMR data.[b] Kiski Valley ordered McCutcheon to cease discharges to the plant May 19, 2011.	83,559	16,867.61
Waste Treatment Corporation	PA0102784	Allegheny River	0.21	DMR data monthly since 2008, but no TDS data.[b]	91,540.16	1,014.28
Sunbury Generation Wastewater Treatment System	PA0008451	Susquehanna River	0.08	This is a power generating facility. DMR data available but not specific to brine.[b] Suspended intake of Marcellus produced water in April 2011.	121,868.4	0
					1,971,019.2	41,331.13

[a] See requested analyses at epa.gov/region3/marcellus_shale/#npdeslets.
[b] Some Discharge Monitoring Report (DMR) data are available at cfpub.epa.gov/dmr/index.cfm. Some additional data are also available at ahs.dep.state.pa.us/NRS/.

Beneficial Reuse

The beneficial reuse of oil and gas brines has a long history in many states. For low-TDS produced water, a number of beneficial reuses have been investigated, including livestock watering, wildlife watering and habitat, aquaculture and hydroponic vegetable culture, irrigation of crops, washing of equipment, and fire control.[63] None of these reuses are applicable to produced water from highly saline formations like the Marcellus Shale. They are not discussed further here.

In many areas, produced water can be used for dust control on unpaved roads (including lease roads in the oil or gas field and rural roads in the region) and for deicing or ice control on roads in northern climates during the winter. In 1983 Michigan published an evaluation of produced water that began with review of management in 1937. In the 1930s and 1940s, brine was either returned to the subsurface, used by the chemical industry for extraction of sodium or calcium chloride, or left in pits to evaporate or seep away. Application to roadways was first reported in 1952 (although it has occurred since the advent of the industry) and increased with the reduction in the use of earthen pit disposal in the early 1960s.[64]

The use of oil field brines for roadway dust suppression was previously studied by a number of states as management of production brines became more common. In general, produced waters are not as effective as commercial products and require more frequent reapplication; however, they are generally cost-effective.[65] Produced waters can also be used for dust suppression in coal mining; it is not clear how widespread this use might be in coal regions as commercial products provide superior control.[66]

Brine spreading management plans are usually prescriptive in the application rate and frequency; they also contain restrictions on proximity to water bodies and application during rain or when rain is imminent.[67] The application of Marcellus brines for this beneficial reuse is permitted in Pennsylvania, provided they meet specified parameters for total salts, chloride, barium, and other constituents. According to press reports, in 2005 10 million gallons of brine were sprayed on roads in Pennsylvania.[68]

Residuals Disposal

In addition to the treated wastewater, all treatment methods produce residuals. These are solids removed in settling, coagulation, and precipitation processes; concentrated brines created through membrane desalination; and solid salts created through thermal desalination processes. These residuals must be managed. Wastewater sludges that are not dominated by salts can be managed through conventional processes, such as land application or landfill, depending on their characteristics. POTW sludge management is regulated on the basis of pathogen removal and metals content.[69] Potential management options include land application, stabilization, and composting. Completely dewatered salt solids can go to solid waste disposal in a landfill. In Pennsylvania, landfills are required to monitor for radioactivity in waste.[r]

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[r] The solid waste facility operator must investigate any truck containing greater than 10 μR/hour. Vehicles exceeding 2 mR/hour in the cab or 50 mR/hour on any other surface require notification of PADEP and isolation of

Highly concentrated brine wastes have the same disposal options as the original produced waters, at lower transportation costs. The predominant disposal option for concentrated brines from inland desalination is deep well injection. If desalination brines are sent to conventional brine treatment facilities without TDS discharge limits, benefits of the concentration of these wastewaters are completely lost. For example, during a recent demonstration process, after treatment the residual brine that had been concentrated was then trucked to an approved commercial produced water disposal facility that operates under exemption to the Chapter 95 TDS standards.[70] The concentrated brine was effectively re-diluted in the surface water discharge of the facility, negating all environmental benefit of the treatment process.[s] While the PADEP requests that drillers not take Marcellus produced waters to Chapter 95-exempt facilities, it does not specifically mention treatment residuals. It is not reasonable to concentrate produced water through an energy-intensive process and then dispose of the concentrate through dilution in surface waters. Concentrated brine should be disposed of through deep well injection (at UIC Class II wells).

Resource Extraction

A potential technology applied to other oil and gas brines, but not yet to shale gas produced water, is resource extraction.[71] Methods for recovery of iodine and bromine from oil field brines were pioneered by Dow Chemical Company in the 1920s; this represented the only domestic production of iodine for many decades. Today iodine is produced in the United States from oil field brines in Oklahoma and Montana.[72] Similarly, bromine recovery from oil field brines also has a long history. Current commercial production comes from non-oil-associated brines in Arkansas and Michigan.[73] Lithium has also been extracted from brines in Nevada.[74]

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waste and/or the vehicle for further investigation. See details in PADEP guidance: elibrary.dep.state.pa.us/dsweb/Get/Document-48337/250-3100-001.pdf.

[s] The system manufacturer notes that the brine disposal method selected for the demonstration will not reduce salt load to surface water, and that highly concentrated waste brines should be disposed of through deep well injection.

Chapter 2. Technology Analysis for Produced Water Treatment

This chapter builds on the content of Chapter 1, which presented an overview of produced water management that included wastewater treatment options. This chapter summarizes technical details of treatment options and discusses how options are selected for specific produced waters.

Wastewater treatment can involve a number of different techniques, almost all of which have been tried for produced water from oil and natural gas development. There have been numerous reviews of produced water technologies for oil and coal bed methane produced water; Appendix A provides a list of these resources. Many of the same technologies are applicable to produced water from hydraulically fracturing shale formations for gas extraction. A critical difference for produced water from shale formations, and especially from the Marcellus formation, is the high concentration of salts.[75]

The quality of the produced water, regardless of its source, dictates the options for management. As described in the previous chapter, options include reuse and recycling, disposal, and treatment. This chapter deals exclusively with treatment. Treatment choices are determined by the nature and concentration of the contaminants in the wastewater, but other factors are also important. Treatment is designed to remove contaminants to *specific target concentrations*, so initial analysis of the wastewater *and* the objective in terms of the final water quality together influence treatment choices.

Contaminants of Concern

As discussed in Chapter 1, the major constituents of concern in produced water from natural gas development are (1) salts (measured as salinity, conductivity, or total dissolved solids), including metal ions, some of which are toxic, (2) organic hydrocarbons (sometimes referred to as oil and grease), (3) inorganic and organic additives, and (4) naturally occurring radioactive material (NORM). Many of these are present in produced waters from any oil and gas activity, although produced water from hydraulic fracturing may also include diluted quantities of the chemicals used for fracturing.

There are many ways to categorize the contaminants present in produced water from shale gas development. Contaminants can be organic or inorganic; soluble, insoluble, or suspended; scale-forming; oxygen-demanding; toxic; and naturally occurring or anthropogenic. Because the present analysis focuses on treatment options, contaminants will be categorized as they would be divided in specific routine analyses. It is always possible to produce a complete chemical analysis of any wastewater, but it is often prohibitively expensive to do so. Treatment decisions are often made on the basis of surrogate or lumped terms, or according to representative analyses rather than full chemical speciation of the wastewater.

Figure 1 shows the typical division of wastewater components in standard analysis. Filtration separates a wastewater into components that are suspended particles (like sand) and those that are dissolved chemicals (like salt or sugar). Suspended contaminants can be measured as total suspended solids (TSS, in mg/L) or as turbidity (in nephelometric turbidity units, or NTU).[t] Suspended inorganic components are typically sand, grit, and scale. Suspended organic components include bacteria, oil and grease, and high-molecular-weight organic compounds such as natural and anthropogenic colloids and polymers. Inorganic and organic components of suspended solids can be determined separately by additional analysis. In analysis, organics are removed by heating the sample to volatilization temperature. The residual inorganics are called nonvolatile suspended solids, and the organics are classified as volatile suspended solids (VSS). When measured, VSS may also include smaller compounds that are sorbed to particulates; these chemicals might normally be soluble, but in the presence of suspended solids they may be removed as if they were solids themselves. This characteristic can be used to increase removal of dissolved organic compounds by addition of suspended solids with high sorptive capacity, such as powdered activated carbon.

Dissolved contaminants can be measured as total dissolved solids (TDS, in mg/L) or indirectly assessed by evaluating the electrical conductance of the water (EC, in mS/cm). Dissolved inorganics can be individually quantified (as in measures of chloride concentration) or can be assessed through lumped terms (e.g., hardness, alkalinity). Dissolved organics include ionizable organic acids (e.g., acetic acid) and uncharged low-molecular-weight organics with moderate or high solubility (e.g., alcohols, BTEX). A lumped term, dissolved organic carbon (DOC), can be measured and represents the soluble organics in the system. Total organic carbon (TOC) can also be measured before filtration and will represent the dissolved and suspended carbon in the system.

Organic compounds can also be measured in units of oxygen demand. Oxygen demand units are routinely used in wastewater treatment to represent the amount of oxygen that would be used up if the contaminant were released into a water body. When oxygen-demanding waste enters the environment, microbial systems biodegrade it, using up oxygen; this leads to poor water quality and impairment of aquatic life. Chemical oxygen demand (COD) includes all oxygen demand, whether available to microbial systems or not, while biochemical oxygen demand (BOD) is generally measured using bacterial systems and represents compounds that are biodegradable. The BOD/COD ratio is widely used to characterize the biodegradability of a wastewater. A high BOD/COD ratio indicates that most of the compounds in the water that use up oxygen are biodegradable, while a low ratio indicates that the waste contains more materials that are not biodegradable. Biodegradable compounds are likely to be removed in conventional wastewater treatment in POTWs. Non-biodegradable compounds have less direct effect on oxygen consumption in the environment, but they may have other deleterious effects. And, by their nature, they are less likely to break down, possibly leading to accumulation in natural systems.

[t] Turbidity is a measure of the cloudiness of the water and is determined by measuring light attenuation through the sample.

Figure 5. Wastewater Component Characterization

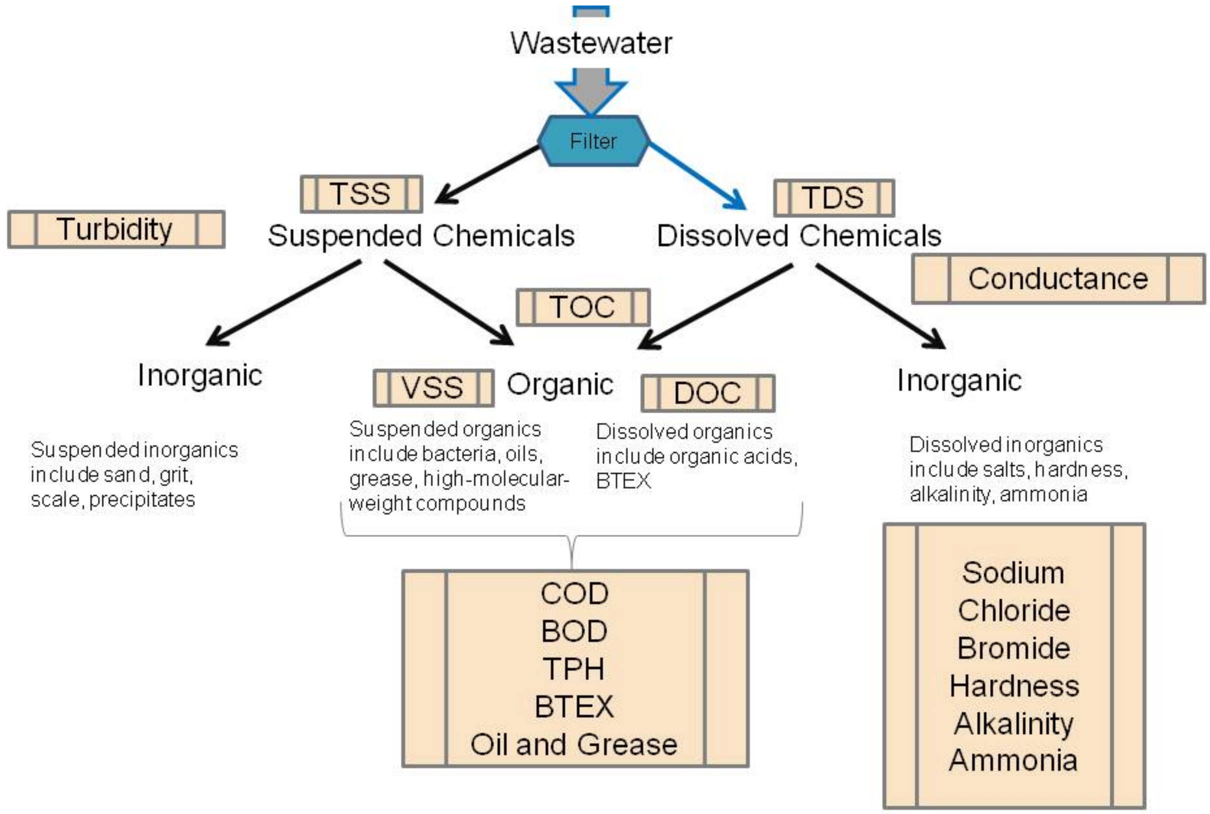


Table 1 provides summary data for the analysis of produced water from Marcellus Shale development. Most notable is the wide range of values for most constituents, suggesting high variability in the wastewater that will require treatment.

Table 1. Chemical Constituents in Produced Water from Marcellus Shale Development[76,u]

Chemical constituent or surrogate parameter	Unit of measure	Range reported in produced water from wells drilled in Marcellus Shale at 5 days post hydraulic fracturing	Range reported in produced water from wells drilled in Marcellus Shale at 14 days post hydraulic fracturing
Total Suspended Solids (TSS)	mg/L	10.8–3,220	17–1,150
Turbidity	NTU	2.3–1,540	10.5–1,090
Total Dissolved Solids (TDS)	mg/L	38,500–238,000	3,010–261,000
Specific Conductance	umhos/cm	79,500–470,000	6,800–710,000
Total Organic Carbon (TOC)	mg/L	3.7–388	1.2–509
Dissolved Organic Carbon (DOC)	mg/L	30.7–501	5–695
Chemical Oxygen Demand (COD)	mg/L	195–17,700	228–21,900
Biochemical Oxygen Demand (BOD)	mg/L	37.1–1,950	2.8–2,070
BOD/COD Ratio (% biodegradable)			0.1 (10%)
Alkalinity	mg/L	48.8–327	26.1–121
Acidity	mg/L	<5–447	<5–473
Hardness (as $CaCO_3$)	mg/L	5,100–55,000	630–95,000
Total Kjeldahl Nitrogen (TKN)	mg/L as N	38–204	5.6–261
Ammonia Nitrogen	mg/L as N	29.4–199	3.7–359
Nitrate–N	mg/L as N	<0.1–1.2	<0.1–0.92

[u] These data are from a single source (Hayes, "Sampling and Analysis of Water Streams"), with the exception of NORM (from Rowan et al., "Radium Content of Oil- and Gas-Field Produced Waters"). NORM data did not specify how long after well completion the samples were taken, and thus cannot be associated with either 5 or 14 days post hydraulic fracturing. BTEX and VOC data provided here have significant uncertainty. Data marked J are estimated due to analytical limitations associated with very high concentrations. Extensive data on produced water quality throughout the United States are available (see energy.cr.usgs.gov/prov/prodwat/intro.htm). Additional data specific to Marcellus are available from a variety of sources (produced water treatment plants, PADEP, drilling companies), although they have not been collated into a single database, making summative analysis difficult.

Chemical constituent or surrogate parameter	Unit of measure	Range reported in produced water from wells drilled in Marcellus Shale at 5 days post hydraulic fracturing	Range reported in produced water from wells drilled in Marcellus Shale at 14 days post hydraulic fracturing
Chloride	mg/L	26,400–148,000	1,670–181,000
Bromide	mg/L	185–1,190	15.8–1,600
Sodium	mg/L	10,700–65,100	26,900–95,500
Sulfate	mg/L	2.4–106	<10–89.3
Oil and Grease	mg/L	4.6–655	<4.6–103
BTEX (benzene, toluene, ethylbenzene, xylene)	µg/L		Non-detect to 5,460
VOC (volatile organic compounds)	µg/L		Non-detect to 7,260
Naturally occurring radioactive materials (NORM)	pCi/L	Non-detect– 18,000 pCi/L; median 2,460 pCi/L	
Barium	mg/L	21.4–13,900	43.9–13,600
Strontium	mg/L	345–4,830	163– 3,580 J
Lead	mg/L	Non-detect–0.606	Non-detect–0.349
Iron	mg/L	21.4–180	13.8–242
Manganese	mg/L	0.881–7.04	1.76–18.6

Finished Water Quality Targets

As described in Chapter 1, produced water management can include recycling/reuse, disposal, and treatment. Partial treatment is required for some reuse and disposal options, and water treatment criteria depend on the ultimate disposition of the water. Reuse may require partial treatment to avoid the reintroduction of scale-forming or biofouling contaminants into the next well. Similarly, disposal wells can become clogged if untreated produced water is disposed, and partial treatment is often undertaken to minimize this potential. Preventing well fouling generally requires removing suspended solids, organics that might encourage bacterial growth, and inorganics that precipitate (calcium carbonate and barium sulfate) with constituents expected in the formation.[77] Reuse may also require reducing dissolved solids that alter water characteristics (e.g., increasing friction) or inactivate key additives. Table 2 provides general characteristics required for specific end uses of treated water. Most reuse water quality criteria would not permit the direct use of produced water from a high-salinity shale gas formation like the Marcellus, although water that returns during the early flowback period is often suitable for reuse. Partial treatment of produced waters from high-salinity formations might enable their use in applications requiring lower salt contents.

Table 2. Finished Water Quality Criteria for Specific Treatment Goals[78]

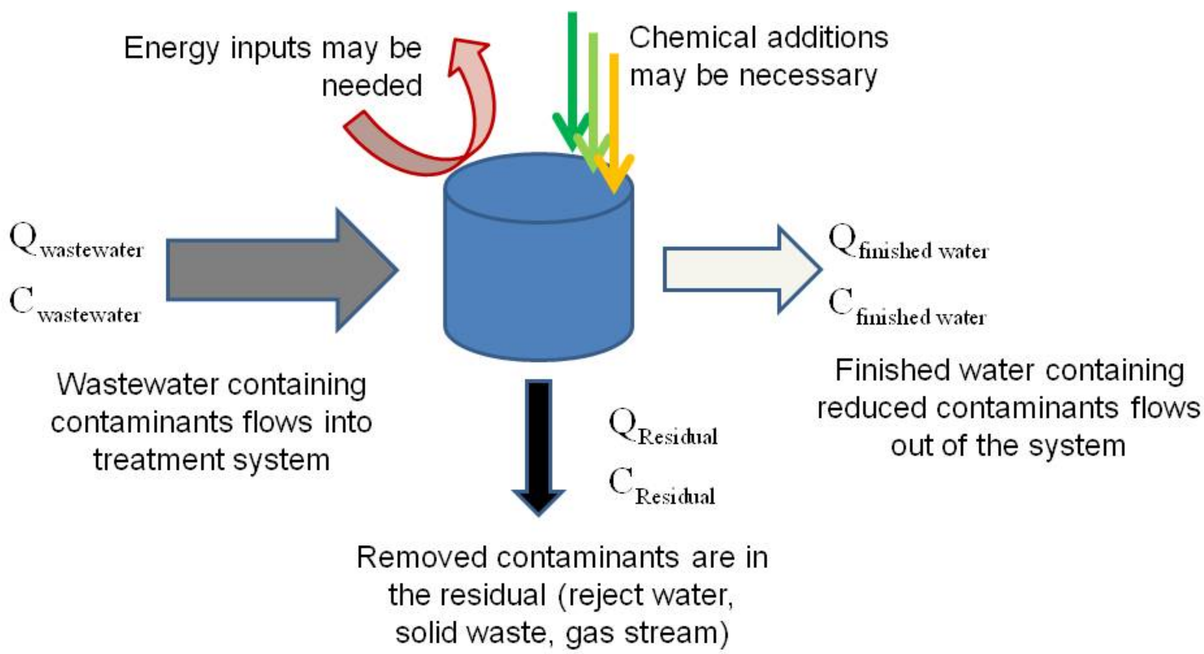
Treatment Goal	Water Quality Needed	Potential for Use
Discharge to surface water in Pennsylvania	<500mg/L TDS <250 mg/L chloride <250 mg/L sulfates <10mg/L total barium <10mg/L total strontium	Only with extensive treatment.
Reuse for hydraulic fracturing	Moderate TDS Low SS Low Ca, Mg, Fe, sulfate (scale formers)	Very likely and routinely practiced, often with partial treatment or dilution.
Deep well disposal	Low Ca, Mg, Fe, sulfate (scale formers) Low SS	Very likely and routinely practiced, sometimes with partial treatment to reduce scale-forming potential.
Crop irrigation	Low salinity (TDS) Low sodium adsorption ratio (SAR <6) Low toxicity	Only with extensive treatment.
Wildlife and livestock consumption	Moderate TDS (<5,000 mg/L) pH 6.5–8 SAR 5–8	Only with extensive treatment.
Aquaculture and hydroponic vegetable culture	Moderate TDS Low metals	Only with extensive treatment.
Dust control on roads and in mining	Low SS Low in specific constituents like metals	Possible for some produced water and for treated brines.
Vehicle and equipment washing	Low SS Moderate TDS	Possible with dilution.
Power-generation cooling	Low SS Moderate TDS Low Ca, Mg, Fe, sulfate (scale formers)	Possible but unlikely due to fouling problems.
Fire control	Low SS Low organics	Possible but unlikely.
Potable reuse	SDWA[v] criteria Low DBP formation potential Adequate mineral content	Very unlikely. Indirect potable reuse through aquifer recharge possible with extensive treatment.

Generic Treatment Technology Analysis

[v] SDWA: Safe Drinking Water Act. Potable reuse requires meeting all primary drinking-water standards. Drinking-water users may also desire water that meets secondary standards for aesthetics like color, taste, and odor.

All treatment methods have the same general characteristics (see Figure 2). Wastewater containing a mixture of contaminants (C_1, C_2 ... C_i) enters the treatment process at a specific flow rate (Q). A chemical, physical, or biological process takes place in the treatment system to produce a finished water that is lower in the target contaminants. The process creates a residual containing the contaminants that have been removed or the by-products of their transformation. This residual can be a liquid stream, a solid or sludge product, or a gaseous stream. The separation of the contaminant from the water generally requires significant chemical and energy inputs. The nature of the inputs depends dvon the process, the quality of the influent wastewater, and the desired quality of the effluent finished water.

Figure 6. Generic Wastewater Treatment



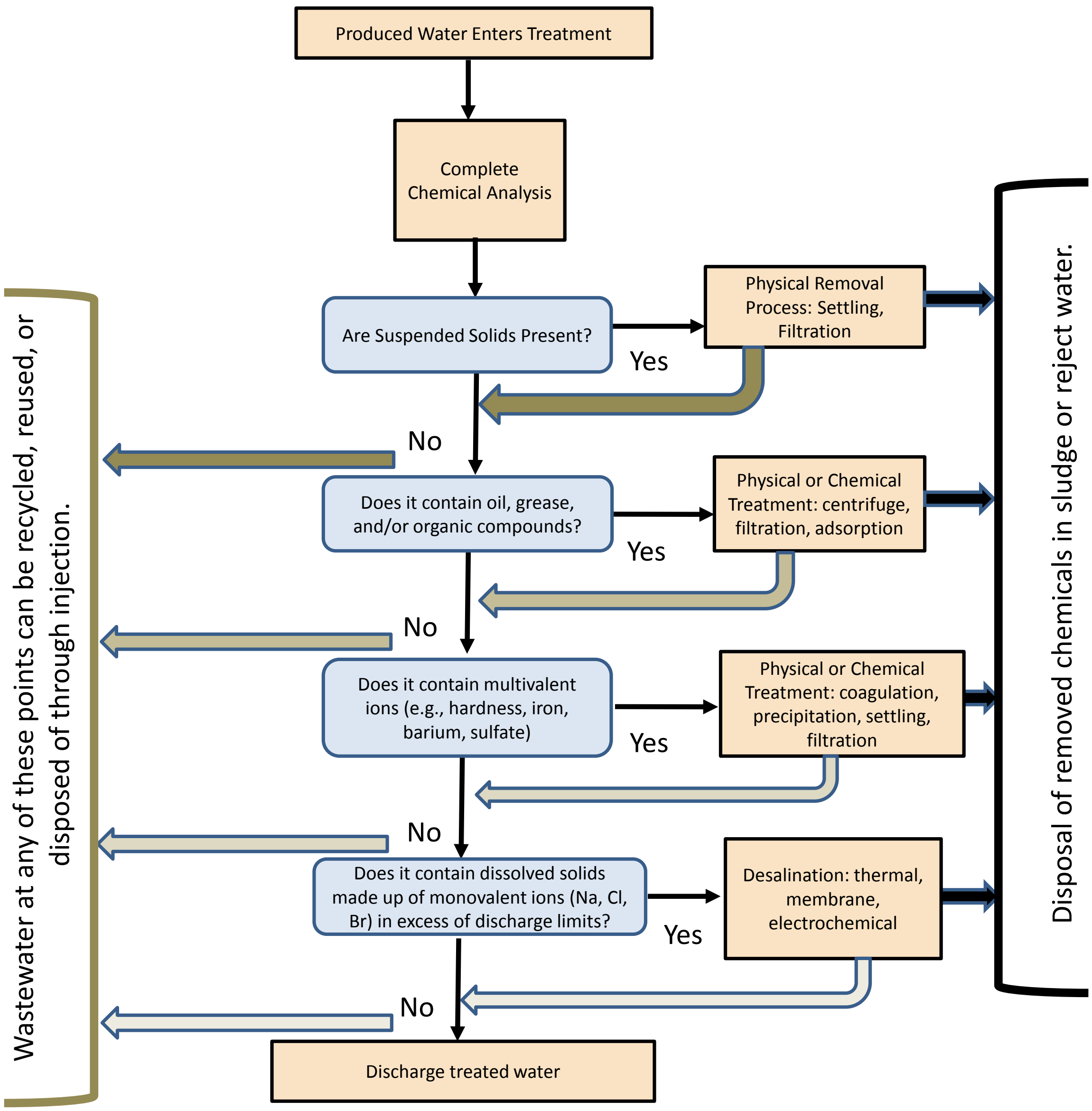
Selecting Treatment Processes

Once the influent wastewater is characterized (see Figure 1), and the final water quality desired is known (see Table 2), a treatment system made up of different components can be selected (see Table 3). Figure 3 details the decision framework for a generic wastewater that might contain all the constituents of concern described above. A treatment system must begin with removal of suspended solids, inorganic or organic, and then remove dissolved organics and potentially scale-forming constituents. Finally, when all that remains is simple dissolved salts, desalination can be accomplished. While it is possible to combine treatment steps, desalination is typically very sensitive to contaminants that foul membranes or reduce efficiency. Thus, if the target is water quality suitable for discharge to surface water, all of the shown treatment steps will be necessary, with water moving through each stage. Reuse or disposal targets that do not require desalinated water will need fewer stages. Shown on the left of Figure 3, partially treated water can be sent to reuse or disposal after any unit operation. Shown on the right, residuals are formed from each treatment step. At the bottom, fully desalinated water can be used for any application; however, distilled water is corrosive and requires re-mineralization for most uses. Within each treatment step, there are various technologies that can be employed. For example, soluble organics can be removed through biodegradation, sorption, or chemical oxidation. Table 3 shows the treatment options for each type of removal. Treatment methods are summarized in this section.

Table 3. Treatment Methods for Classes of Contaminants in Produced Water

Class	Examples	Surrogate Parameter	Treatment Methods
Suspended solids	Sand, grit, scale Bacteria	Total suspended solids Turbidity	• Coagulation/flocculation with sedimentation and filtration • Microfiltration or ultrafiltration
Suspended organics	Oil, grease, colloids, bacteria	Oil and Grease Total organic carbon Chemical or biological oxygen demand	• Dissolved air flotation • Biodegradation • Adsorption (activated carbon, zeolites) • Microfiltration and ultrafiltration
Dissolved organics	BTEX: benzene, toluene, ethylbenzene, xylene Phenols, organic acids	Dissolved organic carbon BTEX VOC Specific chemical additives (see Table 4 in Chapter 1)	• Adsorption (activated carbon, organoclays, zeolite, resins) • Chemical (ozonation, fenton) • Electrochemical or photocatalytic oxidation • Biodegradation • Nanofiltration or reverse osmosis
Dissolved multivalent ionic species	Scale-formers: Ca, Mg, Fe, Sr, Ba, sulfate NORM	Hardness Specific metals (Iron, Strontium, Barium) Specific anions (sulfate, nitrate-nitrogen)	• Metals: aeration, settling, filtration; ion exchange, reverse osmosis • Hardness: ion exchange • NORM: ion exchange, lime softening, reverse osmosis
Dissolved monovalent ionic species	Na, K, Cl, Br, I NH_4^+	Specific ions: Na, Cl, Br Ammonia-nitrogen	• Thermal desalination • Membranes • Electrochemical

Figure 7. Decision Flowchart for Produced Water Treatment



Treatment Processes

As the right side of Figure 3 shows, numerous treatment methods might be employed for produced water, depending largely on the target contaminants for removal. There are some overlaps, with certain physical, chemical, and biological processes suitable for multiple targets. For detailed technical analysis, refer to the Produced Water Management Information System (PWMIS) developed by Argonne National Laboratory and accessible on the U.S. Department of Energy website, managed by the National Energy Technology Laboratory (NETL).[79] The PWMIS includes a decision support tool that incorporates technological as well as policy and regulatory aspects into selection of an appropriate produced water management decision. Similar decision support tools have been suggested to include an evaluation of trade-offs including environmental effects, costs, and health and safety issues.[80]

Physical Processes for Removal of Suspended Solids

Particles settle out of the water when they are of sufficient size and density. For example, sand particles will settle out of water that is not moving. Simple gravity settling tanks are sufficient for large particles. If particles are smaller or less dense, filtration can be used. Simple filtration removes suspended solids from produced water by passing the water through a medium (e.g., sand and gravel) where particles are captured by physical sieving or by electrostatic interaction with the media. Membrane filtration systems (e.g., ceramic or cellulosic) can also be used for suspended solids removal, but energy needed for these systems increases as pore size decreases. When smaller particles or higher amounts of suspended solids are present, coagulation can be used. Chemical addition encourages the formation of larger particles that can be removed through gravity settling tanks or filtration.

Marcellus Shale produced water has moderate suspended solids, and simple gravity-driven settling or media filtration at the well is routinely practiced to allow reuse of water produced during the flowback period. Similar separation is often included in pretreatment of water that will be disposed of through deep well injection, as solids can damage equipment and cause premature clogging of the formation receiving the produced water.

Physical or Chemical Treatment for Removal of Organic Compounds

Removal of organics in produced water is typically via physical or chemical methods. Physical means are well suited to organics that exist in a separate phase from water, such as oil and grease, which are often removed in the same settling tanks used to remove particles. Oil and organics that are dissolved in the oil are less dense than water, forming a separate phase that rises to the top of settling tanks, also called “knockout tanks” in the oil production industry. Selective withdrawal of materials from the tank allows removal of the oil layer at the top and the sediment layer at the bottom. Cleaner water is withdrawn from the mid-level. Additional physical processes including centrifugation and cyclones can also be used to separate materials by density, with lighter oils and organics separated from heavier water and suspended solids. Membrane-based physical methods for oil and organics removal have also been used for produced water.[81] Multistage filtration is often required to reduce fouling on small-pore filters. Ultra- and nanofiltration are based on metal oxides and carbides that are stable under harsh chemical and thermal conditions; however, they have high initial costs and large footprints. Physical treatment based on sorption (onto activated carbon or zeolite) can also be used.

Chemical treatment methods can involve addition of chemicals that oxidize the organic matter to CO_2 and water. Such additives can also oxidize inorganics (e.g., metals) to forms that are less soluble and can be removed after precipitation. Biological processes can also be used for oxidation of organics; however, halophilic (salt-tolerant) organisms must be used due to the high salinity of the produced water.[82]

Physical or Chemical Treatment for Removal of Dissolved Multivalent Ions

Many dissolved metals can be removed from water through chemical processes that enhance formation of insoluble precipitates. For example, raising the pH will increase precipitation of hydroxides of many different metals, and chemical oxidants will oxidize metals to less soluble forms (e.g., Fe^{2+} to Fe^{3+}). Addition of sulfate will precipitate barium salts. Such processes have been used in industrial and potable water treatment systems for many decades and are well understood and relatively simple to operate. Once dissolved solids are converted to insoluble form, they can be removed as other suspended solids through coagulation, settling, and filtration systems. For example, lime softening involves addition of chemicals that precipitate Mg and Ca ions (removing hardness). Lime softening is also effective at removal of radium- 226 and radium-228 (constituents of NORM). Polyvalent anions can also often be removed through precipitation. For example, sulfate and phosphate can be removed through addition of aluminum or iron salts that form insoluble precipitates that are then settled or filtered.

Ion exchange is a physical process that can be used to remove specific ions by replacing them with ions of less concern (e.g., barium can be exchanged for calcium). Ion exchange is effective for a wide range of metals including NORM (Ra226/228, uranium, and beta particle emitters).

Chemical additives are not inexpensive; however, such processes are much less costly than desalination. Produced water treatment systems based on this type of chemical processing are widespread. An example process, the Advanced Oxidation and Precipitation Process (AOPP), involves oxidation of metals with ozone to induce precipitation and is designed to facilitate reuse of produced water by reducing scale and microbial growth.[83]

Existing Physical–Chemical Treatment Plants in the Marcellus Region

Many of the brine treatment plants currently operating in Pennsylvania (as described in Chapter 1) use the technologies for removal of suspended solids, soluble organics, and multivalent ions reviewed above. The final step shown in Figure 3, desalination, is the most energy intensive, and consequently many facilities treat to this point and then repurpose the water for activities in oil and gas development. Specifically, reuse of produced water that contains only simple salts (e.g., NaCl, KBr) is widespread and generally economical if disposal wells are distant or freshwater sources are limited.

For example, Reserved Environmental Services, located in Hempfield Township in Pennsylvania's Westmoreland County, operates a treatment facility designed to handle 1 million gallons per day of produced water from gas development in the Marcellus Shale. Currently it removes multivalent ions (metals like iron and anions like sulfate) and organics through coagulation, settling, and filtration. It produces a finished water that is still quite high in TDS, but predominantly sodium and chloride. Similarly, Hydro Recovery LP is using a Siemens Water system composed of staged precipitation and dewatering to treat produced water in Tioga County, Pennsylvania. Suspended solids, metals, and hardness are removed, and the resulting brine is reused after dilution in subsequent hydraulic fracturing.

Brine treatment facilities that process produced water with subsequent discharge under exemption to the Chapter 95 TDS standards also usually follow a conventional treatment process that removes suspended solids and uses physical and chemical reactions to remove sulfate and multivalent cations (e.g., iron, calcium, barium). Effluent monitoring from these facilities indicates high TDS and detectable concentrations of other contaminants. Table 4 summarizes data for three facilities in southwestern Pennsylvania.[w] Because no specific data are available regarding influent concentrations of the brine entering these plants, which is likely a mixture of coal bed methane produced water and oil and gas produced water from many different formations, treatment efficiencies cannot be assessed. However, it is clear that multistep conventional treatment does not remove all contaminants, either organic (measured here as oil and grease) or inorganic (measured as TDS and specific ions). The wide variability in finished water quality is likely related to the wide variability in water quality sent to these plants rather than any operational variability; however, this cannot be confirmed. Treatment plants using traditional physical-chemical methods will usually remove significant amounts of suspended solids, some organic constituents, and some dissolved multivalent ions. Some organic and inorganic dissolved constituents and almost all monovalent salts will pass through treatment, as indicated by high levels of TDS, chloride, and bromide in the discharged water reported in Table 5.

[w] See Chapter 1, Table 6, for facility details and volumes of Marcellus wastewater delivered to these facilities in 2011.

Table 4. Water Quality Analysis of Brine Treatment Plant Effluent[x]

Chemical Constituent or Surrogate Parameter	Unit of Measure	Pa Brine (Josephine) Discharge (PA0095273) Nov.–Dec. 2011	Pa Brine (Franklin) Discharge (PA0101508) Nov.–Dec. 2011	Hart Resources Discharge (PA0095443) March–Dec. 2011	Waste Treatment Corporation (PA0102784) Jan.–Dec. 2011
Flow	MGD	0.155	0.18	0.018-0.045	0.164-0.214
Total Suspended Solids (TSS)	mg/L	20.5-32	<10 to 33	6-19.5	<2.5-17
Oil and Grease	mg/L	5.25-10.6	2.25-9.49	3.8-22	<5-6.8
Total Dissolved Solids (TDS)	mg/L	133,050-198,400	91,600-108,000	7,200 – 179,900	Not reported
Alkalinity (as $CaCO_3$)	mg/L	185-236	57-95	45-258	45-56
Acidity (as $CaCO_3$)	mg/L	0	0	1 to <2	1-31
Chloride	mg/L	64,404-96,909	48,600-54,300	3300-91, 728	69,800 – 131,725
Bromide	mg/L	1100-8290	603-727	76.20-6630	Not reported
Sulfate	mg/L	975-1000	634- 841	104-1500	Not reported
Iron	mg/L	0	0.31-0.519	0.14-1.37	0.13-1.84
Strontium	mg/L	Not reported	299-303	Not reported	Not reported
Barium	mg/L	12.3-18.5	6.78-8.99	2.775-13.78	Not reported
NORM:					
Uranium	µg/L	ND	ND	ND	Not Reported
Radium-228	pCi/L	8.39-15.6	3.6-15.6	2.63-8.31	
Gross Alpha	pCi/L	0.132	0.132-156	6.39-117	
Radium-226	pCi/L	1.75-2.23	1.75-1.77	0.815-7.94	

These data from the DMR website at: http://www.ahs.dep.state.pa.us/NRS/ and from data submissions to EPA posted at http://www.epa.gov/region03/marcellus_shale/ Note that DMR data and EPA web site disclosure data to not agree on a number of constituents, suggesting they represent different grab samples. Data ranges here represent maximum and minimum reported to either agency. Values are based on average monthly when available, daily maximum when no average was reported.

[x] These data are from the DMR website at ahs.dep.state.pa.us/NRS/ and from voluntary data submissions to EPA posted at epa.gov/region03/marcellus_shale/. Note that DMR data and EPA website disclosure data do not agree on a number of constituents, suggesting they represent different grab samples. Data ranges here represent maximums and minimums reported to either agency. Values are based on monthly average when available and daily maximum when no average was reported. All available data are provided; no data are reported for items not specified in the permit, for example, hydraulic fracturing chemical additives. NORM and bromide were reported separately in response to a special request from EPA and are not routinely monitored for permit compliance.

Treatment for Removal of Monovalent Ions: Desalination

While treatment to remove suspended solids, dissolved organics, and multivalent ions is widespread and relatively cost-effective, treatment to remove monovalent ions (e.g., Na, K, Cl, Br) is much more challenging. The removal of monovalent ions is commonly referred to as desalination or demineralization. Desalination has been used to produce potable water from seawater for thousands of years, and simple methods based on boiling water and collecting the condensate remain relatively easy to execute. However, they are prodigious consumers of energy. Extensive research on lower-cost desalination methods has yielded a number of viable thermal-based methods such as vapor compression, distillation, multistage flash, dew vaporization, freeze-thaw, evaporation, and crystallization. New non-thermal-based methods are also being developed, including reverse osmosis (RO) with or without vibratory shear-enhanced processing (VSEP), nanofiltration, electrodialysis, electrodeionization, capacitive deionization, membrane distillation, and forward osmosis. Each method has its challenges, and no method works across all produced water characteristics. Table 5 summarizes the treatability range (in TDS) and energy required for the major desalination methods. Details are briefly provided in this section. Again, please refer to the PWMIS for detailed technical specifications relevant to produced water treatment.

Thermal Methods

Thermal desalination methods are all based on the fundamental process of changing the phase of the water. Evaporation of water from brine results in water vapor and a more concentrated brine or solid salt residual. Significant energy is required to evaporate water, which must be supplied by sunlight in the case of evaporation ponds[84] or solar-driven desalination plants,[85] or by the freeze-thaw cycle[86] or externally supplied heat in the case of industrial desalination plants.[87] Conventional desalination techniques can be more energy efficient when water is being produced under pressure or returns at an elevated temperature, and therefore on-site treatment may be preferable to centralized facilities that would not have access to the warm produced water.[88]

A wide variety of methods have been developed based on thermal processes, and traditional distillation/evaporation methods have been applied to shale gas produced water.[89] For example, in Fort Worth in the Barnett Shale, Devon Energy has a thermal desalination system that treats 2,500 barrels/day of produced water and yields 2,000 barrels/day of freshwater. It requires 100 MCF/day of natural gas as the energy source.[90] Also in Fort Worth, Chesapeake employs an evaporative method using waste heat from a compressor.[y]

The potential to use waste heat is an important consideration in energy-intensive operations, and co-location of the desalination system with the gas compression equipment provides this opportunity.[91] Altela, Inc. has a patented process based on evaporation/condensation that uses waste heat or natural gas (AltelaRain®). Finished water from the process has been permitted for reuse and discharge in New Mexico and Colorado and meets discharge criteria for Pennsylvania.[92] This is an evaporation-based humidification-dehumidification process, which is typically quite energy intensive.[93] However, several reports indicate costs are 30 percent of comparable distillation/evaporation processes.[94] Finished water is 80 percent of source water by volume and contains significantly reduced dissolved solids (9–400 mg/L).[95]

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[y] Waste heat is heat that is generated from electrical units unintentionally. This heat is typically dissipated in the environment, but it can be captured and used for evaporative processes.

AquaPure Ventures has teamed with Eureka Resources to provide treatment of produced water with the Fountain Quail Water Management System. Portable pretreatment and mechanical vapor recompression evaporation provides treatment to 500 mg/L TDS.[96] Purestream Technology markets several thermal desalination methods for produced water, including AARA, a vapor compression method, and Trilogy, a flash evaporation method. General Electric (GE) markets a truck-mounted mobile evaporator with crystallization.[97]

Non-Thermal Membrane Methods

Membrane-based methods include desalting membranes (reverse osmosis, nanofiltration, forward osmosis, direct-contact membrane distillation) and electrically driven processes (electrodialysis, electrodialysis reversal, electrodeionization). Membrane methods are designed to remove small monovalent ions; reverse osmosis is also known to be effective for removal of constituents of NORM, including alpha and beta particle emitters, radium-226, radium-228, and uranium. Methods and their applications in produced water are summarized here, but most of these methods are not viable for Marcellus-associated produced water, which usually have TDS greater than 60,000 mg/L.

Reverse osmosis (RO) membranes are well suited to desalination of moderate brines (up to 35,000 mg/L) in the absence of oil and other organics.[98] Organics cause membrane fouling and reduce the efficiency of salt removal; consequently, extensive pretreatment is often necessary to control water chemistry and reduce fouling. Reverse osmosis has been used on lower-TDS produced waters from natural gas extraction. EnCana is operating an RO membrane with a 10,000 barrel/day throughput. It can handle chloride content of up to 20,000 ppm, and it requires 100 MCF/day of natural gas as the energy source.[99] GE developed a mobile unit based on RO to process low-TDS flowback water (<35,000 – 45,000 mg/L TDS).[100] Advances in membrane technology may improve RO performance, but at present most Marcellus-derived produced waters cannot be treated through RO as TDS exceeds 40,000 mg/L.[101]

Forward osmosis (FO) is an osmotically driven membrane process that uses high-salinity water to draw water across a membrane.[102] It can be used to desalinate with input energy or to generate energy with input freshwater. In 2010, NETL reported funding a project at West Virginia University to evaluate the use of FO for Marcellus produced water. Separately, the U.S. Department of Energy’s National Energy Technology Laboratory funded the New Mexico Institute of Mining and Technology to test a produced water treatment system based on FO.[103] Results are not available for these studies yet; however, FO has well-known challenges having to do with fouling.

Direct-contact membrane distillation (DCMD) induces a partial vapor pressure gradient and direct condensation of extracted vapor in a cold freshwater stream.[104] DCMD can desalinate high-concentration brines, and it can take advantage of the heat associated with the brine as it returns to the surface.[105] In 2010, NETL reported on research ongoing at Sandia National Laboratory in membrane distillation for treatment of Marcellus produced water.

Electrodialysis (ED) is an electrically driven membrane process using stacks of alternating anion and cation selective membranes that separate dissolved ions from water as it passes through. ED reversal (EDR) involves reversing the polarity of the electrodes frequently to reduce the formation of scales, which reduce efficiency. ED and EDR achieve low final TDS (~200 mg/L) and can be used to remove multivalent as well as monovalent ions, eliminating the need for some pretreatment steps. Lower pressures are needed than for RO, reducing energy costs, and the product stream is 90 percent of the influent stream. Sirivedhin et al. report on treatment of produced water from multiple locations using ED, which worked well for low-salt waters (~5,000 mg/L) but was prohibitively expensive for high-salt waters (>60,000 mg/L).[106] Electrodeionization (EDI) is a modification of ED whereby ion-exchange media are placed between the membranes. This enables removal of salt to very low concentrations (<10 mg/L TDS) with reduced energy input.[107] EDI is often used where very low-salt process water is needed, but it is rarely applied to produced waters due to the high cost associated with high TDS.

Capacitive deionization (CDI) is a “new” technology based on an old process, the removal of ions dissolved in water with electric current.[108] Capital costs are higher than for membrane systems, but operation and maintenance costs are lower. CDI can also regenerate electricity during a capacitive discharge step. Organics can foul the electrodes and reduce performance, so pretreatment is necessary in this application as in most membrane-based processes. CDI is suited to low-TDS wastewaters (1,500− 5,000 mg/L) and is not likely to be applied to shale gas produced water.[109] A modified CDI-ED method has been applied to coal bed methane produced water; however, the range of TDS treated remains low (2,000-10,000 mg/L).[110] A modification called membrane capacitive deionization (MCDI) has been applied to higher-TDS waters.[111] Advances in CDI/MCDI are expected as improved membranes are developed, particularly those based on carbon nanotubes.[112] In 2010, NETL reported funding a project at West Virginia University on capacitive deionization for coal bed methane produced water; results are not yet available.

Table 5 summarizes desalination treatment technologies. Most methods are suitable for low- and moderate-TDS wastewaters (up to 40,000 mg/L). Thermal methods must generally be used above that level. All methods are energy intensive and produce concentrated brine or solid salt residuals. Finished water from desalination can be of very high quality, with the TDS in the product water controlled by the energy inputs. Very low-TDS water can be produced; however, caution should be used when designing a system to achieve distilled water quality. Soft water (low in calcium and magnesium) can be corrosive; pipe transport of desalinated water will leach metals and pipe wall precipitates. Fully desalinated water is not considered potable, and remineralization is necessary,[113] so full desalination is not typically the target unless a constituent (e.g., bromide) must be reduced to very low levels (below tens of mgs/L).

Table 5. Desalination Technologies and Their Characteristics[114]

Desalination Technology	Maximum TDS Treatable (mg/L)	Finished Water TDS (mg/L)	Energy Requirement	Residual Produced
Humidification-dehumidification		<10	Using waste heat: 485 MCF/100 bbl or 5–7 kWh/m^3 water	Concentrated brine
Capacitive deionization	5,000	Variable	20 kWh/100 bbl	Concentrated brine
Reverse osmosis (RO)	45,000	200–500[a]	15–30 kWh/100 bbl or 2.5–7 kWh/m^3 water	Concentrated brine
Electrodialysis, electrodialysis reversal (EDR), and eletrodeionization (EDI)	40,000	200 (ED and EDR), <10 (EDI)	Less than RO. 0.5 kWh/m^3 water per 1,000 mg/L of ionic species removed	Concentrated brine
Evaporation	100,000	<10	400 kWh/100 bbl	Solid salts or concentrated brine
Membrane distillation	250,000	Variable	600–700 kWh/100 bbl	Concentrated brine
Crystallization	300,000	<10	1,000–1,300 kWh/100 bbl	Solid salts

[a] Finished water quality is under operational control in RO. Single-pass RO of seawater typically achieves drinking water standard of 500mg/L TDS. Additional passes are needed for lower TDS, or to treat influent water that is higher in TDS than seawater.

Evaluating Treatment Options

Selecting a treatment process for produced water is made on the basis of influent wastewater characteristics and desired effluent water quality, as described above. Also relevant are system criteria such as the cost of construction, operation, and maintenance (including expenditures on energy and chemical additives) and the reliability and robustness of the system. Table 6 provides a list of typical criteria for selection of a technological solution for produced water treatment.

Table 6. Criteria for Evaluation of Treatment Technologies

Criteria for Evaluation of Treatment Technology	
Product water recovery	$\%Recovery = \frac{Q_{finishedwater}}{Q_{wastewater}}$
Product water quality	$\%Removal = 100x \frac{(C_{wastewater} - C_{finishedwater})}{C_{wastewater}}$
Quantity and quality of residual wastes (see product recovery and product water quality)	
Energy requirements	
Treatment chemicals needed	
Reliability and robustness of treatment	
Treatment cost (see energy and chemicals)	
Residual waste management options	
Known challenges: biological fouling, system failure points	
Ability to operate at field conditions	

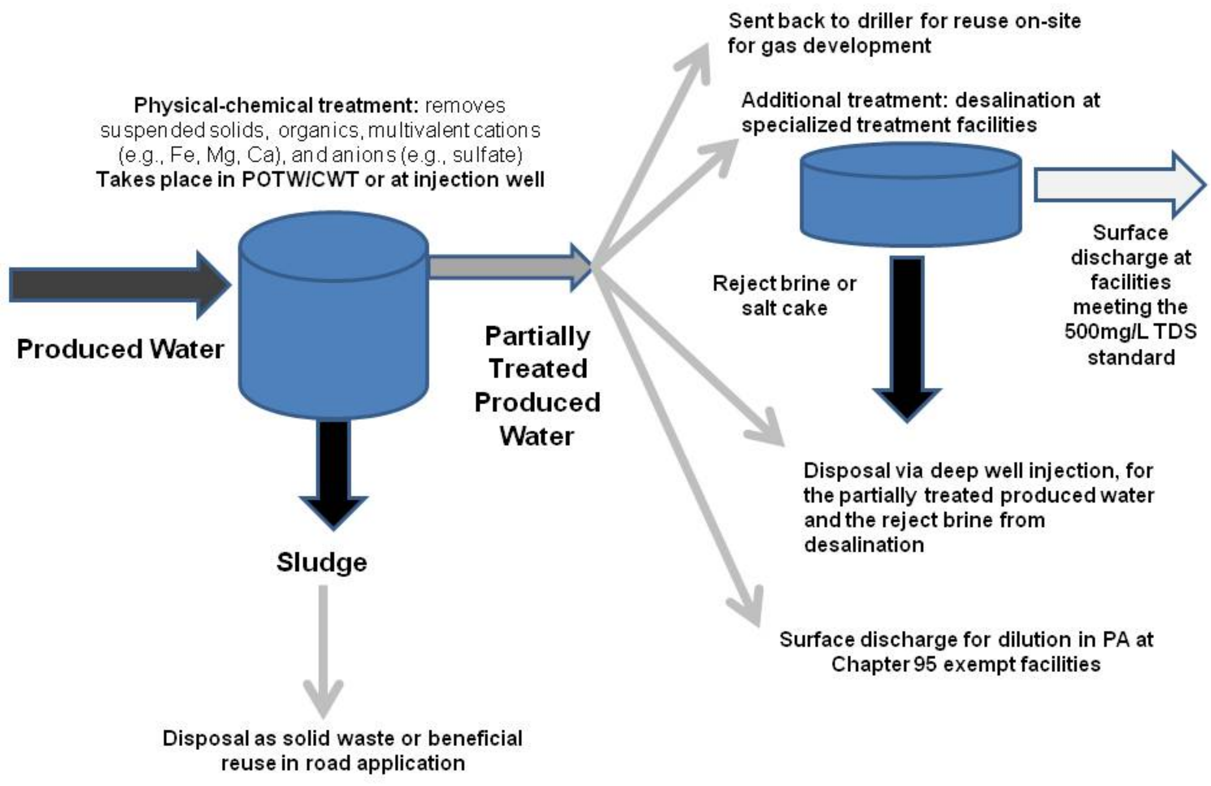
Selecting a Management Option

This chapter has dealt exclusively with treatment options for produced water. The reader will recall that Chapter 1 discussed all management options very generally. It is now possible to integrate treatment into that broader perspective of off-site management options. Chapter 1 summarized options for management and focused on treatment options with disposal and residuals management. With the details of treatment steps and processes now described in this chapter, we return to overall management options with a deeper understanding of decision points.

On-site treatment is designed for reuse only and will incorporate the minimum treatment technology necessary for reuse without compromising the chemistry of the hydraulic fracturing makeup water. Desalination is possible for on-site operations but is rarely necessary to produce water suitable for re-fracturing operations.

Off-site options and decisions are more complex. Once produced water leaves the drilling site, it can be sent to a POTW or a CWT for treatment or to a UIC well for disposal. At all these sites, initial analyses of the water will determine its fate. High levels of NORM will require special handling, as will high levels of scale-forming chemicals and suspended solids if deep well injection is planned. Regardless of its ultimate fate, preliminary treatment of some kind is likely. Figure 4 shows this schematically. After some preliminary treatment, the partially treated produced water can be returned to the well site for use in hydraulic fracturing, undergo additional treatment for demineralization with subsequent surface discharge or reuse, be disposed of via deep well injection, or, in Pennsylvania, be discharged to surface water for dilution. Brines and sludges created through treatment processes can be disposed of as solid waste or sent to UIC wells for disposal.

Figure 8. Comprehensive Produced Water Treatment Options



Appendix A. Studies and Surveys of Produced Water Management in the Oil and Gas Industry

	Year Published
Geochemistry of Oilfield Waters, Chapter 14, "Subsurface Disposal," and Chapter 16, "Environmental Impacts."[115]	1975
EPA Report to Congress: "Management of Wastes from the Exploration, Development, and Production of Crude Oil, Natural Gas, and Geothermal Energy," EPA/530-SW-88-003.[116]	1987
Produced Water, J. P. Ray and F. R. Engelhart, eds., Plenum Press.[117]	1992
Produced Water 2, M. Reed and S. Johnsen, Plenum Press.[118]	1995
"Overview of Emerging Produced Water Treatment Technologies," T. Hayes and D. Arthur, 11th Annual International Petroleum Environmental Conference.[119]	2004
"Guide to Practical Management of Produced Water from Onshore Oil and Gas Operations in the United States," Interstate Oil and Gas Compact Commission.[120]	2006
"An Integrated Framework for Treatment and Management of Produced Water," RPSEA Project at Colorado School of Mines.[121] Also see related management tool: aqwatec.mines.edu/produced_water/index.htm	2009
"Water Management Technologies Used by Marcellus Shale Gas Producers," DOE Project, Argonne National Laboratory for NETL.[122]	2010
Working Paper from the NPC North American Resource Development Study 2-17, "Management of Produced Water from Oil and Gas Wells."[123]	2011
Produced Water: Environmental Risks and Advances in Mitigation Technologies, Kenneth Lee and Jerry Neff, eds., Springer.[124]	2011

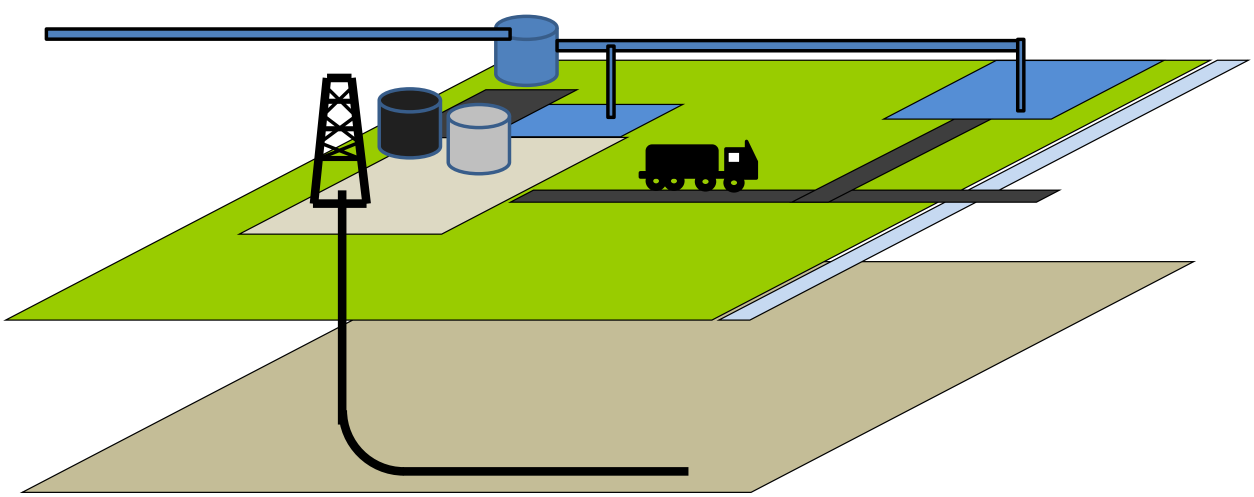
Chapter 3. Potential Water Impacts of Shale Gas Produced Water Management

Chapter 1 provided an overview of management options, and Chapter 2 presented a detailed analysis of treatment choices. We now return to the larger perspective of all management options and evaluate *potential water impacts related to wastewater management choices*. This evaluation will describe the potential impacts that can result from current wastewater management practices, along with the health and environmental effects of particular wastewater constituents. We will also assess impacts that could be mitigated through changes in those practices. Non-water impacts (e.g., effects on air quality or soil productivity) and indirect impacts on water from the full life cycle of natural gas development (e.g., water used in the creation of drilling equipment and chemicals, or water used in the consumption of the natural gas as a fuel) will not be considered.

Introduction

Shale gas development occurs in multiple stages, including site preparation, drilling, hydraulic fracturing (also called well completion), and operation. Wastewaters can be generated during all of these phases, and water can be affected by operations as well as by the generation of wastewater. Figure 1 shows several ways water (in blue) can be stored (centralized impoundments, impoundments at the well pad, tanks at the well pad) as well as ways wastewater (gray/black) can be stored (impoundments at the well pad, tanks at the well pad). Trucks transport water from sources to the well and from the well to wastewater management options. Pipelines are also an option for water transit, as shown.

Figure 9. Water and Wastewater During Well Development



Produced water returning to the surface associated with hydraulic fracturing and later associated with the production of gas must be managed to ensure low risk of environmental harm.

Pathways to Environmental Effects

Environmental effects begin with the interaction between an activity and an environment in which it could cause harm. Many management techniques discussed in Chapters 1 and 2 are designed to prevent or reduce environmental effects. This section provides a review of the management options described in Chapter 1 and their potential environmental effects due to release of chemical constituents in produced waters to environmental systems.

Potential Impacts During Well Development: On-Site Impoundments and Tanks

As with any liquid material in storage, accidental spills and mismanagement can cause releases to the environment that could contaminate nearby waters and soils. Open impoundments, also called pits, should be designed and constructed to minimize the risk of contamination. Liners prevent leaching of water and contaminants into the soil under the impoundment. The maintenance of a target freeboard reduces the risk of water rising to the top of the impoundment and spilling over the edges.[z] In Pennsylvania, liners are recommended (although not required) *around* impoundments to provide additional protection should a large storm increase the volume in the pit high enough to overtop the berms. Closed tanks are also sometimes used for collection of produced water during the flowback period; secondary containment is recommended but not required for these tanks. Secondary containment is a best management practice where the tank sits within a traylike structure with raised sides or berms such that materials released during a tank rupture would be contained and not leach into soil or travel to nearby waterways. Secondary containment is required for many types of wastewaters; all hazardous waste materials must be stored within secondary containment.[aa] (This requirement does not apply to shale gas wastewater due to a statutory exemption discussed in Chapter 4.)

The recent State Review of Oil and Natural Gas Environmental Regulations (STRONGER) regulatory review included a recommendation that Pennsylvania require secondary containment for tanks used in hydraulic fracturing operations. It further recommended that inspection or certification of pit construction be required, in order to assess pit preparation and liner placement.[125] These recommendations to strengthen preventive measures related to leaks and spills are consistent with reviews of environmental violations at drilling sites in Pennsylvania, which indicate that 25 percent of violations in 2010 were associated with pit and storage problems, including leaks and improper construction.[126] Industry best management practices do not universally include a secondary containment recommendation for tanks or a liner recommendation for impoundments.[127,bb] Neither the STRONGER recommendation nor American Petroleum Institute best management practices specifically deal with produced water storage tanks.

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[z] Freeboard is the depth between the water level and the top edge of the impoundment. In Pennsylvania, the freeboard requirement for water and wastewater impoundments is 2 feet, as codified in 25 Pa Code 78.56 and 57.

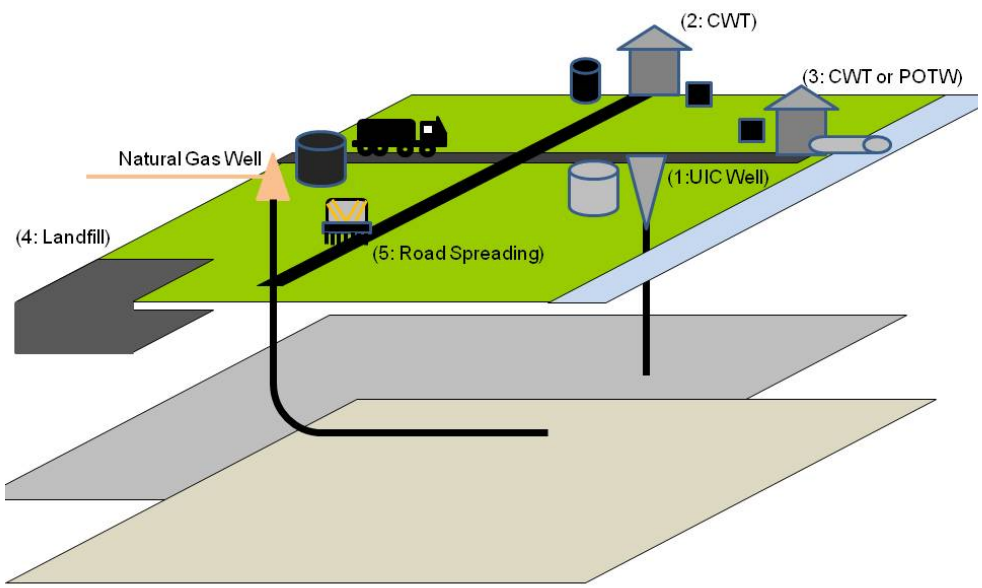
[aa] RCRA requires secondary containment for all hazardous waste tanks in Section 265.193.

[bb] API E5 (API 1997) indicates liners should be used for "any area subject to spillage or contact," while API HF2 (API 2010) is silent on the use of liners outside of the impoundment itself. Neither document discusses secondary containment for tanks. API HF3 (API 2011) briefly mentions that operators should evaluate the potential for spills and use this information to determine the type and size of primary and secondary containment.

Potential Impacts Away From the Well Site

Despite the significant utilization and management of water and production of wastewater during the short process of drilling and completing a well, the most significant potential for water impacts from generated wastewaters occurs away from the well site and is associated with the long-term production of water from the well. Figure 2 presents wastewater management options during production schematically. To the left, on-site tank storage of produced water occurs at the well site while gas is produced from the formation. Wastewater is trucked from the storage tank to one of three types of facilities: (1) a disposal well for injection, with or without pretreatment, (2) a centralized wastewater treatment (CWT) facility that returns partially treated water to the drilling company for reuse, or (3) a CWT or municipal facility (sometimes called a publicly owned treatment works, or POTW) that provides partial treatment with discharge of treated water to a surface water like a stream or river. Residuals generated at any of these locations might be sent to a disposal injection well (1) if they are liquid brines or to a landfill (4) if they are solids. There is also another option for the original produced waters or the treated brines in some states: beneficial reuse, such as spreading on roads for dust suppression or ice control (5).

Figure 10. Produced Water Generation and Transport to Waste Management Facilities



At any of the locations where produced water is handled, the potential exists for releases due to accidents, inadequate facilities management or staff training, or illicit dumping.[128] There is a need for best practices and good management to minimize this potential and for contingency plans to reduce the impact of accidental or illicit releases.

This chapter will not focus on the risk of such events, as significant uncertainty surrounds accident rates, current practices and their relationship to best practices, and operator variability in management and training. Recent legal action in Pennsylvania alleging long-term illegal dumping raises questions about the difficulty of detecting this behavior and quantifying it on a regional basis.[129] Increased oversight of operators who accept, transport, or manage produced water should be undertaken to ensure that best practices are being used and legal disposal is being provided.

The focus of this chapter is on the impacts of current wastewater management techniques that fall within current regulatory requirements.

Deep Well Injection Potential Effects

Underground injection of wastewaters was designed to isolate materials that could cause harm if released to the surface water environment. Partial treatment of produced waters either prior to injection or at the injection well facility is often used to reduce the likelihood of well clogging due to suspended solids, precipitation of constituents in the wastewater, or growth of bacteria. This treatment generally involves settling and filtration, producing a residual solid waste or spent filter media. These residuals are disposed of with other solids waste. Residuals management is discussed below.

Many kinds of wastes have been disposed of via underground injection, including hazardous and nonhazardous wastes, brines associated with oil and gas production, fluids associated with solution mining, and CO_2 for sequestration. Different types of wastes are disposed of in different classes of injection well; the classes of wells subject to federal regulation are described in Chapter 4. An EPA risk analysis determined that injection via strictly regulated Class I hazardous waste wells is a safe and effective technology that presents a low risk to human health and the environment.[130] Additional studies have confirmed this assessment.[131] Such comprehensive studies of other classes of injection well, like the Class II wells into which oil and gas wastes are injected, have not been completed. Prior to the establishment of the current federal regulatory program, four significant cases of injectate migration occurred at hazardous waste wells due to practices that are not permitted under current regulations.[132]

Surface Water Discharge Potential Effects

Treatment at a CWT or POTW followed by discharge of treated water has the potential to affect surface water downstream of the discharge, depending upon the discharge limits for specific chemicals and the assimilative capacity of the receiving water. In many cases, the impact of a treated wastewater discharge cannot be determined *a priori*, without consideration of the receiving water and the other activities taking place in the basin. Chemical hazards, both to ecosystems and to human health, are generally concentration-dependent. Only when waste discharges in combination with contaminants from other sources exceed the assimilative capacity of natural systems do impacts emerge. Discharges that have little or no impact are rarely restricted. For example, while calcium and magnesium ions contribute to water hardness, which can affect water aesthetics, in general the presence of these ions is not a problem and may even be beneficial.[133]

The Clean Water Act limits pollutant discharges. Pollutants may present a concern because of their direct toxicity to ecosystems or human health (e.g., BTEX) or because of their interaction in the environment to produce unwanted effects (e.g., nutrients like ammonia, which can encourage harmful algal blooms). Other pollutants are a concern because of their potential to affect the beneficial use of the water downstream (e.g., sulfate, which can make drinking water taste bad) or to disrupt ecosystems (e.g., chloride, which alters fish reproduction).

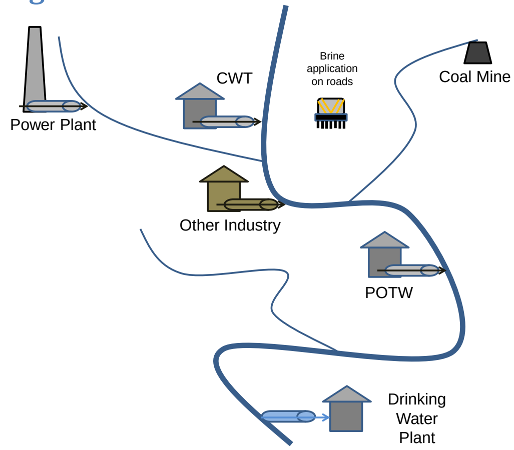
Water quality standards for many pollutants are set by the EPA or state regulatory agencies, and discharges are not permitted that would cause the receiving water to exceed these standards. For example, consider the schematic of a watershed shown in Figure 3. If a new wastewater treatment plant is to be sited in this basin, the multiple point and non-point discharges and their volumes and concentrations of wastes must be considered along with the total flow in the river at all the different points, as freshwater entering the system through runoff or tributary streamflows dilutes existing contaminants. This type of full-watershed analysis is complex and requires significant data on the natural and engineered systems operating in an area.

There are many constituents in produced water that might be of concern if directly discharged to surface water. These have been described in Chapters 1 and 2 and include naturally occurring radioactive materials (NORM), chemicals associated with hydraulic fracturing fluids, ammonia, and salts and organics from the formation. As discussed in Chapter 2, CWTs and POTWs may remove some constituents. Residuals that are likely to be released to surface water even after conventional POTW or CWT treatment include total dissolved solids and the monovalent ions sodium, chloride, and bromide. Other constituents may be partially removed, including metals, sulfate, organic carbon, oxygen demand, and forms of nitrogen (TKN, ammonia, and nitrate). POTWs that have nutrient limits in their permits may find the increased nitrogen loading from produced water to be a problem.

CWT treatment that includes desalination is expected to remove constituents to very low levels. When CWTs target a TDS concentration of 500 mg/L, pretreatment for membrane systems or thermal methods usually removes most organics, metals, and multivalent anions, which can interfere with desalination techniques. Thus, CWTs that meet the revised Pennsylvania discharge limits for TDS are expected to have significantly less impact in the environment. Discharges meeting low TDS levels are not without impact, however, as they may still contain concentrations of bromide that can affect downstream drinking water plants.

Specific effects associated with each class of contaminant are discussed later in this chapter.

Figure 11. Schematic of Watershed with Multiple Wastewater Inputs



Land Application Potential Effects

Management choices that result in land or road application of produced waters or treatment residuals from produced waters can result in environmental effects. This is due to the potential for runoff from rainfall to introduce the materials in the produced water to surface waters and groundwaters that support ecosystems and may be sources of drinking water.

While the specific impact of applying produced water to land surfaces has been studied only somewhat, several closely related practices have yielded extensive information that is relevant to the potential impacts of this practice. This section will provide background on the application, known environmental effects, and specifics for produced water application when available.[134]

Road application of produced waters is either for dust suppression or for deicing. Produced water brines from oil and gas development are not identical to traditional dust suppression or deicing chemicals, but to the extent they are useful in these applications, they share certain characteristics. They contain salts, and they are prewetted (being brines, not solids).

The environmental impact of dust suppression chemical applications has been studied.[135] A well-known case in Times Beach, Missouri, illustrates the potential negative effects of using waste products for dust suppression. This practice led to evacuation and subsequent abandonment of the town in 1983.[cc] An expert panel, convened in 2002 by the EPA, identified the need for increased information about the potential environmental and health impact of dust suppressants, citing the following *potential* environmental impacts: surface and groundwater deterioration; soil contamination; toxicity to soil and water biota; toxicity to humans during and after application; air pollution from volatile dust suppressant components; accumulation in soils; changes in hydrologic characteristics of soils; and impacts on native flora and fauna populations.

Most dust suppression chemicals contain salts, such as calcium and magnesium chlorides, which are easily dissolved in water and can migrate from the road surface during rainfall events.[136] Calcium and magnesium, which are ubiquitous, naturally occurring metal cations, are unlikely to

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[cc] A documentary of the events at Times Beach was produced by the History Channel as part of its Modern Marvels series *Engineering Disasters.*

migrate far from the application site. Chloride ions are likely to move easily from the application site and are of greater concern, with chloride toxicity to aquatic and terrestrial organisms well documented.[137] Produced waters also contain significant chloride (see Table 4, Chapter 2) and significantly more sodium than calcium or magnesium.

Some other dust abatement chemicals contain organics that have the potential to raise the biological oxygen demand (BOD) in nearby receiving waters, although quantities are low and effects are thought to be negligible.[138] Produced waters contain highly variable concentrations of organics that might demand oxygen in receiving waters; however, reported BOD to COD ratios for Marcellus Shale produced water suggest the constituents are not readily biodegradable. Consequently, they are unlikely to cause oxygen depletion, although their persistence is a concern if they are toxic or bioaccumulative.

While the use of produced waters for anti-icing and deicing in northern climates is permitted in some states, the environmental impacts of this practice have not been widely studied.[dd] However, the effect of the application of road salt in the United States has been extensively reviewed.[139] The effects of road salt application and produced water road spreading may be similar due to the presence of chlorides in both substances. Road salt application is known to increase chloride concentrations in downstream locations near roads[140] and to create a long-term source of chloride to groundwater.[141] Chlorides from road salt are transported in surface runoff and infiltrated through soils into groundwater.[142] Road salt storage in recharge areas contaminates water supplies, and addition of brine to antiskid material piles (i.e., sand and cinder) is prohibited for this reason.[143] Road salt movement through the environment has been linked to a variety of negative ecological effects.[144,ee] As previously noted, effects of elevated chloride concentrations on aquatic life have been extensively studied.[145] Deicing chemicals are also known to accelerate the deterioration of concrete and steel structures and to cause vehicle corrosion.

The use of oil field brines as roadway dust suppressants was previously studied by a number of states as management of production brines became more common. In general, produced waters are not as effective as commercial products and require more frequent reapplication; however, they are generally cost-effective.[146] Produced waters can also be used for dust suppression in coal mining, It is not clear how widespread this use might be in coal regions because commercial products provide superior control.[147]

Several potential impacts on water may be associated with application of produced water to roads during summer for dust control. First, transport of materials away from the application site through rainfall and runoff may result in stream or groundwater contamination. This potential is increased when application rates are high or take place in close proximity to rainfall events. When brines contain volatilizable organic matter, their distribution via spraying on roads is likely to result in transfer of the volatile compounds to the air. Brine spreading management plans are usually prescriptive in the application rate and frequency of application, and they usually contain restrictions on proximity to water and on application during rain or when rain is imminent.[148] In the past, significant violations of these plans have been commonly observed in some locations.[149]

[dd] Deicing is the application after snow has fallen, while anti-icing applications are completed in advance of a storm.
[ee] The literature in this area is beyond the scope of this report. See D'Itri (1992) for an introduction to this extensive research topic.

When produced waters are used for road spreading, they may replace equally effective dust suppressant and deicing agents yet result in higher chloride loads (due to higher concentrations or more frequent applications). Many years ago, Michigan reported on seven cases of well water contamination that were linked to road brining activities and summarized previous reports of runoff from brine-treated roads affecting nearby trees.[150] In Ohio, a study was conducted to identify and quantify changes in the quality of groundwater in aquifers underlying roads where brine spreading is practiced. Chloride concentrations that exceed EPA public drinking water standards were observed in down-gradient wells from an oil field brine application on a gravel roadbed despite 99 percent dilution of the solutes in the brine.[151] Attenuation of strontium by adsorption and benzene by volatilization and adsorption were also reported, suggesting benzene release to the air and strontium held in the soil, where subsequent release to groundwater is possible.[152] Eckstein reports on a much more recent case of aquifer contamination near Wooster, Ohio.[153]

Residuals Management Potential Effects

Regardless of the treatment option selected, there will be residuals: concentrated brines and solids containing the chemicals removed from the produced water. Management of these residuals is just as critical as management of the original produced water.

Residuals from oil and gas brine treatment are typically disposed of at injection wells or landfills, or they can be put to beneficial reuse.[154] Concerns related to brines are similar to those detailed for the original produced waters. Solid wastes from POTWs will contain mixtures of contaminants from domestic wastewater as well as from produced water. Solid wastes from CWTs contain the original contaminants from the wastewater as well as treatment chemical residuals.

Since chemicals present in these residual wastes are present at higher levels than in the original produced waters, careful management is essential to avoid negating the value of the treatment process through release of residuals to the environment. Surface discharge of concentrated brines or land or road application of solid salts produced through treatment will result in watershed effects of greater concern than those associated with the original produced water as even more dilution will be required.

Concentrated brines should be disposed of in injection wells to avoid introducing contaminants removed from produced water back to the environment, where human health and ecological impacts might occur. Similarly, solids and sludges generated in treatment plants for produced water should be disposed of in landfills with adequate protection against the formation of subsequent brines in the leachate. Environmental releases of by-products of produced water management should be avoided.

Specific Contaminants and Their Environmental Effects

The management options described above have the potential to release constituents in produced water to surface waters and near-surface groundwaters in ways that can affect ecosystems and human health. This section summarizes known effects of specific constituents in produced water that are likely to be released to the environment under the management options described above.

By statutory exemption, wastes produced in oil and gas development are not classified as hazardous wastes under the Resource Conservation and Recovery Act (RCRA).[ff] Despite the exemption, the contaminants in produced water fall into several groups, all of which can contain hazardous and nonhazardous components. When not exempt by statute, wastes are defined by RCRA as solid hazardous waste[gg] if the "quantity, concentration or physical, chemical or infectious characteristics may (a) cause, or significantly contribute to, an increase in mortality or an increase in serious irreversible, or incapacitating reversible, illness; or (b) pose a substantial present or potential hazard to human health or the environment when improperly treated, stored, transported, or disposed of, or otherwise managed." Determining if a waste is hazardous involves ascertaining if it is a "listed" hazardous waste or if it meets the narrative criteria defined in (a) and (b) above.

Certain types of wastes are categorically "listed" as hazardous under the statute and are grouped into categories (F, K, P, and U). Non-listed hazardous wastes are categorized by the characteristics that define their hazard: ignitability (I), corrosivity (C), reactivity (R), toxicity (E), acutely hazardous (H), and toxic (T).[hh]

Testing is required to evaluate a hazardous waste for toxicity. A toxicity characteristic leaching procedure (TCLP) is completed, and the concentration of chemicals in the leachate is compared with TCLP limits set for arsenic, barium, cadmium, chromium, lead, mercury, selenium, and silver and for a longer list of organics. A few states further require testing for zinc, copper, and nickel. Produced water from the Marcellus formation has reported concentrations from non-detect to above the TCLP limit for barium (which is 100 mg/L).[155] (Other metals sometimes detected at lower concentrations are arsenic, chromium, lead, mercury, and selenium.) Some produced waters would therefore be classified as hazardous wastes due to toxicity associated with barium. Treated waters from some CWT plants (see Table 4, Chapter 2) show much lower levels of measured barium (below 20 mg/L in all samples reported). Treated waters from CWT plants meeting new discharge limits for TDS would be expected to be even lower in dissolved metals and thus unlikely to be categorized as hazardous due to toxic metal concentrations; however, chemical analyses of treated waters from CWTs meeting the Chapter 95 discharge limits for TDS were not available for review in the preparation of this report.

In addition to listed wastes and characteristic wastes, EPA has published a Priority Chemicals (PC) list.[156] The National Waste Minimization Program focuses on reducing these 31 chemicals. PCs present in additives used in hydraulic fracturing include naphthalene and lead (see Table 4, Chapter 1). Lead was detected in produced water from Marcellus Shale gas wells at levels reported from non-detect to 606 μg/L.[157]

[ff] The details of the RCRA exemption are discussed in Chapter 4.
[gg] Note "solid" here does not refer to a state of matter. Solid, liquid, and gaseous wastes can be classified as hazardous solid wastes under RCRA.
[hh] "Toxicity" and "toxic" are defined differently. Toxic wastes contain a toxic constituent and pose a risk due to the presence of that toxic constituent. Toxicity characteristic wastes are based on the toxicity characteristic leaching procedure (TCLP), which assesses the release of constituents that demonstrate toxicity to test organisms.

The identification of hazardous characteristics is complicated by the fact that materials in waste streams are often evaluated on the basis of composite measurements. For example, total dissolved solids or salts can include hazardous elements such as lead and barium as well as non-hazardous elements such as sodium and chloride. Lead and barium are classified as hazardous due to their characteristics (and evaluation of the waste via TCLP). If a wastewater process removes barium, for example, but leaves other salts, the TDS may not be much different from that of a wastewater that contains low-hazard salts as well as heavy metals.

The determination of hazard for oil and gas produced waters does not follow the procedures described above because they are exempt from RCRA classification. This is discussed further in Chapter 4.

Total Dissolved Solids

By far the largest constituent of concern that is not removed through current treatment in CWTs or POTWs is salt, predominantly sodium and chloride ions, but also calcium and bromide ions and other dissolved cations and anions.[ii] As shown in Table 1, Chapter 2, produced waters from the Marcellus formation have sodium concentrations from 26,900 to 95,500 mg/L and chloride concentrations from 1,670 to 181,000 mg/L (measured 14 days after well completion). These levels of salt alone make the water 3 to 10 times saltier than ocean water. Effluent concentrations from CWTs (Table 4, Chapter 2) show chloride concentrations from 3,300 to 131,725 mg/L in waters with TDS from 7,200 to 198,400 mg/L.

Discharge of waters at the salinity of produced waters from the Marcellus formation would require either treatment to reduce salinity or dilution with pure water to 100 to 500 times their volume to reach drinking water levels. While large rivers in the United States have significant flow rates, many others, like those in southwestern Pennsylvania, already receive significant TDS loads from current industrial activities, other resource extraction activities (including coal mining, coal bed methane extraction, and conventional oil and natural gas production), and legacy wastes like acid drainage from abandoned coal mines. There is little additional assimilative capacity for salts in these systems, especially during low-flow conditions. This is a well-documented problem throughout the Appalachian region.[158]

Water is considered fresh when TDS is less than 1,500 mg/L, and the secondary drinking water standard in the United States is 500 mg/L.[jj] Secondary standards are non-mandatory and not enforced. The secondary standard for TDS is set due to the objectionable taste, odor, or color associated with high-TDS waters. High-TDS water is also associated with increased corrosivity and scaling and sedimentation, which can have significant economic impacts. Corrosive water can stain household fixtures, can have an unacceptable metallic taste, and can reduce the usable life of water pipes in the distribution system and in households. Highly scaling water causes mineral deposits to build up in pipes and in water fixtures (especially those associated with heating, including hot water pipes, boilers, heat exchanges, hot water heaters, and dishwashers).

[ii] CWTs that meet Pennsylvania's revised effluent requirements for discharge remove salt to 500mg/L. Those facilities will not have the effects discussed in this section.

[jj] Primary drinking water standards address human health effects, while secondary standards are associated with taste, odor, corrosivity, and scale-forming potential. Some pollutants, like TDS, do not have primary standards, either because they do not cause health impacts or because they have never been observed at drinking water plants at concentrations that could cause health impacts.

Drinking water treatment plants do not include methods to remove TDS, but their use of treatment chemicals to remove other contaminants may actually increase TDS in finished water. Therefore, it is critical that source waters remain below 500 mg/L TDS to ensure finished drinking water meets customer requirements for usability.

Produced waters containing high TDS should be disposed of in ways that do not raise surface water concentrations of TDS above the secondary drinking water standard of 500mg/L for potable water. Seasonal variation in flow conditions may require different management options during different flow conditions to avoid exceeding this level in source waters.

Chloride

As noted above, produced waters from the Marcellus formation have chloride concentrations from 1,670 to 181,000 mg/L (14 days post completion), and effluent concentrations from CWTs (Table 4, Chapter 2) show chloride concentrations from 3,300 to 131,725 mg/L. Chloride has a high solubility and moves easily in the environment. Produced waters applied on land or roads will lead to chloride runoff into surface waters and groundwaters.

The effect of high-salt loads on watersheds has been extensively documented through the study of road salt effects,[159] and aquatic ecosystem impacts can be significant and far-reaching.[160] Toxicity studies have focused on fish and macroinvertebrates, and toxicity is species-dependent. Fathead minnow embryos show toxicity below 1,000 mg/L,[161] while some aquatic invertebrates can tolerate values in the 5,000 to 10,000 mg/L range.[162] Beyond direct toxicity to aquatic life, salinity affects the structure and function of aquatic ecosystems. For example, salinity affects microbes, macrophytes, riparian vegetation, invertebrates, fish, amphibians, reptiles, mammals, and birds that make up the complex food web in aquatic systems.[163]

Further, disposal of waters that contain dissolved solids (salts) in rivers can have effects beyond an increase in salinity of the receiving water. Kefford found saltwater disposal was associated with increased total phosphorus (TP), soluble phosphorus (PO_4^{3-}), total Kjeldahl nitrogen (TKN), and suspended solids and with changes in macroinvertebrate community structure independent of direct salinity effects.[164] High chloride levels are also known to be associated with the invasive and devastating golden algae (*Prymnesium parvum*), although high salinity alone cannot trigger a toxic bloom.[165] A *Prymnesium* bloom was responsible for the loss of all gill-breathing organisms in 26 miles of Dunkard Creek in southwestern Pennsylvania in the fall of 2009.[166]

For chloride, the EPA in-stream recommended standard to protect aquatic life is 250mg/L, set in 1988 and based on limited toxicity studies with sodium chloride.[167] Potassium, magnesium, and calcium chlorides are generally more toxic than sodium chloride.[168] The Iowa Department of Natural Resources, in setting its chloride standard in 2009, reviewed more extensively available data and took into account the synergistic effects of sulfate and hardness (calcium and magnesium) on chloride toxicity.[169] British Columbia set standards for freshwater aquatic life at a maximum of 600mg/L and a 30-day average of 150 mg/L.[170] Discharge standards for chloride can be much higher as they take into account dilution in the receiving water.

Bromide

A recently identified concern in produced waters is the concentration of bromide. Bromide is a trace element in the earth’s crust, with typical concentrations below 6 mg/kg, except in shales, which can have bromide concentrations in the 4–24 mg/kg range.[171] Bromide is also a trace element in seawater, with a concentration of 65–80 mg/L, about one three-hundredth the chloride concentration. Bromide is rarely observed at significant concentrations in fresh surface water systems (e.g., inland rivers and lakes in the United States). For example, Bowen reports 0.014–0.2 mg/L (14–200 μg/L) in surface water systems.[172]

Bromide is present in produced waters from Marcellus Shale in the range of 15.8–1,600 mg/L and is reported in treated brine from CWTs at approximately five times those concentrations, in the range of 76–8,290mg/L (see Tables 1 and 4, Chapter 2).[kk] The source of produced water at the CWTs when these effluent values were measured is not known; however, these concentrations, if not diluted, are of concern for direct bromide effects on ecology as well as indirect effects on downstream drinking water plants.

Bromide itself is not a significant human health or environmental concern except at very high levels. Bromide has been used medicinally for more than 100 years, and its human toxicity is well established.[173] Acute toxicity is very rare in humans. Chronic toxicity effects on the endocrine and reproductive systems in animals have been observed at high doses. The World Health Organization recommends an acceptable daily intake of up to 1 mg/kg body weight; Flury and Papritz recommend no more than 0.1 mg bromide per kg body weight.[174] An intake of 0.4 mg/kg body weight yields an acceptable total daily intake of 24 mg/person. Assuming 50 percent from food and 50 percent from water, an adult consuming 2 liters/day could consume water containing up to 6 mg/L; for a 10-kg child consuming 1 L/day, the value would be up to 2 mg/L.[175]

Ecotoxicity of bromide is also generally low, with impaired growth of evaluated organisms only at high bromide concentrations (>2 g/L for microorganisms and >2.5–7.8 g/L for fish).[176] Canton et al. propose a critical acceptable maximum concentration for water based on the ecotoxicology effects of 1.0 g /L.[177]

The main concern regarding bromide in the environment is its role in drinking water systems. The presence of bromide in water that is subject to disinfection for pathogen control in drinking water increases the formation of disinfection by-products (DBPs) that are regulated due to their carcinogenic and possibly teratogenic characteristics.[ll] When source waters are higher in bromide, DBPs contain more bromide,[178] and those with bromide are suspected to be more of a concern for human health.[179]

For drinking water treatment plants in the U.S. that employ chlorine as a disinfectant, the average observed concentration of bromide in source water is 0.043 mg/L and the maximum concentration is 0.6 mg/L.[180] EPA conducted a nationwide survey of drinking water utilities. The resultant report describes moderate bromide as 0.15 mg/L and high bromide to be 0.4 mg/L.[181] High bromide levels in source waters were associated with increased levels of DBPs in finished waters.

[kk] Bromide concentrations in treated brine that are higher than concentrations in Marcellus wastewater can result from other types of wastewater also being treated at the CWT, or from treatment methods that result in a concentrated finished water.
[ll] Carcinogens cause cancer. Teratogens cause birth defects.

In the fall of 2008, when total dissolved solids increased in the Monongahela River in southwestern Pennsylvania, drinking water utilities using this source water reported increases in a type of DBP called trihalomethane (THM). Plants in the river basin reported that 85 percent to 94 percent of the formed DBPs were brominated.[182] Since that time several researchers have reported increasing source water bromide concentrations in the Monongahela River and the Allegheny River.[183] In the spring of 2011, in response to reports of increasing bromide concentrations and the associated increases in brominated THM at drinking water plants on both rivers, the PADEP issued a request to companies drilling in the Marcellus Shale formation to stop delivering produced water from the Marcellus formation to POTWs and CWTs that were not designed to remove bromide. As described in Chapter 2, there was a 99 percent reduction in produced water from Marcellus Shale development going to these surface discharge facilities. Bromide levels in the Monongahela River in mid- and late 2011 were lower; however, a very wet season made detection more challenging, and conclusions regarding the effect of restricting this wastewater cannot yet be drawn.[184] Many water utilities in the region continue to monitor source water bromide.[185]

Produced waters containing bromide above levels that will adequately dilute in surface waters should not be discharged to the environment without treatment specifically to remove bromide. Since bromide removal is generally not economical, produced water enriched in bromide should be disposed of through underground injection to avoid contamination of surface waters used as drinking water sources.

Naturally Occurring Radioactive Material (NORM)

As discussed in Chapter 1, NORM is typically present in shale gas produced water at levels slightly above background.[186] Oil and gas development in some states has produced elevated NORM at levels of concern, and some states have adopted regulations with action levels.[mm] Elevated NORM has not typically been observed and conventional oil and gas facilities in Pennsylvania;[187] however, produced water from Marcellus wells does show elevated radioactivity.[188] The most abundant types of NORM in produced water are radium-226 and radium-228, produced from radioactive decay of uranium and thorium present in the shale formation.

Data on produced water from the Marcellus Shale indicate NORM is sometimes detected at levels above background and above drinking water standards (see Table 4, Chapter 2). Drinking water standards require uranium below 30 μg/L; radium-226 and radium-228 combined below 5 pCi/L, alpha emitters below 15 pCi/L, and beta particle radioactivity below 4 mRem/year. CWT-treated wastewaters summarized in Table 4, Chapter 2, report non-detect for uranium, and radium-226 and radium-228 levels between 0.8−15.6 pCi/L, with gross alpha reported between 0.132−156 pCi/L.

In 2011 in southwestern Pennsylvania, concerns were raised regarding the potential for surface water discharges of treated produced water to raise levels of radioactivity above acceptable source water levels for drinking water. PADEP requested testing at all public drinking water

[mm] Louisiana, Texas, Arkansas, and Michigan set action levels at 50 microR/hr. Mississippi set a level of 25 microR/hr.

supplies in the region, and no levels of concern were reported.[189] The effect of NORM on other water uses and on ecosystem health was not evaluated in the present work.

Produced water intended for treatment followed by discharge to waterways or for surface application should be tested for NORM, and restrictions on levels of NORM in waters that will be managed in these ways should be set to avoid environmental releases that could compromise drinking water resources downstream of discharges.

Conventional Pollutants

Produced water contains conventional pollutants that have well-studied effects on ecosystems. Conventional pollutants are those amenable to removal in POTWs using conventional treatment; they do not include toxic substances. Conventional pollutants include bacteria, BOD, COD, TSS, oil and grease, and nutrients. Wastewater treatment plants are designed to remove organic carbon-containing compounds that would cause oxygen depletion if released to the environment. Some wastewater treatment plants are also designed to remove nutrients (nitrogen and phosphorus) to prevent eutrophication in receiving waters. The BOD in produced waters is not very degradable (see Table 1, Chapter 2 for the BOD/COD ratio) and so is not expected to be removed in conventional POTW treatment or to have significant oxygen-depleting effects in the receiving stream. The recalcitrant organic materials might slowly degrade in the environment or might be persistent.

Organic and inorganic nitrogen levels in produced water are a concern for surface discharge because they can contribute to oxygen depletion in receiving streams and nutrient loading leading to eutrophication. Nitrogen is unlikely to be completely removed in conventional POTWs or CWTs; however, ammonia can be removed in POTWs designed for nitrification, which will control the oxygen-depleting effects of the nitrogen. Produced water that contains high levels of ammonia could increase concentrations such that treatment plants that previously did not need to include nitrification might have to begin doing so to meet their discharge permit limits. Plants that do include nitrification might have to adjust their processes (e.g., increase aeration) to achieve treatment with higher influent loads.[nn] Of course, plants without discharge standards for nitrogen do not include treatment technologies for this contaminant, and any addition to their influent will lead to an increase in their effluent discharge of this chemical. Nitrogen in wastewaters released to surface waters should be considered in context with other nutrient loads in receiving waters to ensure that the cumulative effects are sufficiently controlled by dilution.

Similarly, produced waters may contain chemical constituents such as sulfate, hardness, and chloride that are regulated in drinking water due to taste, odor, and scaling considerations, rather than human health effects. Produced waters may contain constituents at concentrations much higher than secondary standards designed to reduce unpleasant characteristics. Surface discharge without adequate dilution could cause source waters to exceed secondary standards, leading to taste, odor, or color development in finished drinking water at plants downstream from discharge

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[nn] POTWs with discharge limits on "total nitrogen," as opposed to discharge limits on ammonia-nitrogen only, may see their treatment processes (and their ability to meet permit limits) affected in more complex ways because of the more complex treatment processes that are required to meet total nitrogen limits.

points. This may lead to customer complaints and additional cost to the drinking water provider to remove these contaminants. Secondary standards relevant to produced water constituents are summarized in Table 1, below. Based on the analysis of produced water from Marcellus Shale development summarized in Table 1, Chapter 2, and analysis of CWT effluent from plants without desalination summarized in Table 4, Chapter 2, effluent from CWTs treating Marcellus produced water is likely to contain high levels of chloride and TDS and may contain high levels of iron and manganese. While produced water is generally low in sulfate, treatment methods to remove barium often involve addition of sulfate, and CWT effluent (Table 4, Chapter 2) can be higher in sulfate than produced water.

Table 7. Secondary Drinking Water Standards for Constituents That May Be Present in Produced Water

Contaminant	Secondary MCL	Effect
Aluminum	0.05-0.2 mg/L	Color
Chloride	250 mg/L	Salty taste
Copper	1.0 mg/L	Metallic taste, staining
Iron	0.3 mg/L	Color, metallic taste, staining
Manganese	0.05 mg/L	Color, metallic taste, staining
Sulfate	250 mg/L	Salty taste, laxative
Total Dissolved Solids	500 mg/L	Hardness, color, staining, salty taste (depends upon constituents in TDS)
Zinc	5 mg/L	Metallic taste

Hydraulic Fracturing Fluid and Formation-Associated Organic Compounds

Some chemicals present in hydraulic fracturing fluids are toxic at very low levels (ppb), as would be expected of biocides. Most hydraulic fracturing fluid will remain in the subsurface; however, water that does return to the surface will not have the same characteristics during early production (flowback period) as it will have later. Chemicals associated with the hydraulic fracturing fluid are more likely to return in the early phase, while those associated with the formation are more likely to return in the later phase.[190] Early-phase water is more likely to be recycled, as discussed in Chapter 1.

However, there is the potential for some added chemicals to remain at very low levels in later produced water, and some organic compounds are present in fracturing additives as well as naturally occurring in the formation (e.g., benzene). Of particular concern are contaminants that are intended to be biologically active (e.g., antimicrobial agents like glutaraldehyde) and those that are known to present human health effects (e.g., benzene, 2-butoxyethanol). Alternatives to chemical antimicrobial agents include surface UV systems, although these inactivate only microbes in the water and do not prevent growth of organisms in the well itself, where bacterial activity may cause corrosion or formation of hydrogen sulfide (H_2S). Organic chemicals that are naturally occurring in the formation (e.g., BTEX) will be in the produced water and cannot be avoided through new technology or the development of new chemical additives.

Some produced water additives and organics present in the rock formation will be removed in conventional POTW or CWT treatment, predominantly through biodegradation or sorption to solids that are removed by precipitation or settling. Little data are available to assess levels of chemicals used in hydraulic fracturing or those from the formation in treated POTW or CWT effluent. Hydraulic fracturing chemical additives are not specifically regulated in discharge permits and thus are not measured for compliance. Salts and some specific components (e.g., TDS, chloride, sulfate) have been measured for compliance with discharge permits (see data presented in Chapter 1). Analysis of the organic compounds would be necessary to determine if the concentrations of specific chemicals such as those in hydraulic fracturing fluids and produced water would be of concern in produced water after treatment.[191] Methods for pretreatment targeting these specific chemicals exist and could be deployed to ensure removal prior to POTW treatment or discharge.

Since some produced waters contain contaminants of concern at concentrations of concern (e.g., BTEX), discharge without treatment or land application of untreated produced waters would release these chemicals to the environment and should be avoided. Full chemical characterization may be prohibitively expensive, so targeted analysis focused on chemicals of concern expected to be present could be used.

Cumulative and Long-Term Impacts

One of the most difficult aspects of evaluating the potential effects of any environmental management decision is considering the cumulative and long-term impacts. Soeder suggests that understanding the longer-term and cumulative effects of shale gas extraction on ecosystems (landscape, terrestrial, and aquatic), water resources, and air quality is an area requiring more attention.[192]

Chemical constituents used in hydraulic fracturing have been the focus of intense public discussion in the past several years, but analysis of produced water suggests that these represent a small part of the overall wastewater management challenge. Most additives will return to the surface in the initial flowback period and will be recycled into subsequent hydraulic fracturing activities, allowing for reduced chemical additions for the next cycle. Formation chemicals, including toxic organics commonly found in hydrocarbon formations (e.g., BTEX) and naturally occurring radioactive materials (NORM), will require careful monitoring within the produced water sent to management options that result in direct or indirect release to the environment.

In regard to total dissolved solids (especially those containing chloride), we are just beginning to focus on the long-term effects of increased use of deicing/anti-icing and dust control chemicals in general. If current trends in use continue, chloride concentrations in streams in some parts of the country are projected to exceed drinking water standards and will become toxic to freshwater life within the next century.[193] This projection suggests a need for renewed focus on alternative approaches to deicing/anti-icing and dust control. Produced water, with its high concentration of chlorides and increased application frequency, is not an alternative that is likely to reduce this problem.

Similarly, for bromide discharges, recent work has focused on significant negative impacts on drinking water at very low levels. Regulatory action to set standards for in-stream concentrations in drinking water sources and discharge limits for Clean Water Act permits is likely to evolve over the next few years in several places in the country. While this will doubtless be a contentious process, the management of produced waters as well as other bromide sources (e.g., mining, coal-based power plants) will have to be considered in the cumulative loading of bromide to drinking water sources.

Residuals associated with the treatment of produced waters (concentrated brines and solids) contain the chemicals removed from the water and therefore continue to present challenges in management. Improper handling of residuals will negate the value of the treatment and must be avoided.

Where produced waters contain toxic organics, NORM, very high chloride, and high bromide, management methods that result in releases of these chemicals to the environment should be avoided. This type of management is widely utilized for produced water from coal bed methane and shallow oil and gas wells, and depending upon the constituents of *those* produced waters, these management choices may be appropriate. However, partial CWT treatment followed by surface water discharge and beneficial reuse as a deicing or dust control agent is inappropriate for produced waters from the Marcellus Shale formation. These activities have the potential for cumulative and long-term impacts that are difficult to predict. These management options should be avoided until the potential impacts are better understood.

Chapter 4. Current Regulatory Framework

Federal regulations prohibit the discharge of shale gas wastewater directly from a production site into surface waters. This prohibition is a primary reason that natural gas operators must use the various treatment and disposal methods described in the preceding chapters. It has also triggered the application of a number of statutes and regulations governing those methods. At the federal level, the Clean Water Act regulates the treatment and discharge of wastewater into the surface waters of the United States, while the Safe Drinking Water Act regulates the underground injection of wastewater. Both of these regulatory programs may be administered at the state level, in states that have been given the authority to do so. The Resource Conservation and Recovery Act, a federal statute that governs the handling of most solid and hazardous wastes, does not apply to oil and gas wastewater due to a statutory exemption. Most other aspects of wastewater handling, treatment, reuse, and disposal are regulated solely by the states.

Treatment and Discharge to Water Bodies

The federal statute regulating the treatment and discharge of shale gas wastewater into surface water bodies is the Federal Water Pollution Control Act, more commonly called the Clean Water Act. Under the Act, "point sources"—often facilities like factories and wastewater treatment plants—may not discharge pollutants into waters of the United States unless the discharge is authorized.[194] Point source discharges may be authorized under Section 402, which establishes the National Pollutant Discharge Elimination System (NPDES) program. Under that program, the U.S. Environmental Protection Agency (EPA), or a state that has been given the authority, issues permits authorizing discharges into surface waters.[195] Consequently, facilities must obtain NPDES permits if they intend to discharge shale gas wastewater—or any by-product resulting from treatment of the wastewater—into a surface water body.[196]

The conditions of NPDES permits are a function of both federal and state law, as the Clean Water Act sets a national baseline that states may exceed through stricter local rules. These permits contain two general types of conditions. The first are technology-based, requiring a minimum level of treatment of pollutants based on available treatment technologies. The second are water quality-based, limiting the discharge of pollutants according to the desired quality of the receiving water.[197] Water quality-based limitations are unique to each discharger and are tailored to local conditions; NPDES permits must contain limits for all pollutants in a facility's discharge that may cause a violation of state water quality standards.[198] Technology-based limitations, on the other hand, are typically set at the national level for major polluting industries. The EPA establishes effluent limitations guidelines (ELGs) for entire categories of industrial dischargers based on the degree of pollutant reduction they can attain by using available technology.[199]

The technology-based requirements for direct discharges from oil and gas facilities into water bodies are contained in 40 C.F.R. Part 435. Those regulations completely prohibit the discharge of wastewater pollutants from point sources associated with natural gas production.[200] Exceptions exist for produced water clean enough for use in agriculture or wildlife propagation west of the 98th meridian (which runs through North Dakota, South Dakota, Nebraska, Kansas, Oklahoma, and Texas), and for *oil* wells producing less than 10 barrels per day.[201] Neither of these exemptions apply to *gas* wells east of the 98th meridian. Consequently, hydraulic fracturing operators in the Marcellus formation may not discharge their wastewater directly into waters of the United States, even with treatment that reduces (but does not eliminate) pollutant levels.

Instead of discharging wastewater directly to surface waters, then, many hydraulic fracturing operators send wastewater to treatment facilities that are authorized to discharge. These facilities include publicly owned treatment works (POTWs) and centralized waste treatment facilities (CWTs). POTWs are plants designed to treat municipal sewage and are typically owned and operated by state or local governments. CWTs are privately owned plants designed to treat industrial wastewater. CWTs may discharge either directly to surface waters or to POTWs (or may completely recycle wastewater for reuse without discharging). The regulations in 40 C.F.R. Part 435 that deal with discharges by natural gas facilities directly to surface waters do not cover discharges into or out of POTWs or CWTs. Rather, separate EPA regulations set requirements for the introduction of industrial wastewater to POTWs (known in EPA regulations as "indirect discharge"[202]) and for the discharge of industrial wastewater from CWTs. States may also establish requirements for these discharges that are stricter than the federal requirements.[203]

Discharges Into and From Publicly Owned Treatment Works

EPA regulations establish three kinds of limits on wastewater introduced to a POTW. First, they forbid industrial facilities from introducing any pollutant to a POTW that will disrupt the functions or processes of the POTW (referred to as "interference"), or that exit the POTW into surface waters in quantities or concentrations that will cause the POTW to violate the pollutant limits contained within its discharge permit (called "pass through").[204] For example, some POTWs' permits contain limits on total dissolved solids (TDS). Shale gas wastewater contains high quantities of TDS, which POTWs are not designed to remove, so introduction of sufficient quantities of that wastewater to a POTW might create the potential for a permit violation. Additionally, some of the individual constituents of TDS may disrupt POTW function in facilities that use activated sludge, nitrification, and anaerobic digestion processes.[205]
Second, the regulations contain categorical pretreatment standards, which set limits on pollutant discharges to POTWs from particular types of industrial wastewater. The EPA develops these technology-based standards under Section 307 of the Clean Water Act.[206] While no categorical pretreatment standards currently exist for shale gas wastewater introduced to POTWs, in October 2011 the EPA announced its plans to develop such standards.[207]

Third, the regulations require POTWs receiving industrial wastewater that causes pass through or interference to develop their own pretreatment programs that contain "local limits" reflecting their specific needs and capabilities.[208] Essentially, local limits translate the general prohibition on pollutants causing pass through and interference into site-specific limitations. EPA provides municipalities with guidance on developing local limits, assisting them with their calculations of maximum allowable pollutant loadings to their POTWs.[209] Many states also provide guidance on establishing local limits, though Pennsylvania has not written its own guidance because the EPA administers the pretreatment program there.[210] All facilities indirectly discharging shale gas wastewater through POTWs must comply with each POTW's local pollutant limits. In practice, however, POTWs have rarely established local limits on pollutants contained in shale gas wastewater, according to the EPA.[211]

In addition to these pretreatment regulations, POTWs must comply with their own NPDES discharge permits. Many POTWs have conditions in their permits limiting the volume of wastewater they accept from oil and gas operations to no more than 1 percent of their average daily flow.[212] (In Pennsylvania, PADEP has sometimes imposed these limits on POTWs through administrative orders rather than through formal permit conditions.[213]) Additionally, under NPDES regulations, permits must include conditions requiring POTWs to provide "adequate notice" to the EPA (and the state permitting authority, if applicable) when the POTW intends to accept new or additional pollutants or waste streams.[214] In practice, this requirement means that the POTW must provide notification *before* it begins to accept the new wastewater. This is to ensure that the permitting authority has enough time to determine if the POTW's permit needs to be modified in order to address the possible effects of the new indirect discharger.[215] As a result, POTWs that intend to accept shale gas wastewater when they have not previously done so must collect information from the natural gas operator on the quality and quantity of wastewater that the operator plans to introduce to the POTW, assess the potential impact of that wastewater on the POTW's discharges, and report this information to the EPA and/or the state.[216]

Discharges From Centralized Waste Treatment Facilities

While some shale gas wastewater is discharged through POTWs, many operators send wastewater to CWTs for treatment and discharge directly to water bodies. (Some wastewater treated at CWTs is reused instead of discharged; regulation of those uses is discussed later in this section.) The technology-based standards for CWT discharges are codified at 40 C.F.R. Part 437. These standards set numerical limits on the discharge of individual pollutants from CWTs based on what can be achieved using available technologies. The standards were developed in 2000 and amended in 2003, before large-scale development of shale gas became widespread.[217] Consequently, the regulations do not include standards for all of the pollutants commonly found in shale gas wastewater. Shale gas wastewater pollutants covered by the standards include oil and grease, total suspended solids, and biochemical oxygen demand. Pollutants not covered by the standards include total dissolved solids, bromide, and radioactive materials.

For pollutants not included in the national standards, limitations must nevertheless be developed for individual CWTs' discharge permits. These are based on state limitations if such standards exist; for example, Pennsylvania regulations set numeric limits for CWT discharges of total dissolved solids and chlorides, as discussed below. In addition to the application of any relevant state standards, additional permit limits are developed on a case-by-case "best professional judgment" basis.[218] When the permit writer (at the EPA or a delegated state's permitting authority) develops limits on this basis, the writer must consider the same factors that the EPA considers when it establishes technology-based nationwide standards.[219] These factors include the age of the facility and its equipment, the treatment processes the facility uses, and the cost of achieving pollutant reductions. Regulations governing discharges from CWTs impose no responsibilities on the generators of shale gas wastewater; the CWTs themselves are responsible for ensuring that their treatment of that wastewater is adequate.

Water Quality Standards

In addition to technology-based requirements, NPDES permits for POTWs and CWTs discharging treated wastewater must also include any more stringent requirements necessary to meet water quality standards.[220] The EPA and delegated states develop standards for each water body by identifying the uses to be made of the water (for example, fishing, swimming, or drinking water supply) and then setting water quality criteria necessary to protect these uses.[221]

The criteria are generally numeric limitations on pollutants in a particular water body that are adequate to support the water body's designated uses.[222]

The EPA has published recommended national water quality criteria as guidance for delegated states. These recommendations include criteria for some pollutants of concern in shale gas wastewater, such as chloride, oil and grease, suspended solids, turbidity, and nitrates.[223] Permitting authorities use the criteria to determine whether a facility's discharge might lead to an exceedance of water quality standards. If so, that facility's permit must contain water quality‒ based limitations.[224] Thus, where a POTW's or CWT's discharge of shale gas wastewater has the potential to cause or contribute to exceedances of water quality standards, the permit for that facility must contain water quality‒ based limits adequate to protect water quality. This requirement may arise for shale gas wastewater pollutants like total dissolved solids and sulfates, which have been known to cause violations of water quality standards in water bodies such as the Monongahela River.[225]

Pennsylvania's Discharge Requirements and Water Quality Standards

Pennsylvania has been delegated authority to administer the Clean Water Act NPDES permitting program. The Pennsylvania Department of Environmental Protection (PADEP) has issued regulations implementing the Act and the state's Clean Streams Law.[226] These regulations require NPDES permits for facilities discharging industrial waste to comply with both EPA-promulgated effluent limitation guidelines and the state's own industrial waste discharge standards.[227] The state wastewater quality standards are set out in Chapter 95 of the Pennsylvania State Code, which contains all requirements for wastewater treatment within the state.[228]

In 2010, PADEP finalized revisions to Chapter 95 addressing the discharge to surface waters of wastewater from natural gas operations.[229] The regulations now require each natural gas operator to implement a wastewater source reduction strategy, identifying the methods and procedures the operator will use to maximize recycling and reuse of wastewater.[230] The regulations prohibit "new and expanding" discharges of shale gas wastewater unless the discharge is authorized by a state-issued permit.[231] Such discharges may be authorized only from CWTs; POTWs may be authorized to discharge shale gas wastewater only if the wastewater has been treated at a CWT first.[232] The regulations provide limits on certain pollutants contained in the wastewater discharged from CWTs, including limits on monthly averages of total dissolved solids (500 mg/l) and chlorides (250 mg/l).[233]

These limits and restrictions apply only to "new and expanding" wastewater discharges. The regulations define these as discharges causing a net increase in total dissolved solids of more than 5,000 pounds per day above a facility's previously authorized loading.[234] Discharges not falling under this definition (i.e., all previously authorized discharges that have not increased beyond the threshold) were "grandfathered" under the Chapter 95 revisions and thus not required to meet these new limits. The grandfathered facilities include both POTWs and CWTs.

In April 2011, after surface water sampling found elevated levels of bromide in western Pennsylvania rivers, the PADEP called on all Marcellus Shale natural gas drilling operators to voluntarily stop delivering their wastewater to grandfathered facilities.[235] At the time, 15 facilities had been accepting wastewater; within two months, PADEP announced that Marcellus operators were largely complying with the voluntary ban and that drilling wastewater was no longer being discharged to rivers or streams in Pennsylvania without treatment sufficient to meet the updated Chapter 95 standards.[236] An independent evaluation of wastewater reports from Marcellus drilling companies to PADEP largely confirms the state's announcement; the reports indicate a 99.5 percent reduction in wastewater volumes being sent to exempt POTWs in the second half of 2011, and a 95 percent reduction in volumes being sent to exempt CWTs in the same period.[237] Pennsylvania's voluntary approach differs from the more mandatory approach taken by states like Ohio, which does not allow any disposal of oil and gas wastewater at POTWs. Ohio regulations list the options for disposing of oil and gas wastewater; disposal to a surface water body, either directly or via a POTW, is not one of them.[238]

In addition to Pennsylvania's Chapter 95 standards for permits, Chapter 93 of the state's regulations designates water quality standards for Pennsylvania water bodies.[239] These standards affect the permitting of facilities discharging to Pennsylvania waters. When a particular facility's discharges may cause water quality violations in a receiving water body, the Clean Water Act requires the state to develop more stringent permit limits.

PADEP has established water quality standards for several pollutants contained in shale gas wastewater: alkalinity, ammonia nitrogen, chloride, nitrate, sulfate, and total dissolved solids.[240] In May 2010 the agency proposed new standards for chloride, one of whose major anthropogenic sources is wastewater from oil and gas wells.[241] Freshwater fish and other aquatic species cannot survive high concentrations of chlorides, so PADEP proposed stricter standards to protect aquatic life from the impacts of increased Marcellus activity.[242] The proposed standard was based on 1988 EPA guidance. In July 2010 an independent regulatory commission reviewed the standard, expressing concerns that the 1988 EPA guidance was out of date.[243] PADEP is now considering a new proposed standard based on Iowa's chloride criteria.[244] In the meantime, EPA has indicated that it may develop new guidance on chlorides.[245]

Underground Injection

While the Clean Water Act regulates the surface discharge of shale gas wastewater, the Safe Drinking Water Act (SDWA) regulates the underground injection of that wastewater.[oo] The SDWA established the Underground Injection Control (UIC) program, which prevents the injection of liquid wastes into underground sources of drinking water by setting standards for safe wastewater injection practices and banning certain types of injection altogether.[246] All underground injections are prohibited unless authorized under this program (except for the hydraulic fracturing process itself, which, as discussed below, is exempt from regulation under the SDWA).[247] As with the Clean Water Act, EPA implements the UIC program unless a state has been given authority, or primacy, to take over control of the program.[248] Even where the EPA implements the UIC program, it must consider local geological, hydrological, and historical conditions.[249]

Under the UIC program, EPA groups underground injection wells into five classes, with each class subject to distinct requirements and standards.[250] Because of a regulatory determination by EPA not to classify shale gas wastewater as "hazardous" (discussed below), it is not required to be injected into Class I wells for hazardous waste. Rather, shale gas wastewater may be injected

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[oo] The Clean Water Act's definition of "pollutant" specifically excludes oil and gas wastewater that is pumped into a well, either to facilitate oil and gas production or for disposal. Consequently, shale gas wastewater injection is exempted from regulation under the Clean Water Act, 33 U.S.C. § 502(6).

into Class II wells for fluids associated with oil and gas production. Class I hazardous waste wells are subject to more stringent requirements than are Class II wells, such as consideration of earthquake risk in well siting, analysis of a larger geographic area surrounding the well, and more stringent procedures for reporting and correcting problems. Class I hazardous waste wells must also be drilled deeper, below the lowest underground source of drinking water, to prevent contamination.[251] Class II wells, while not subject to all of these conditions, are also subject to a number of regulatory requirements under the UIC program.

Before the EPA (or a delegated state) may authorize a Class II well, it must consider the location of existing wells and other geographical features in the area; the well operator's proposed operating data, including daily rate, volume, and pressure of injection; the injection fluid's characteristics; the geological characteristics of the injection zone; the construction details of the proposed well; and the operator's demonstration of mechanical integrity.[252]

When Class II wells are constructed, they must be sited so that they inject into an underground formation which is separated by a fault- and fracture-free zone from any underground source of drinking water (USDW).[253] Moreover, all wells must be cased and cemented to prevent the movement of fluids into or between USDWs.[254] During operation of the well, at no point must the injection pressure exceed a precalculated maximum, to assure that the pressure does not initiate new fractures or enlarge existing fractures in the zone adjacent to USDWs. Well operators must not inject at a pressure that will cause the movement of injection or formation fluids into a USDW.[255] Generally, operators must maintain the mechanical integrity of the well, and if they cannot, they must cease injection.[256]

In the Marcellus region, Maryland, Ohio, and West Virginia have assumed primacy and implement the UIC program. New York, Virginia, and Pennsylvania have not assumed primacy, so EPA directly implements the UIC program in those states. While Pennsylvania does not regulate the injection of wastewater into disposal wells, the state does require a permit for the initial drilling of a wastewater disposal well.[257] To obtain a permit, the driller must show that the well has been approved under the federal UIC program, and also must have a pollution prevention plan (called a "control and disposal plan") and an erosion and sedimentation plan.[258] Unlike states like New York, which requires a site-specific environmental impact review for each disposal well that is drilled, Pennsylvania does not require a general review of all environmental impacts that could result from each well.[259]

Reuse for Additional Hydraulic Fracturing

In contrast to the injection of shale gas wastewater as a disposal practice, the injection of fluids (which may include recycled wastewater) for the hydraulic fracturing process itself is exempted from regulation under the federal Safe Drinking Water Act. The statute's definition of "underground injection" specifically excludes "the underground injection of fluids or propping agents (other than diesel fuels) pursuant to hydraulic fracturing operations related to oil, gas, or geothermal production activities."[260] A bill introduced in Congress in 2011 would remove this exemption and explicitly authorize regulation of hydraulic fracturing under the SDWA.[261] Under current law, however, if shale gas wastewater is managed or treated for the sole purpose of reuse for further hydraulic fracturing, it is not subject to federal regulation.

However, state regulations do apply to the reuse of shale gas wastewater. In Pennsylvania, facilities that process wastewater for beneficial reuse may be authorized under PADEP-issued “general permits,” which establish generally applicable standards. Operations authorized under these general permits are not required to obtain individualized permits for wastewater processing.[262] In Pennsylvania, general permit WMGR123 authorizes the processing of Marcellus wastewater for use in further hydraulic fracturing and other extraction of natural gas, provided that the resulting fluid conforms to industry quality standards for gas well fracturing fluid.[263] This permit, a consolidation of three prior general permits for beneficial reuse, contains new operating conditions developed to allow storage of processed water in tanks and impoundments prior to use for fracturing a well. In effect, the permit relieves operators of the obligation to handle wastewater destined for reuse as a “waste” if it has been treated to meet specified concentration limits, which are based on drinking water standards and water quality standards. Operators must demonstrate that the wastewater meets the constituent limits by submitting analytical data to PADEP. However, any wastewater that is not ultimately reused for further fracturing must be handled as a waste. The permit also contains new recordkeeping and reporting requirements.

Impoundments

Because of an exemption from federal law (discussed below), the storage and disposal of shale gas wastewater in impoundments is regulated solely by the states. In Pennsylvania, facilities that store and dispose of shale gas wastewater in impoundments must obtain permits under Chapter 289 of the PADEP solid waste regulations. Chapter 289 contains construction and design specifications and operating requirements for those impoundments.[264] Under these regulations, operators of impoundments must have water quality monitoring plans to prevent the contamination of groundwater. They are also forbidden from causing any “water pollution” within or outside the impoundment site.[265] This prohibition is a freestanding regulatory requirement unconnected to the impoundment permitting process. According to PADEP regulations defining “pollution,” this means that impoundments must be designed and operated to ensure they do not cause water contamination that could lead to a public nuisance; a threat to public health, safety, or welfare; a detriment to beneficial uses; or harm to livestock or wildlife.[266]

In February 2012, Pennsylvania enacted a law that limited the ability of municipalities to regulate the siting of impoundments. Under this new law, the maximum setback that a local government may require for an impoundment is 300 feet from a residential structure. (The law also establishes maximum setbacks for wells and well pads.) The law also bars local governments from using zoning laws to regulate the siting of impoundments.[267] In March 2012, seven Pennsylvania municipalities filed a lawsuit challenging the statute for infringing on local governments’ control over land use; this lawsuit is still pending.[268]

Land Application

Because of an exemption from federal law (discussed below), the land application of shale gas wastewater is regulated primarily at the state level. This practice is regulated at the federal level only to the extent that stormwater runoff associated with road spreading of wastewater could lead to violations of the Clean Water Act, such as the Act’s prohibition against direct discharges of oil and gas waste[269] or regulations applicable stormwater discharges from roadways.[270] While Pennsylvania’s oil and gas well regulations generally prohibit operators of such wells from discharging brine and other produced fluids onto the ground,[271] the state’s solid waste management regulations state that PADEP may issue permits authorizing land application of waste.[272]

Using this authority, PADEP has issued a general permit authorizing the application of natural gas well brines specifically for roadway pre-wetting, anti-icing, and deicing purposes,[273] as long as the brine meets certain pollutant concentration limits. If shale gas wastewater contains pollutants exceeding these limits—and Marcellus wastewater is likely to exceed them for some pollutants, like oil and grease—then it may not be applied to roads without first being treated to meet the limits. The general permit also limits the quantity of brine that may be applied. The permit states that it does not authorize the runoff of wastewater to surrounding lands and waters. Runoff from road spreading may be minimized through the use of certain management practices,[274] but in reality a certain amount of runoff may be expected to occur.[275] PADEP is currently proposing to amend the permit to also authorize the beneficial use of brines as a dust suppressant and a stabilizer for unpaved roads.[276] These uses were previously allowed, but PADEP was required to approve each operator's use for these purposes on a case-by-case basis.[277] Amending the general permit to include dust suppression and stabilization as authorized beneficial uses will mean that operators will no longer need to seek individual approval.

By contrast, some states prohibit the road spreading of shale gas wastewater. For example, New York prohibits the road spreading of flowback under any circumstances.[278] Additionally, while the state accepts permit applications for road spreading of production-phase water, the New York State Department of Environmental Conservation has stated that it does not anticipate granting any such applications at present because the available data on NORM are insufficient to show that the land application of that water is safe.[279]

Handling, Storage, and Transport Prior to Disposal

State regulations govern the handling, storage, and transport of shale gas wastewater prior to its ultimate disposal. Oil and gas wastes are currently exempt from the hazardous waste provisions of the federal Resource Conservation and Recovery Act (RCRA), which generally regulates the handling and disposal of waste. RCRA Subtitle C creates a federal program that manages hazardous waste from cradle to grave, including regulations for the generation, transportation, treatment, storage, and disposal of hazardous wastes. However, an amendment to the statute passed in 1980 exempted "drilling fluids, produced waters, and other wastes associated with the exploration, development, or production of crude oil or natural gas or geothermal energy" from coverage under RCRA for two years.[280] In the meantime, the amendment directed the EPA to determine whether regulation of those wastes under RCRA was warranted.[281]

In 1988, long before the large-scale development of shale gas became widespread, the EPA made a determination that such regulation was not warranted because existing state and federal regulations were generally adequate to control the management of oil and gas wastes.[282] The agency also found that applying RCRA Subtitle C regulation to these wastes would impose excessive costs on the industry. The EPA concluded that it would be more efficient and appropriate to fill any existing regulatory gaps by strengthening the Clean Water Act and UIC programs.[283] The agency also discussed the possibility of developing tailored management criteria for oil and gas wastes under Subtitle D of RCRA, which provides general environmental performance standards for disposal of solid wastes, but it has never done so.[284]

Consequently, oil and gas wastes remain exempt from the hazardous waste provisions of RCRA. This means that natural gas operators transporting shale gas wastewater, along with the POTWs, CWTs, and any other facilities receiving it, are not transporting or receiving legally "hazardous" wastes and thus do not need to meet the "cradle to grave" safeguards established by RCRA regulations.

In the absence of federal regulations, states control the handling, storage, and transport of shale gas wastewater.[285] In Pennsylvania, wastewater from industrial operations is classified as nonhazardous, and it must be managed and disposed of in accordance with the state's Solid Waste Management Act.[286,pp,qq] As a general matter, the statute requires anyone who stores, processes, transports, or disposes of nonhazardous waste to comply with all PADEP waste management regulations. It also prohibits them from endangering public health or the environment and from causing a public nuisance.[287]

PADEP's waste management regulations impose certain duties on the generators of nonhazardous waste if they generate more than 2,200 pounds of waste per month.[288] Those exceeding this threshold must prepare a strategy aimed at reducing the quantity of waste.[289] They must also submit to PADEP an annual report (Form 26R) containing a chemical analysis of their waste, and a biennial report detailing the types of waste generated and the location or method of the waste's ultimate disposal.[290] Other types of records concerning the ultimate fate of the generators' waste must be kept on site and made available for inspection.[291]

All waste must be transported to processing and disposal facilities that hold appropriate PADEP waste management permits.[292] State regulations provide detailed standards for the storage and transportation of waste.[293] If a spill or accidental discharge occurs during transport, the transporter must notify PADEP and take immediate steps to contain and clean up the spill.[294]

Residual Waste

One additional regulatory issue that arises with regard to shale gas wastewater concerns the handling of residual waste, the material that remains after treatment. This material can be subject to various regulations depending on its composition and the method of disposal.[295]

Liquid residuals from treatment plants, such as concentrated brines, may be discharged to surface waters in compliance with a NPDES permit, or indirectly discharged via a POTW in compliance with applicable pretreatment standards. Nonhazardous liquid residuals may also be disposed of through land application in compliance with state solid waste rules, or injected underground in compliance with UIC regulations.

Residuals in solid form, like sludge or residual "cakes," are typically subject to RCRA regulations and are classified as hazardous or nonhazardous. As discussed, shale gas wastewater is exempt from RCRA, and the EPA has interpreted this exemption as applying to residual wastes in most circumstances. Solid residual waste falling under the RCRA exemption, even if it displays hazardous or radioactive characteristics, may legally be sent to local municipal landfills.

[pp] The Pennsylvania regulations refer to industrial wastewater as "residual waste." Because of the potential confusion with the use of the term "residual waste" to refer to the material that remains after the process of waste treatment has taken place, we use the term "nonhazardous waste" here.

[qq] Similarly, in New York, regulations exempt industrial wastewater, including oil and gas produced water, from the definition of "hazardous waste." 6 N.Y.C.R.R. § 371.1(e)(2)(v).

However, under certain circumstances, residual waste streams generated by treatment and disposal methods may be subject to regulation as hazardous waste under RCRA Subtitle C.[296] To the extent RCRA applies, solid residuals' classification as hazardous or nonhazardous affects the type of landfill in which they may be placed. Nonhazardous waste may be sent to municipal solid waste landfills; hazardous waste landfills are subject to stricter standards. In addition to (or in lieu of) RCRA requirements, state solid waste regulations may also apply. If solid residuals are disposed of through land application practices like road spreading, compliance with the state's land application rules is required.

Finally (again, to the extent RCRA applies), residuals containing concentrated radioactive material greater than a certain threshold must be disposed of in a radioactive waste landfill licensed by the Nuclear Regulatory Commission.

Chapter 5: Policy Recommendations

The current regulation of shale gas wastewater is inadequate to prevent harm to human health and the environment. As described in the preceding chapters of this paper, the improper handling, treatment, and disposal of shale gas wastewater can expose people, fish, and wildlife to toxic, radioactive, or carcinogenic chemicals, and to chemicals that deplete oxygen levels in receiving waters, in the following ways:[rr]

- Wastewater that receives inadequate processing at public sewage treatment plants, or at private industrial wastewater treatment facilities, can be discharged directly to rivers, lakes, and streams.
- Spills from impoundments and holding tanks can contaminate nearby waters and soils.
- Improper injection of wastewater can pollute drinking water supplies or cause earthquakes.
- Partially treated wastewater applied to roads for dust suppression, deicing, and anti-icing can run off into adjacent waterways and seep into groundwater.
- Residual solid wastes left over from treatment processes can be sent to landfills that provide insufficient containment of hazardous pollutants.

To prevent these harms, government oversight of wastewater treatment and disposal must be improved at both the federal and the state levels. This chapter presents a number of policy recommendations for improving the regulation of the primary methods used to manage wastewater from hydraulic fracturing operations. While not an exhaustive list, these recommendations, if adopted, would significantly strengthen regulatory safeguards.

Treatment and Discharge to Water Bodies

Improved regulations are needed to protect surface waters from the impacts of pollutants contained in shale gas wastewater. Currently, discharge of such pollutants, including total dissolved solids, bromide, and radioactive materials, can occur in amounts and concentrations detrimental to water quality. EPA and the states must develop limits on both the discharge of shale gas wastewater from POTWs and CWTs and on the amount of pollution allowable in surface water bodies.

1. *EPA and states should ban or more strictly regulate the discharge of shale gas wastewater to POTWs.*

At present, a regulatory gap exists with regard to shale gas wastewater that is sent to POTWs. The discharge of shale gas wastewater to POTWs is allowed in most jurisdictions. (As discussed, Pennsylvania regulations require shale gas wastewater sent to certain POTWs to be treated at CWT facilities first; the state has asked operators not to send untreated wastewater to POTWs exempted from the regulations, but compliance with this request is voluntary.[297]) However,

[rr] As noted in the Introduction, polluted wastewater may also be released into the environment through accidental spills associated with the transport of wastewater, but that topic is beyond the scope of this paper. Accordingly, spill prevention and cleanup is not addressed in the recommendations in this chapter. Similarly, pollution from wastewater generated while wells are being drilled (i.e., before fracturing fluid is injected) is also beyond the scope of this paper.

POTW discharge of shale gas wastewater can have serious environmental consequences, since it includes pollutants, such as dissolved solids (i.e., salts), that pass through POTWs untreated or interfere with POTW functions by disrupting biological treatment units. The Clean Water Act's general prohibition against pass-through and interference at POTWs is difficult to implement and enforce for shale gas wastewater because many POTWs are not required to test their discharges for the pollutants that such wastewater contains.[298] In addition, POTWs have rarely established local limits on those pollutants.[299] Many states have not developed their own pretreatment standards for shale gas wastewater. Consequently, national pretreatment standards are needed to fill this regulatory gap and create a uniform baseline that will provide consistent protection for water quality in areas undergoing shale gas development.

EPA recently announced plans to develop categorical pretreatment standards for shale gas wastewater.[300] In doing so, the agency should set a no-discharge standard for POTWs (i.e., ban the discharge of shale gas wastewater to POTWs altogether), as NRDC and other groups recommended in comments on EPA's proposed plan.[301] Even if standards could be set that limit the pollutants in pretreated shale gas wastewater adequately to protect POTWs and the environment, POTWs have limited capacity, and that capacity is already needed to treat municipal wastewater. Regulators must be careful to avoid situations in which a growing volume of shale gas wastewater displaces other types of wastewater that need POTW treatment. This is a dynamic that could occur if shale gas operators were to offer higher prices to POTWs in return for the ability to discharge. While all forms of shale gas wastewater management present certain risks and potential impacts to health and the environment, other disposal options are likely less harmful and more appropriate than discharge through POTWs.

EPA has the legal authority to set a "no discharge" standard. The Clean Water Act directs the agency to set pretreatment standards that are adequate to "prevent the discharge of any pollutant through [POTWs], which pollutant interferes with, passes through, or otherwise is incompatible with such works."[302] The most reliably effective way to prevent these impacts is to forbid the introduction of shale gas wastewater to POTWs altogether. Consistent with this understanding of the Act, the agency's guidance document for the national pretreatment program states that one of the possible types of categorical pretreatment standards for industrial wastewater is "[s]tandards that prohibit discharges of any kind."[303] Indeed, the agency has set such a "no discharge" standard for several other types of industrial wastewater, including coastal oil and gas wastewater.[304] EPA should do the same with its shale gas wastewater categorical pretreatment standards and set a "no discharge to POTWs" standard for shale gas wastewater.

If EPA does continue to allow discharge to POTWs, pretreatment standards should be set as stringently as possible. Under the Clean Water Act, pretreatment standards for existing sources are to be based on the "best available technology economically achievable."[305] This standard means that EPA must take into account not only the best available technology currently used in the treatment of shale gas wastewater, but also the best available technology currently used in other subcategories, even when it is not common practice in the shale gas industry.[306] In addition, pretreatment standards for new sources are to be based on the best available demonstrated control technology.[307] The agency should exercise the maximum authority allowed under the law to establish pretreatment standards that will prevent pass-through and interference.

These pretreatment standards should be comprehensive (applying to *all* constituents found in shale gas wastewater) and protective (imposing an appropriately low maximum concentration for each constituent). They should also specify the total maximum volume of shale gas wastewater that POTWs may accept. At minimum, EPA's pretreatment standards should be as stringent as the standards that have been set by the states, like Pennsylvania's pretreatment standard of 500 mg/L total dissolved solids and 250 mg/L chlorides.[308] Creating a consistent pretreatment baseline will ensure that all surface waters are protected and that industry does not cluster in locations that are subject to a lesser pretreatment standard, a situation that could create pollution "hot spots."

If EPA does not ban shale gas wastewater discharges to POTWs or develop sufficiently stringent pretreatment standards, states should take these actions on their own. Regardless of whether a state is authorized to implement either the NPDES or the pretreatment program, if it develops its own pretreatment program, it may enforce requirements that are more stringent than federal standards.[309]

2. EPA or the states should update pollution control standards for CWTs that accept shale gas wastewater.

CWTs are subject to federally established effluent limitation guidelines (ELGs) limiting the pollutants that they may discharge.[310] However, these ELGs are out of date; they were developed prior to the emergence of hydraulic fracturing methods of shale gas extraction and do not address all pollutants of concern in the wastewater generated by such operations. The ELGs were adopted in 2000 and revised in 2003,[311] yet large-scale shale gas extraction was not practiced at all until 1997 and did not become common until the mid-2000s.[312] For example, in Pennsylvania, no Marcellus Shale produced water was reported in natural gas operators' wastewater reports until 2004.[313] In fact, although shale gas represents about 30 percent of total U.S. natural gas production today (as of August 2011), in 2001, when the CWT ELGs were first developed, shale gas provided less than 2 percent of the total.[314]

EPA should update the CWT ELGs to adequately address all of the constituents present in shale gas wastewater, as NRDC and other groups recommended in comments on EPA's plan to develop pretreatment standards for such wastewater.[315] In particular, the ELGs should be revised to include limitations on discharges of NORM, total dissolved solids, and bromides, which were not considered in developing the original guidelines. The state of Pennsylvania has recommended that EPA update the CWT ELGs to include limits on these pollutants.[316] The ELGs' limits on toxic organics, NORM, chlorides, and bromides should not allow any releases of these chemicals to the environment. These pollutants have the potential for cumulative and long-term impacts, such as chronic toxicity to aquatic life and violations of drinking water standards, that are difficult to predict and not yet well understood.

If EPA does not update these standards, states should develop and implement more protective standards on their own. Under the Clean Water Act, states have the authority to develop their own limitation guidelines or to impose limitations in individual permits that are more stringent than those contained in federal ELGs.

3. EPA and the states should develop water quality criteria for all chemicals in shale gas wastewater.

Water quality criteria are numeric limitations on pollutants in a particular water body that are adequate to support the water body's designated uses. EPA develops recommended water quality criteria, which states uses as guidance in setting and updating their own local criteria. Additionally, EPA must approve state water quality standards and can promulgate standards for a state if the state fails to adopt adequate ones on its own.[317] When a facility's discharge has the potential to cause criteria for a receiving water body to be violated, that facility's permit must contain water quality− based limitations to ensure that water quality is protected.

EPA has developed criteria for some pollutants of concern in shale gas wastewater, such as chloride, oil and grease, suspended solids, turbidity, and nitrates.[318] However, many other pollutants of concern—like total dissolved solids, bromide, and NORM—lack EPA-recommended criteria. EPA is currently updating its recommended water quality criteria for chlorides, which were developed in 1988.[319] The agency has also expressed interest in developing criteria for bromides but has not taken any formal steps to do so.[320]

EPA should proceed with both actions. More generally, it should update all of its recommended criteria for shale gas wastewater constituents and ensure that states expeditiously update their own criteria to provide equivalent protection. These criteria are needed to provide states with guidance on how to set limits on pollutants that are adequately protective of water quality. In the absence of national EPA-recommended criteria, states should develop their own improved criteria for pollutants in shale gas wastewater. In particular, Pennsylvania should complete the new standards it began developing for chlorides in 2010.[321]

4. Water bodies impaired by pollutants in shale gas wastewater, or with the reasonable potential to become impaired, should be identified, and pollution loads to those waters should be reduced.

Under Section 303(d) of the Clean Water Act, states (and EPA, where states have not been delegated authority to implement the Act) must identify waters for which a water quality standard has not been met, even after required minimum levels of pollution control technology have been adopted. Such waters are considered "impaired waters."[322] Under the Clean Water Act, no NPDES permit may be issued to a new discharger if the discharge will contribute to a violation of water quality standards, as when new discharges are made to waters that are already impaired.[323] Further, existing discharges must be reduced so they no longer cause or contribute to the impairment.[324] As a result, a determination that a water body is impaired affects whether new discharges may be allowed, as well as permissible pollutant loadings from existing dischargers. Moreover, even when there is no existing impairment in a receiving water body, a discharger that has the "reasonable potential" to cause or contribute to impairment must be assigned a permit limit strict enough to prevent that from happening.[325]

The states (and EPA) should formally designate water bodies that are impaired by pollutants found in shale gas wastewater. This is a key step toward protecting against new wastewater discharges that could further worsen water quality. Additionally, once a water body is designated as impaired, the state (or EPA) must develop a "total maximum daily load" (TMDL) for the pollutant(s) causing the impairment.[326] A TMDL is a "pollution budget," which calculates the maximum amount of a pollutant that a water body can safely receive each day and divides it up among pollution sources. Clean Water Act permits must then be revised to ensure that no individual source exceeds its allocation under the TMDL.[327] Further, even before a TMDL is developed, once a water body is identified as impaired, the permitting authority must begin imposing stricter limits in dischargers' permits.[328]

Pennsylvania, for example, has proposed that 68 miles of the Monongahela River be designated as impaired for sulfate, a constituent of shale gas wastewater.[329] If EPA approves the proposal, a TMDL must be established for sulfate in the designated sections of the river. Existing pollution sources will have to reduce their discharges, and new sources will not be allowed unless and until assimilative capacity exists in the river.

5. Water bodies not yet impaired by shale gas wastewater should be protected.

When a water body is receiving discharges of shale gas wastewater but is not yet impacted by that wastewater, the state and EPA must take care to protect it. Clean Water Act regulations require states to develop "anti-degradation" policies and implementation procedures to protect water bodies in good condition. Among other things, the anti-degradation rules require that existing uses of a water body must always be protected and that, where a water body is currently cleaner than the minimum water quality standards to support fishing and swimming, any incremental decrease in water quality is permissible only under limited circumstances.[330] These rules should be used to protect water bodies that have not yet been negatively impacted by shale gas wastewater. More specifically, state anti-degradation policies should be applied to prohibit or restrict shale gas wastewater discharges into water bodies that are in good condition.

Handling, Storage, and Transport Prior to Disposal

Improper handling, storage, or transport of shale gas wastewater can lead to spills and other releases of pollutants that contaminate nearby lands and waters with toxic or radioactive material. Yet in 1988, EPA decided that oil and gas wastewater should not be regulated as a hazardous waste, even when it in fact poses a hazard to human health and the environment. This regulatory exemption must be ended, either by Congress or by EPA. Even if both fail to act, states should use their authority to regulate waste more strictly than the federal government does and treat shale gas wastewater as hazardous.

1. Congress or EPA should eliminate the RCRA exemption for shale gas wastewater.

Because of the 1980 amendments to the Resource Conservation and Recovery Act (RCRA) and EPA's subsequent determination not to regulate oil and gas wastes under Subtitle C of the statute, shale gas wastewater is not controlled as stringently as hazardous waste, even though it may have hazardous characteristics. As described elsewhere in this paper, wastewaters from hydraulic fracturing contain many substances known to have harmful effects on human health and the environment. Many of these wastewaters would meet the RCRA definition of hazardous waste absent the regulatory exemption.[331] For example, some produced waters would be classified as hazardous due to toxicity associated with barium.[332] Were it not for the oil and gas exemption, any entity generating, transporting, recycling, treating, or disposing of such produced waters would be subject to rigorous standards and rules.[333]

Currently, however, shale gas wastewater is exempt from such federal RCRA hazardous waste regulation, and state regulations and enforcement are inadequate to ensure safe management of the waste. Numerous instances of spills and releases of oil and gas wastewater due to equipment failure, accidents, negligence, or intentional dumping have been documented; it is likely that these events could have been prevented through stricter regulation of waste handling.[334]

Consequently, Congress should amend RCRA to eliminate the exemption. Specifically, it should delete the section of the statute that exempts oil and gas wastes and instructs EPA to determine whether regulation of such wastes is warranted.[335] If this section were struck from the statutory text, oil and gas wastes would have to be regulated according to their actual characteristics, as are other wastes.

In the interim, EPA should reverse its determination that regulation of oil and gas wastes under RCRA is not warranted, as NRDC petitioned the agency to do in 2010.[336] The wastes generated now by the hydraulic fracturing process are very different from the wastes EPA considered when making its 1988 determination. These differences relate to the nature and number of chemicals used, waste management practices, proximity to populations and their drinking water sources, and amount of waste generated. The agency needs to address the impacts of 2012 hydraulic fracturing practices by revisiting its determination.

Nothing in RCRA prevents EPA from doing so. The exemption for oil and gas wastes in the 1980 RCRA amendments was for a limited period of time that has now expired. Courts have upheld EPA's authority to reconsider regulatory determinations made pursuant to the 1980 amendments.[337] Moreover, statements made by EPA in its 1988 regulatory determination indicate that the agency never intended the determination to be its final word on oil and gas waste. Instead, EPA established a three-pronged plan and intended to take further action to fill in existing gaps in the regulations governing the disposal of such wastes.[338] To date this three-pronged plan—which included improving alternative federal regulatory programs, working with states to improve state regulatory programs, and working with Congress to develop new statutory authorities—has not been pursued. Gaps in the regulatory system governing oil and gas wastes have grown even wider, and evidence of the substantial harm these wastes can cause to human health and the environment has continued to accumulate. EPA must revisit its 1988 regulatory determination to fulfill its obligations and protect human health and the environment from the significant risks posed by shale gas wastewater.

2. States should classify shale gas wastewater as hazardous when it meets relevant technical criteria and regulate it accordingly.

RCRA establishes a cooperative federal-state scheme that allows states to manage wastes through regulations that are more protective than the federal government's.[339] In California, wastes (such as oil and gas wastewater) that are exempted from federal RCRA regulations are subject to state hazardous waste requirements if they exhibit the physical and chemical characteristics of hazardous waste.[340] Other states should follow California's lead in treating shale gas wastewater as hazardous when it is *in fact* hazardous. States (like Pennsylvania and New York) that define oil and gas wastewater as nonhazardous in their regulations should eliminate those definitions. In light of the federal RCRA exemption for shale gas wastewater, state hazardous waste regulation is needed to ensure that this waste is handled, stored, transported, and treated in such a way as to prevent harm to human health and the environment.

3. States should require regular testing of shale gas wastewater.

States should require regular testing of shale gas wastewater. This is needed to assess whether wastewater from any given source, at any given time, possesses hazardous characteristics. The volume and chemical characteristics of flowback and production phase water change considerably over time. In effect, operators are not handling the same type of waste from day to day, so different handling, storage, and disposal methods may be appropriate. Only regular testing can reveal the variations in wastewater characteristics over time. Specific measurements are needed for produced water and post-treatment residuals to ascertain the presence and concentrations of potentially hazardous components. This information will assist in making decisions about how to manage the wastewater. EPA Region 2 has made the same recommendation, suggesting that regular testing be performed to determine whether shale gas wastewater poses a threat to health or the environment.[341]

Additionally, if the RCRA exemption for oil and gas wastewater is lifted, EPA regulations will require operators to determine whether their wastewater possesses hazardous characteristics, either by testing the wastewater or by applying knowledge of the wastewater's contents.[342]

Underground Injection

Shale gas wastewater should be disposed of in Class I hazardous waste disposal wells, which are subject to regulations that are more protective of health and the environment than the regulations for the Class II wells currently used for oil and gas waste disposal. Injecting wastewater into Class II wells instead of Class I hazardous waste wells may increase the risk of injection fluids' migrating into sources of drinking water. It may also increase the risk of earthquakes, such as the one in Ohio in January 2012, caused by a shale gas wastewater disposal well that intersected an unmapped fault.[343] Other recent earthquakes in Texas, Arkansas, and West Virginia have also been linked to the injection of shale gas wastewater.[344] These unnecessary risks could be minimized through the elimination of the RCRA exemption for oil and gas wastes or through an amendment to the Underground Injection Control (UIC) program regulations. States can also use their authority to more strictly regulate Class II oil and gas waste wells.

1. *EPA should require wastewater with hazardous characteristics to be injected into Class I hazardous waste wells.*

Because of the RCRA exemption for oil and gas wastewater, waste from hydraulic fracturing operations is currently injected into Class II disposal wells. If the exemption were eliminated, all wastewater with hazardous characteristics (defined in the RCRA regulations, as described above) would instead have to be injected into Class I hazardous waste wells.[345] Alternatively, EPA could amend the UIC regulations to directly require that shale gas wastewater displaying specified hazardous characteristics be disposed of in Class I hazardous waste wells.

Class II wells are subject to regulations that are less stringent than those governing Class I hazardous waste wells. Class I hazardous waste wells must be sited such that they only inject below the lowest underground source of drinking water (USDW) in the area of the well, whereas Class II wells may inject above or below a USDW.[346] Unlike Class II wells, Class I hazardous waste wells must submit more information demonstrating that the well will be sited in a location that is geologically suitable, taking into account earthquake risks.[347] Class I hazardous waste well operators must consider an area within a two-mile radius of the well to determine if there may be pathways from the injection zone to USDWs; for Class II wells, the area of review is only the area within a quarter-mile radius.[348] Well construction, operation, testing, and monitoring requirements are more stringent for Class I hazardous waste wells.[349] Operators of such wells are required to continue monitoring the well and groundwater after the well is plugged, while Class II well operators are not.[350]

Finally, the criteria under which states can seek primacy for regulation of Class II wells are less stringent than the criteria for all other classes, including Class I. States seeking primacy over all other classes of wells must demonstrate that their regulations are as stringent as those of the federal program. States seeking primacy over Class II wells need only show that their regulations are "effective" in protecting USDWs.[351] For all of these reasons, disposal of shale gas wastewater in Class I hazardous waste wells is preferable to disposal in Class II wells.

2. In the interim, states should use their authority to more strictly regulate Class II wells for oil and gas wastewater.

Under the UIC program, states have a significant amount of discretion regarding the development of regulations for Class II wells.[352] At minimum, states with primacy over Class II wells must show that their programs are "effective" at protecting underground sources of drinking water, but there is no maximum stringency that their programs are prohibited from exceeding. Consequently, states are free to regulate Class II wells as strictly as they regulate Class I hazardous waste wells, or even more strictly if they so desire. All states with primacy over their Class II well injection programs can and should regulate Class II wells into which oil and gas wastewater is injected at least as strictly as Class I hazardous waste wells.

Reuse for Additional Hydraulic Fracturing

The hydraulic fracturing process itself should be federally regulated. However, when fracking occurs, reuse of wastewater for additional hydraulic fracturing can offer many benefits (although these benefits can in some cases be offset by energy use and the generation of concentrated residuals). Where appropriate, states should encourage or even require the reuse and recycling of shale gas wastewater.

1. Congress should eliminate the Safe Drinking Water Act exemption for hydraulic fracturing.

An amendment to the Safe Drinking Water Act in 2005 excluded hydraulic fracturing activities from the definition of "underground injection," except for fracturing fluid that contains diesel fuels. As a result, the underground injection of fluids other than diesel fuel for the purpose of fracturing is not federally regulated. While all of the major oil and gas producing states regulate oil and gas production to protect water resources to some degree, these regulations are uneven in their level of protectiveness. Not all states' regulations mention hydraulic fracturing specifically. Moreover, some states lack important provisions in their programs. For example, most states have well construction requirements that include provisions for cementing above oil or gas producing zones and across groundwater zones. These requirements may be very detailed, as they are in Alabama, or may simply be general mandates not to harm water resources, as they are in Arizona.[353]

Because of this uneven state regulation, federal regulation of hydraulic fracturing is needed to create a national baseline of groundwater protection. Congress must act to eliminate the SDWA exemption. If hydraulic fracturing activities were subject to regulation under the statute, EPA would have to ensure that injection of fracturing fluid would not endanger drinking water sources nationwide.[354] In addition to this general standard, EPA would be able to enforce regulations governing the construction, operation, and monitoring of unconventional gas wells that are to be hydraulically fractured. EPA could choose to regulate hydraulic fracturing as a Class II activity, subject to the same requirements as wells used to inject oil and gas wastewater underground for disposal. It is also possible that EPA could classify oil and gas production wells that are hydraulically fractured under a different class, or develop an entirely new regulatory structure or subclass of wells.[355] Either way, the end result would be improved regulation of shale gas wells.

In the current Congress, the proposed Fracturing Responsibility and Awareness of Chemicals Act of 2011 (the FRAC Act), H.R. 1084 and S. 587, would achieve this result. The bill contains two amendments to the SDWA: one that would amend the definition of underground injection to include hydraulic fracturing, and another that would create a new public disclosure requirement for the chemicals used in hydraulic fracturing. Congress should pass this bill or one similar to it. Conversely, Congress should *not* pass bills such as the Fracturing Regulations Are Effective in State Hands Act (the FRESH Act), S. 2248, which would eliminate all federal authority to regulate hydraulic fracturing activities.[356]

2. States should encourage or require reuse of shale gas wastewater in the hydraulic fracturing process where appropriate.

Greater reuse of shale gas wastewater for additional hydraulic fracturing would reduce the amount of wastewater disposed of by other methods that pose greater risks to health and the environment. It would have the added benefit of reducing the amount of freshwater withdrawn from other sources to use in the hydraulic fracturing process. In the Marcellus formation, wastewater reuse can often occur even without treatment.[357] However, where treatment is necessary, wastewater recycling creates residual byproducts that are not well regulated (as discussed below), and the recycling process can be energy-intensive. When the benefits of recycling and reuse outweigh these disadvantages, states should encourage or require natural gas operators to reuse wastewater for additional hydraulic fracturing.

Policies encouraging recycling and reuse of wastewater are consistent with the federal Pollution Prevention Act (PPA), which aims to reduce pollution through changes in industrial production, operation, and raw materials use. While the PPA creates no binding obligations, it establishes a national policy of encouraging source reduction in the first instance, then recycling, and then treatment and release as a last resort.[358] Reusing shale gas wastewater furthers the goal of source reduction by reducing the amount of new wastewater generated with the fracturing of each well.

Some states already encourage the reuse of flowback and production phase water. Pennsylvania requires well operators to develop a wastewater source reduction strategy that identifies methods and procedures to maximize recycling and reuse.[359] The Susquehanna River Basin Commission (a regional governmental agency whose members are New York, Pennsylvania, Maryland, and the federal government) incentivizes reuse by relaxing review and approval requirements for interbasin diversions of flowback or produced water from one drilling site to another for use in further fracturing.[360] Other states should follow suit and encourage or require shale gas wastewater recycling. (However, while evaluation of energy implications is beyond the scope of this paper, it is nonetheless important to note that the energy demands of on-site treatment technologies for reuse may be an important consideration when deciding to incentivize this practice.)

Impoundments and Tanks

Using open impoundments or tanks for the storage and disposal of shale gas wastewater creates a risk of spills or leakage of wastewater into the ground, potentially contaminating soil, surface water, or groundwater. Additionally, impoundments cause large land disturbances and generate hazardous air pollution. To eliminate the risk of these avoidable impacts, the use of impoundments should be prohibited, or at a minimum more strictly regulated; tanks should be more strictly regulated as well.

1. States should not allow the storage or disposal of shale gas wastewater in open impoundments.

Prohibiting impoundments is necessary to eliminate the impacts summarized above. Rather than collecting wastewater in centralized open impoundments either on or away from the drill site, flowback and production phase water should be collected at the well and either recycled or routed directly to disposal. EPA Region 2 has supported New York's proposal to ban the storage of flowback water in open pits on the well pad.[361] New York and other states should also ban the use of centralized open impoundments away from the drill site. In the event that storage of wastewater is necessary, it should be done in closed tanks (which should be strictly regulated, as described below).

2. If impoundments are not prohibited, they should be more strictly regulated. Storage tanks should be more strictly regulated as well.

If states do not prohibit impoundments, at minimum they should more strictly regulate their location, construction, operation, and remediation. For example, states should require the maintenance of a sufficiently protective "freeboard" (the distance between the water level and the top edge of the impoundment) based on local conditions, such as the likelihood of flooding, and should require groundwater monitoring in the impoundment area.[362]

The U.S. Department of Energy recommends that all pits used for the long-term storage of wastewater be required to use a natural or artificial liner to protect groundwater.[363] DOE also recommends that impoundments not be excavated to a depth that extends below the seasonal high-water table, and that pits not be allowed within the boundaries of 100-year floodplains without extra precautions. (However, these boundaries might not be adequately protective, given that many floodplain maps are out of date, and given that climate change is projected to increase the intensity and frequency of future flooding events.[364]) Finally, DOE recommends that states consider prohibiting the use of pits within the boundaries of public water supply and wellhead protection areas.[365] States should incorporate these recommendations into their regulatory requirements for impoundments.

Additionally, states should *not* restrict the ability of local governments to regulate the siting and zoning of new impoundments, as Pennsylvania did in February 2012. Pennsylvania's new law requires local governments to authorize impoundments as a permitted use in all zoning districts. It also prevents local governments from establishing setbacks (the distance between an impoundment and an occupied structure) of more than 300 feet.[366] Pennsylvania should repeal this law, and other states should not pass laws similar to it. Local governments should retain the authority to site and regulate impoundments as necessary to protect health and welfare.

States should also regulate the use of tanks for the storage of shale gas wastewater. Generally speaking, tanks should be maintained in a manner that prevents leakage. To that end, secondary containment should be required for all tanks. Secondary containment is a management practice wherein the tank sits within a traylike structure with raised sides such that materials released during a tank rupture would be contained and not released into the environment. The Department of Energy has recommended the use of secondary containment, suggesting requirements for containment dikes to meet a permeability standard, and suggesting that containment areas outside of tanks be kept free of fluids. DOE further recommends that regulations specify how long releases or other fluids inside a containment dike may remain before removal. [367]

Finally, if the RCRA exemption for oil and gas wastewater is lifted, EPA should strictly regulate surface impoundments for shale gas wastewater by enforcing the minimum technological and operational requirements for hazardous waste impoundments contained in the statute and regulations.[368]

Land Application

Because application of shale gas wastewater to land and roadways can lead to environmental contamination through runoff of toxic pollutants into surface waters, it should be prohibited, or at minimum strictly regulated.

1. *States should not allow the land application or road spreading of shale gas wastewater.*

Applying shale gas wastewater to land and roads causes a serious runoff problem, sending contaminants into nearby surface water bodies. The Pennsylvania general permit for road spreading states that it does not authorize runoff into water bodies. In practice, however, some runoff can be expected to occur, as common management practices are inadequate to completely prevent it. One study found chloride concentrations up to five times greater than that allowed under EPA public drinking water standards in down-gradient wells from an oil field brine application on a gravel roadbed, despite 99 percent dilution of the solutes in the brine.[369] These results indicate that even when precautions are taken, road spreading can still cause environmental contamination.

EPA Region 2, in its comments on New York’s environmental review of hydraulic fracturing, warned that road spreading could lead to surface infiltration of wastewater and risk contamination of underlying aquifers.[370] Consequently, the Region supported New York’s decision to prohibit the road spreading of flowback and urged the state to consider extending that prohibition to production phase water as well.[371]

As discussed earlier in this paper, other substances are available for use on roads for dust suppression and deicing that are as effective as shale gas wastewater but have less environmental impact. For example, other dust suppression agents contain less chloride than shale gas wastewater. Other substances used for road spreading are also preferable because, unlike shale gas wastewater, they do not contain radioactive material. A study conducted by Argonne National Lab for the U.S. Department of the Interior concluded that land spreading of diluted NORM waste presented the highest potential dose of exposure to the general public of all waste disposal methods studied.[372] Consequently, the use of shale gas wastewater for road spreading should be prohibited.

2. If land application and road spreading are not prohibited, they should be more strictly regulated.

If states do not ban land application and road spreading, these practices should only be authorized subject to strict limits on pollutant concentrations and required measures to prevent runoff. At minimum, permits should limit how often brine can be spread on lands and roads; application rates for brines; provisions for regular testing of brines; limits on application during rain, before rain, or while the road surface is saturated; limits on the maximum grade of the road to which brines may be applied; limits on how close to water bodies brines can be applied; provisions for additional study of the long-term effects of brine use on roads; provisions for testing for accumulations of contaminants; and limits on radionuclide levels in brine used on roads.[373]

Additionally, EPA and states should enforce existing Clean Water Act requirements for controlling polluted runoff from municipal storm sewer systems, to ensure that any road spreading does not violate the requirements to the reduce polluted runoff to the "maximum extent practicable" and to avoid causing violations of water quality standards. EPA should also complete its ongoing development of new rules to strengthen the CWA stormwater regulatory program, including new standards specifically tailored to controlling polluted runoff from roadways and other transportation facilities.[374]

Residual Waste

Just as shale gas wastewater should not be categorically exempt from regulation under RCRA, residual waste derived from the treatment of that wastewater should not be exempt from regulation if it displays the characteristics of a hazardous waste. Any residual substance left over from the treatment of wastewater that displayed hazardous characteristics will most likely display hazardous characteristics as well, as chemicals are present at higher concentrations in the residuals than in the original wastewater. Further, given its higher pollutant concentrations, residual waste may, in some cases, meet the criteria for hazardous waste even where the untreated wastewater did not.

1. Shale gas wastewater treatment residuals with hazardous characteristics should be regulated under RCRA Subtitle C.

As discussed, shale gas wastewater is currently exempt from regulation under RCRA. However, under certain circumstances, residual waste streams generated by treatment and disposal methods may be subject to regulation as hazardous waste under RCRA Subtitle C.[375]

The issue of whether residual waste is exempt from regulation as a hazardous waste is an important one. Post-treatment residual wastes contain the same pollutants of concern as the original wastewater, but in much greater concentrations. Thus, careful management of residuals is needed to avoid releasing even small amounts of them into the environment. Congress or EPA should require that residual waste with hazardous characteristics be regulated as hazardous under RCRA. This result could be accomplished if Congress or EPA were to eliminate the RCRA exemption for shale gas wastewater.

Public Disclosure

Regardless of which treatment or disposal method an operator uses to manage its shale gas wastewater, it should be required to publicly disclose the final destination of the waste. For example, Pennsylvania requires every operator to submit information, which the state posts on its website, revealing the name and location of the specific destinations where the operator sends its wastewater. These include treatment facilities, injection wells, landfills, road spreading, and reuse for further hydraulic fracturing.[376] However, the data sheets available from Pennsylvania DEP contain extensive errors, most notably due to inconsistent categorization of disposal methods. Consequently, Pennsylvania should review operator-submitted data for consistency. Pennsylvania should also post online the other forms and reports that operators submit to the state, such as the 26R forms that contain wastewater chemical analyses. These forms are not currently made available online and are difficult and expensive to obtain through state open records requests. Other states should develop their own public disclosure rules as well, so that citizens everywhere can learn about the composition and ultimate fate of the wastewater generated in their states.

"Model" Regulations

The federal Bureau of Land Management (BLM) is currently developing regulations for hydraulic fracturing activities on federal lands, including management of produced water.[377] The content of the forthcoming regulations is presently unknown. However, given that the BLM's authority over development of federal oil and gas resources and activities on federal lands is expansive, the BLM rulemaking presents an opportunity to create a model that states can adopt. If the regulations set strict technology standards, they may also spur innovation in new and improved wastewater treatment technologies. Consequently, the BLM regulations should be set to be as protective of health and environment as possible, and should include at minimum (to the extent BLM has regulatory jurisdiction) all recommendations set forth in this paper.

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