Chapter 11
Disposal of Water for Hydraulic Fracturing: Case Study on the U.S.

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Abstract In 2012, the U.S. oil and gas industry produced approximately 3.4×10^9 cubic meters (m^3) of water, equivalent to 9.1×10^6 m^3 per day and greater than six times the amount of water treated by the City of Houston, Texas. This "produced water" consists of drilling or completion fluids that exit a well shortly after it is brought into production, along with water occurring naturally in the rock formation that exits with the oil and/or gas. Produced water can be contaminated by hydrocarbons, metals, radioactive material, and salts, which can make recycling and disposal difficult. In this chapter, we will discuss two aspects of produced water handling—regulation and technology—specifically focusing on five U.S. regions—the Permian, Eagle Ford, Bakken, Marcellus, and Niobrara. We will explore various disposal practices used in each region and consider how the regulatory framework influences those practices. The focus will be on regulations in six states – Texas, North Dakota, Pennsylvania, Ohio, Colorado, and Wyoming – with jurisdiction over the above regions. Just as the regions have remarkably different geology, and therefore different quality of produced water, these six states also have different regulatory frameworks. To illustrate these differences, we undertake a detailed exploration of the regulations in Texas and Pennsylvania and compare other states' regulations where appropriate. The analysis highlights the complexity of produced water regulation, treatment, and disposal within the United States.

Keywords Waste disposal · Injection wells · Produced water · Recycling · Frac fluid · Texas · Pennsylvania

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11.1 Introduction

Oil and gas development uses large amounts of water, both in the initial drilling of a well (e.g., to clean and lubricate the drill-bit), and during subsequent well completion processes (e.g., hydraulic fracturing). A portion of the water injected during well drilling and completion returns to the surface, as does water occurring naturally in the rock formation (together "produced water"). The amount of these return flows varies between geological formations, ranging from just 10% of injected volumes in the Marcellus to over 100% in the Barnett (EPA 2015, p. 4–3). The produced water is often contaminated—containing oils, solids, salts, metals, hydrocarbons, and naturally occurring radioactive materials ("NORM")—which makes its treatment difficult. Perhaps for this reason, most produced water in the U.S. is currently disposed of through underground injection, with little or no treatment. Underground injection can have serious environmental impacts and results in produced water, particularly flowback water, being permanently removed from the hydrological cycle. This, along with the use of freshwater for hydraulic fracturing operations, may contribute to water shortages, particularly in arid areas.

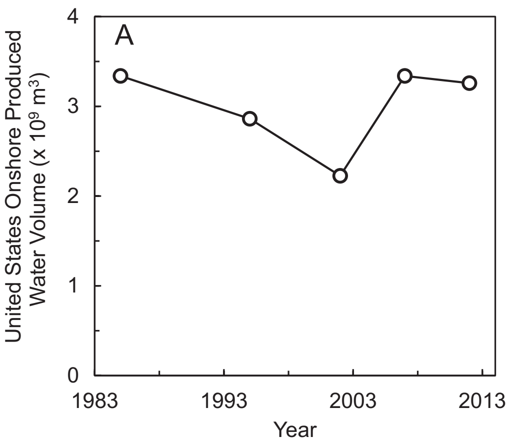
Rather than disposing of produced water, oil and gas operators could reuse it. This has dual benefits for operators, reducing their need to source freshwater and dispose of produced water. Despite these benefits, however, recycling is limited in many areas. This is likely due to economic factors, including the cost of treating produced water for reuse. Unless and until the economics change, regulatory intervention may be needed to encourage recycling. At a minimum, it is important that regulations not prevent or hinder recycling. This may occur where, for example, recycling operations are subject to overly burdensome and/or complex permitting requirements. However, care must be taken to ensure that any change in those requirements does not undermine environmental protections.

Several major oil and gas producing states, including Pennsylvania and Texas, have recently streamlined the permitting of recycling operations (PDEP 2012; RRC 2016). Texas has also sought to encourage recycling by providing tax incentives therefor (Texas Tax Code § 151.355(7)). Recycling could be further encouraged through other regulatory changes, such as restrictions on produced water disposal. This chapter discusses the regulatory framework for disposal in six oil and gas producing U.S. states, namely Texas, North Dakota, Pennsylvania, Ohio, Colorado, and Wyoming, with a particular focus on the regulations in Texas and Pennsylvania. At the time of writing, regulations in all six states allowed produced water to be disposed of through underground injection and surface water discharge. Five of the states' regulations also permitted wastewater disposal on land. The wide range of disposal options has likely hindered adoption of produced water recycling.

11.2 Water Production in Oil and Gas Operations

Oil and gas in both conventional and unconventional reservoirs coexist with water, and water exits a producing well along with the targeted oil and gas. Unless otherwise specified, the produced water regulations discussed here do not apply only to wells that are treated using hydraulic fracturing, but rather all wells that produce oil and gas. As the well ages, the water-to-oil ratio ("WOR") and/or the water-to-gas ratio ("WGR") increases. It was estimated that the U.S. national average WOR in 2012 was 9.2 cubic meters ("m^3") of water per m^3 of oil (Veil 2015). Therefore, the main fluid exiting oil wells is, in fact, water, and 3.4×10^9 m^3 of water was produced in the U.S. in 2012 (Veil 2015). While water is coproduced in conventional oil and gas and other types of unconventional wells, the hydraulic fracturing process changes some of the characteristics of that water, notably at the start of production. Specifically, fracturing fluid contributes to flowback water, which is more similar chemically to the fracturing fluid than the reservoir water. Flowback water, therefore, may contain corrosion or scale inhibitors, disinfectants, friction reducers, acids, or surfactants that are not naturally present in the formation. However, over time, produced water composition more closely resembles the formation water.

Onshore generation of produced water has increased since the early 2000s (Fig. 11.1a). This increase coincides with an increase in oil and gas activity due to exploitation of unconventional sources, including shale formations, oil sands, and coal bed methane. However, the increase in water production in more recent years is not as high as one may expect given the rise in oil and gas production (Fig. 11.1b), perhaps indicating that younger unconventional wells do not tend to produce as much water as older conventional wells. In 2012, Texas was the biggest generator of



B) Produced Water Volumes ($\times 10^9$ m^3)

State	Year 2007	Year 2012
Texas	1.173	1.182
Wyoming	0.374	0.346
Colorado	0.061	0.057
North Dakota	0.021	0.046
Pennsylvania	0.001	0.005
Ohio	0.001	0.001

Fig. 11.1 Onshore produced water volumes. (**a**) Trends in onshore produced water production in the United States from 1985 to 2012. (**b**) Produced water volume estimates for the six states described in this chapter. Data from API (1988), Veil et al. (2004), Clark and Veil (2009), and Veil (2015)

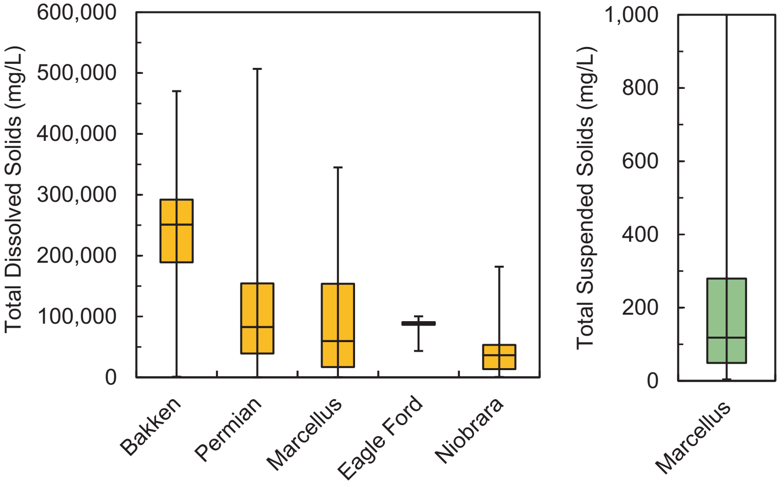


Fig. 11.2 Total dissolved solids (TDS) and total suspended solids (TSS) concentrations in selected basins and formations in the United States. In these box plots, the bottom of the box represents the first quartile and the top represents the third quartile. The horizontal line in the box represents the second quartile or median. The error bars show the spread of the data (minimum to maximum value). Data from Blondes et al. (2016)

produced water, generating 1.2×10^9 m^3, 36% of the produced water generated onshore (Veil 2015). Behind Texas, top water producing states include California, Oklahoma, Wyoming and Kansas.

The composition of produced water impacts the management method and treatment necessary (Igunno and Chen 2014). Although many different water parameters are considered when determining if water must be treated prior to disposal, reuse in enhanced oil recovery ("EOR"), or other potential uses, a few parameters will be discussed here. It is important to note that the concentration of each of these parameters varies (Fig. 11.2) widely depending on the formation and the well (Fakhru'l-Razi et al. 2009; Blondes et al. 2016). For example, in oil and gas wells, produced water may have a pH[1] as low as 3.1 or as high as 10. Likewise, the total suspended solids ("TSS")[2]—including clays, sand, precipitated salts, and bacteria—can range from 1.2 to 1000 mg/L. A value of interest for water recycling, especially if it is to be reused for irrigation, livestock watering, or released into a freshwater body, is the number of total dissolved solids ("TDS"). These dissolved solids include salts, such as sodium chloride, and metals, and many dissolved solids can be costly to remove. In produced water, TDS may range from 2600 to 360,000 mg/L (Fakhru'l-Razi et al. 2009; Blondes et al. 2016). For reference,

[1] A water's pH is an indicator of its acidity. Water with a lower pH value is acidic, while water with a higher pH value is basic. Neutral pH is 7.0. For reference, lemon juice has a pH of about 2, while an ammonia solution has a pH of about 11.

[2] TSS can be expressed using the unit "mg/L" referring to milligrams per liter. Therefore, there may be as much as 1000 mg or 1 g of suspended solid particles in 1 liter of produced water.

seawater has about 32,000 mg/L TDS—so, some produced water has greater than ten times the salt concentration of seawater. Both TSS and TDS concentrations, like all water quality parameters, vary between and within formations, as shown in Fig. 11.2. Finally, water from oil producing wells contains between 2 and 565 mg/L of oil, which must be removed prior to surface discharge to protect aquatic organisms. The wide variation in produced water composition contributes to regional variation in management strategies, state regulations and, likely, the treatment technologies employed.

11.3 Regulatory Framework Governing Produced Water

Despite its potentially dangerous nature, produced water is not subject to federal hazardous waste regulations adopted under the Resource Conservation and Recovery Act ("RCRA") (42 U.S.C. § 6901 et seq.). The RCRA aims to, among other things, assure "that hazardous waste management practices are conducted in a manner which protects human health and the environment" (42 U.S.C. § 6902(a)(4)). Hazardous waste is defined in section 2(5) of the RCRA (42 U.S.C. § 6903(5)) as:

> solid waste[3], or a combination of solid wastes, which because of its 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.

Certain wastes with these characteristics are, however, exempt from regulation as hazardous wastes. In October 1980, Congress provided a conditional exemption for certain wastes from oil and gas exploration and production ("E&P Waste"), pending review of their adverse effects (Pub. L. 96-482, October 1, 1980, 94 Stat. 2334). The U.S. Environmental Protection Agency ("EPA") conducted the review, which determined that regulation of E&P Waste as a hazardous waste is "not warranted," because existing state regulatory programs are "generally adequate" for controlling such waste, and additional federal controls would be uneconomical (EPA 1987). Thus, E&P Waste remains exempt from the hazardous waste regulations.

The exemption for E&P Waste covers "drilling fluids, produced waters, and other wastes associated with the exploration, development or production of crude oil or natural gas" (42 U.S.C. § 6921(b)(2)(A); 40 C.F.R. §261.4(6)).[4] These wastes are, however, only exempt from regulation under Subtitle C of the RCRA (i.e., the provi-

[3] Section 2(27) of the RCRA (42 U.S.C. § 6903(27)) defines "solid waste" to mean any "discarded material, including solid, liquid, semisolid, or contained gaseous material resulting from industrial, commercial, mining, and agricultural operations, and from community activities."

[4] The term "other wastes" encompasses waste material intrinsically derived from primary field operations associated with oil and gas exploration, development, or production, such as materials produced from a well in conjunction with oil or gas (EPA 2002).

sions dealing with hazardous wastes). RCRA Subtitle D, dealing with non-hazardous waste, continues to apply. The subtitle confers primary authority for regulating non-hazardous wastes on the states. The six oil and gas producing states examined in this chapter have each adopted their own regulations governing the management of produced water and other E&P Waste. Such waste is also subject to regulation under several federal statutes, including the Safe Drinking Water Act (42 U.S.C. § 300f et seq.) and Federal Water Pollution Control Act (commonly known as the "Clean Water Act") (33 U.S.C. § 1251 et seq.). Further information on the state and federal regulations is provided in Sects. 11.5 and 11.6.

11.4 Handling of Produced Water in the U.S.

In 2007, it was estimated that 96% of produced water (onshore and offshore) in the U.S. was disposed of via injection. Approximately 58% was injected into producing formations for EOR (Clark & Veil 2009). Approximately 38% of injected water was placed in non-producing formations. The remaining ~4% was discharged to surface waters. In 2012, injection was still the preferred disposal method in the U.S., with 45% of produced water injected for EOR, 39% sent to disposal wells, and 7% sent to off-site commercial disposal wells (Veil 2015).

Notable differences in management practices in the states are observed (Fig. 11.3). All states in our case study, except for Pennsylvania, manage their produced water primarily through injection for either disposal or EOR. (In Fig. 11.3a, data was only gathered for these two options.) In 2012, Pennsylvania, notably, allocated >85% of its produced water for beneficial reuse, mainly as fluid for oil and gas operations, such as completions (Fig. 11.3b). This shift occurred because of economics and geography, and is discussed in detail below. Colorado and Ohio also show modest beneficial reuse rates, 12% and 5%, respectively (Veil 2015). Produced water reuse in Colorado, like Pennsylvania, is primarily for use in oil and gas operations. Reuse of produced water in this manner—for example, as part of the fracturing fluid—is attractive because the dissolved solids do not need to be removed. Although no reuse in Texas was reported in the study depicted in Fig. 11.2, Nicot (2013) reported produced water reuse and recycling in Texas in 2012, stating that 5% of hydraulic fracturing makeup water in the Barnett Shale and in East Texas was sourced from reused or recycled water. This number was as high as 20% in the Anadarko Basin in North Texas. Several industry reports suggest reuse has increased in Texas in the past few years, as discussed in Sect. 11.6.2.

11.5 Regulation of Produced Water Disposal

As shown in Fig. 11.3, underground injection is the primary means of disposing produced water in the six oil and gas producing states examined in this chapter, except for Pennsylvania. During the early development of the Marcellus shale, large

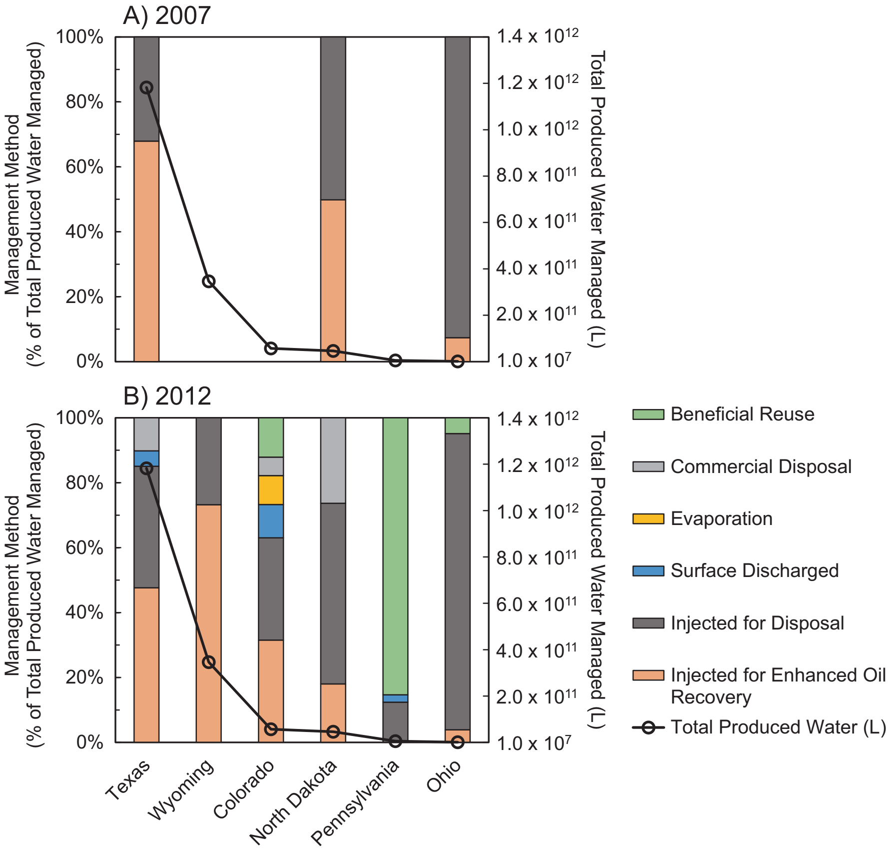


Fig. 11.3 Estimated volumes of produced water and management methods in Texas, North Dakota, Pennsylvania, Ohio, Colorado, and Wyoming in (**a**) 2007 and (**b**) 2012. Data from Clark and Veil (2009), and Veil (2015). Although it is likely that beneficial reuse, commercial disposal, evaporation, and surface discharge were produced water management strategies employed in 2007, data on volumes managed using these strategies was not collected in the referenced study. Management strategies were self-reported to the authors of these two studies, and numbers were not reported if the data are not shown

amounts of produced water were sent to sewage treatment plants ("publicly owned treatment works" or "POTWs"). However, conventional sewage treatment plants are unequipped to remove the large amounts of dissolved solids (i.e. salts) present in produced water. This practice, therefore, led to degradation of the water into which these treatment plants discharged their effluent. Seeking to minimize the potential for water contamination, oil and gas producers in other states often inject produced water into disposal wells. However, geologic conditions in Pennsylvania are such that the state has few sites suitable for injection. Oil and gas operators are, therefore, often forced to truck produced water to neighboring states, such as Ohio, for injection. The high cost of trucking has led some to pursue alternative practices. This section focuses on common disposal practices—underground injection, surface discharge, and land application—with the regulations governing each summarized in Table 11.1.

11.5.1 Disposal Via Underground Injection

Primary regulatory authority over underground injection rests with EPA. Through its Underground Injection Control ("UIC") Program, established under the Safe Drinking Water Act (42 U.S.C. § 300f et seq.), EPA regulates the injection of produced water into non-producing formations. The UIC Program does not regulate injection into producing formations for EOR (EPA 2016a). Such injection is generally considered part of the production process and may be regulated as such by the state in which it occurs.

EPA's UIC Program aims to prevent the contamination of underground sources of drinking water due to fluid injection (EPA 2016b). Wells used for injection are divided into six classes, based on the type of fluid they accept, with those accepting produced water falling into Class II (EPA 2016b). Federal regulations provide for the permitting of Class II wells. Existing wells are permitted by rule, meaning that the operator generally does not have to obtain an individual permit, unless specifically required to do so by EPA (40 C.F.R. § 144.21(a)). An individual permit must be obtained for any new well (40 C.F.R. § 144.31(a)).[5] Permits are issued by the EPA or, in states that have assumed primary responsibility for underground injection, the relevant state agency. The permit holder must comply with minimum standards relating to well construction and operation (40 C.F.R. pt. 144, 146). These include ensuring that the well is situated outside any formation containing underground sources of drinking water (40 C.F.R. § 144.22(a)) and cased and cemented to prevent the movement of waste into drinking water (40 C.F.R. § 146.22(b)–(e)).

By establishing permitting and other requirements for Class II wells, the UIC Program may affect the pace at which new wells are constructed. Limited availability of wells could increase the costs of disposal via underground injection and thereby encourage greater produced water recycling. That has been the experience of Pennsylvania which, as of February 2015, had just nine active Class II wells (EPA 2015, p. 8–69). Other key oil and gas producing states have a much larger number of wells, however. There are approximately 36,000 disposal wells nationwide, primarily in the west and south (EPA 2016a). Nearly one-quarter of the wells are in Texas, which had 8100 active disposals wells as of July 2015 (RRC). Due to the widespread availability of disposal wells, underground injection is typically inexpensive, often costing less than 6.3 USD/m^3 (Cook et al. 2015, p. 57). This is likely less than the cost of recycling.

[5] The Director may issue a permit on an area basis, rather than for each well individually, in certain circumstances (40 C.F.R. § 144.33).

Table 11.1 Regulation of produced water disposal in major oil and gas producing states

State	Regulation of produced water disposal methods		
	Underground injection	Treatment and discharge	Land application
Texas	***Authorized*** with permit from the RRC	***Authorized*** at a CWT that holds an NPDES permit issued by the EPA	***Authorized*** subject to permitting by the RRC. Permit not required to dispose of:
		Authorized at a permitted POTW if the produced water originates from conventional oil and gas extraction facilities or coal-bed methane extraction facilities	Low-chloride water-based drilling fluids on-site through land-farming;
			Dewatered low-chloride water-based drilling and other fluids through on-site burial; and
			Spent completion and work-over fluids through burial
North Dakota	***Authorized*** with permit from the North Dakota industrial commission	***Authorized*** at a CWT that holds an NPDES permit issued by the EPA	***Not authorized***
		Authorized at a permitted POTW if the produced water originates from conventional oil and gas extraction facilities or coal-bed methane extraction facilities	
Pennsylvania	***Authorized*** with permit from the EPA	***Authorized*** at a CWT that holds an NPDES permit issued by the PDEP	Land application ***authorized*** subject to permitting by the PDEP
		Authorized at a permitted POTW if the produced water originates from conventional oil and gas extraction facilities or coal-bed methane extraction facilities	Disposal in pits ***not authorized***

(continued)

Table 11.1 (continued)

State	Regulation of produced water disposal methods		
	Underground injection	Treatment and discharge	Land application
Ohio	***Authorized*** with permit from the Ohio Department of Natural Resources	***Authorized*** at a CWT that holds an NPDES permit issued by the Ohio Environmental Protection Agency	Road-spreading of brine produced from a vertical well ***authorized*** subject to permitting by the local authority
		Authorized at a permitted POTW if the produced water originates from conventional oil and gas extraction facilities or coal-bed methane extraction facilities	Road-spreading ***not authorized*** for:
			Brine produced from a horizontal well;
			Fluids from the drilling of a well;
			Flowback from the stimulation of a well; and
			Other fluids used to treat a well
			Disposal in pits ***not authorized*** for any fluids
Colorado	***Authorized*** with permit from the Colorado oil and gas conservation commission	***Authorized*** at a CWT that holds an NPDES permit issued by the Colorado water quality control commission	Land application ***authorized*** only for:
			Water-based bentonitic drilling fluids;
		Authorized at a permitted POTW if the produced water originates from conventional oil and gas extraction facilities or coal-bed methane extraction facilities	Produced water (outside sensitive areas only); and
			Drilling fluids and oily waste
			Disposal in pits ***authorized*** only for water-based bentonic drilling fluids and produced water
Wyoming	***Authorized*** subject to permitting by the Wyoming oil and gas conservation commission (for non-commercial wells) or Wyoming Department of Environmental Quality (for commercial wells)	***Authorized*** at a CWT that holds an NPDES permit issued by the Department of Environmental Quality	***Authorized*** subject to permitting by the oil and gas conservation commission (for disposal through road spreading or in pits) or Department of Environmental Quality (for disposal through land farming)
		Authorized at a permitted POTW if the produced water originates from conventional oil and gas extraction facilities or coal-bed methane extraction facilities	

11.5.2 Discharge to Surface Waters

In addition to underground injection, oil and gas producers also have other options for disposing of produced water, including discharging it to surface waters. Any such discharge must be permitted under the Clean Water Act (33 U.S.C. § 1251 et seq.). Section 2(a) of the Act (33 U.S.C. § 1311(a)) prohibits the "discharge of any pollutant from any point source" without a permit. A "point source" is "any discernible, confined, and discrete conveyance from which pollutants are discharged" (40 C.F.R. § 122.2). This includes the discharge of waste by oil and gas producers into surface water bodies.[6]

Section 2 of the Clean Water Act (33 U.S.C. § 1311) established a National Pollution Discharge Elimination System ("NPDES") Program, under which EPA or an authorized state agency may permit the discharge of waste to surface water. While most waste must be treated prior to discharge, there is an exemption for certain classes of oil and gas waste (40 C.F.R. § 435.32).[7] These include produced water generated from onshore facilities located west of the 98th meridian[8] with a use in agriculture or wildlife propagation (40 C.F.R. §§ 435.50, 435.52) and wastewater from facilities producing 1.6 m^3 or less of crude oil per day (40 C.F.R. § 435.60). No other oil and gas waste may be discharged without treatment.

Treatment can occur at private facilities known as centralized waste treatment facilities ("CWTs"). CWTs may be authorized, by permit, to treat and discharge produced water and/or other oil and gas waste. Such waste was, in the past, also treated and discharged by POTWs. However, as those facilities are typically designed to treat municipal wastewater with low pollutant concentrations, their treatment processes may be inadequate for highly polluted oil and gas waste. In the late 2000s, the Monogahela River in western Pennsylvania was polluted by inadequately treated oil and gas waste, discharged from a POTW. In response, the Pennsylvania Department of Environmental Protection ("PDEP") adopted regulations restricting the discharge of "wastewater resulting from fracturing, production, field exploration, drilling, or well completion of natural gas wells" (formerly 25 Pa. Code § 95.10(3)). The regulations prohibited discharges from POTWs unless the wastewater was first treated at a CWT. Because CWTs perform additional treatment processes, not undertaken by POTWs, this likely increased the costs faced by oil and gas operators. These surface water discharge costs, together with the limited

[6] Uncontaminated storm water discharges associated with oil and gas construction and field operation activities are exempt from the permitting requirements in the Clean Water Act (Kundis Craig 2013).

[7] Permits issued under the NPDES Program include limits on the maximum concentration of pollutants in the discharge, which are set based on the available treatment technologies, as well as the desired quality of the receiving water. Procedures for establishing those limits are set out in regulations adopted under the Clean Water Act (40 C.F.R. Pt. 131).

[8] The 98th meridian runs through North Dakota, South Dakota, Nebraska, Kansas, Oklahoma, and Texas.

availability of other disposal methods (e.g., underground injection), may have contributed to the high rate of recycling in Pennsylvania.

Following Pennsylvania's lead, EPA has adopted its own regulations with respect to the treatment of produced water by POTWs, which apply nationwide (40 C.F.R. pt. 435, subpt. C). The regulations establish a "zero discharge" requirement, which prevents POTWs accepting any waste from onshore facilities[9] used in the extraction of unconventional oil and gas, defined as oil and gas produced from a shale or other tight formation (40 C.F.R. §§ 435.30, 435.33). POTWs can accept waste from conventional oil and gas extraction facilities and coal-bed methane extraction facilities. Such waste must not, however, contain pollutants that will "pass through"[10] or cause "interference"[11] with the operations of the POTW (40 C.F.R. § 430.5(a)(1)). A POTW receiving such waste must specify pollutant limits, which translate the general prohibition on pass-through and interference into site-specific limitations, based on the POTW's capabilities (40 C.F.R. §§ 403.5(c), 403.8(f)(4)). All persons delivering waste to the POTW must comply with those standards.

11.5.3 Land Application

Produced water can also be disposed of on land, though this is less common than both underground injection and discharge to surface waters. There are no federal regulations governing land disposal. The practice is, however, generally regulated by the states. Regulations in five of the six oil and gas producing states examined in this chapter allow some land disposal of oil and gas waste. Three of those states—Texas, Ohio, and Colorado—restrict the types of waste that can be disposed of on land. Texas permits only low-chloride water-based drilling fluids to be disposed of through land-farming (i.e., where the waste is mixed with or applied to soil in such a manner that it will not migrate to other areas). Certain drilling and other fluids can, however, be disposed of through burial in Texas. In Colorado and Ohio, road-spreading is permitted for certain wastes that meet pollutant concentration limits.

Most states allow produced water and certain other oil and gas waste to be disposed of in earthen impoundments or pits. In Texas, for example, produced water may be disposed of in a pit with a permit from the Railroad Commission ("RRC"). The RRC may only issue a permit if it determines that the disposal will not result in

[9] "Onshore facilities" are those located landward of the inner boundary of the territorial sea (40 C.F.R. § 435.30).

[10] Clean Water Act regulations define "pass-through" as occurring where a pollutant is not removed through treatment at the POTW (40 C.F.R. § 403.3(p)).

[11] Clean Water Act regulations define "interference" as occurring where a pollutant inhibits or disrupts the POTW, its treatment processes or operations, or its sludge processes, use, or disposal, resulting in a violation of the POTW's NPDES permit, or certain statutory provisions (40 C.F.R. § 403.3(k)).

the waste of oil, gas, or geothermal resources or the pollution of surface or ground water. The permit will specify minimum requirements for pit construction and operation, designed to protect water resources. Many other states have similar requirements in their regulations. Some states, such as Colorado, also impose requirements aimed at minimizing air pollution from disposal pits. Open-air pits, where oil and waste is left to evaporate, often emit volatile organic compounds ("VOCs") which are harmful to human health and contribute to ground-level ozone formation.[12] Seeking to reduce emissions, the Colorado Air Quality Control Commission has prohibited the disposal of VOC-containing waste through evaporation, unless the so-called "RACT" (reasonably available control technology) standard is met. In broad terms, RACT reflects the degree of emissions reduction that can be achieved through application of control technology that is found to be reasonably available, considering technological and economic feasibility. Thus, compliance with the standard may require changes to pit design and/or the installation of emissions controls, thereby increasing the cost of disposal.

11.6 Regulation of Produced Water Recycling

Most produced water reuse is for EOR, though some is reused as makeup water for hydraulic fracturing fluid. These two uses require relatively minimal treatment, as there is little need for salt removal. Some states, noting the potential benefit of reusing produced water for industrial purposes, have encouraged oil and gas operators to do so through streamlined regulation.

11.6.1 Available and Emerging Recycling Technologies

Many technologies for the treatment of produced water and other oily or saline wastewaters are currently in use, and several more are under development. Ultimately, the choice of technology depends upon the quality of the produced water (discussed in Sect. 11.2), the intended fate of the treated water, the scale of treatment (i.e. the size of the plant), the duration of treatment, and the cost. In most cases, several processes will be used to meet the water quality requirements of the treated water. Produced water treatment can be broadly grouped into two categories: (1) removal of oil and solids prior to injection for disposal, EOR, or other industrial uses and (2) removal of dissolved solids and potentially toxic compounds for non-industrial beneficial reuse. Disposal via injection and EOR require less treatment than non-industrial reuse. In some cases, the quality of the produced water is such that beneficial reuse for irrigation of salt tolerant crops or livestock watering is achievable without dissolved solids removal (Fipps 2016; Higgens et al. 2016);

[12] VOCs include benzene, ethylbenzene, toluene, and xylene.

however, most non-industrial beneficial reuse applications would require some degree of salt removal. Thus, produced water treatment desalination is presently an active area of research (Fakhru'l-Razi et al. 2009; Igunno and Chen 2014; Hayes and Arthur 2004).

Most produced water treatment in the U.S. removes primarily oil and suspended solids (Stewart and Arnold 2011). Treatment technologies that remove oil and solids can be grouped roughly into three different categories: (1) gravity separation, (2) gas flotation, and (3) filtration. Both gravity separation and gas flotation take advantage of the density[13] (or specific gravity[14]) of oil droplets and suspended solids. The settling velocity, v, of a suspended particle (either oil or solid) can be estimated using Stokes Law. Specifically, given the density of a particle, ρ_p, the particle radius, R, the density and viscosity of the fluid, ρ_f and μ, and the gravitational force, g, one can predict the settling velocity of the particle per the following equation:

$$v = \frac{2\left(\rho_p - \rho_f\right) g R^2}{9\mu}$$

Thus, the settling velocity of the particle, v, will increase with the particle size, R, or the gravitational force, g. The settling velocity also increases if the difference between the density of the particle, ρ_p, and the density of water, ρ_f, increases. Thus, larger, more dense particles sink more quickly. In addition to being applied to solid particles, this equation may also be applied to oil droplets, which have a density less than that of water. The resulting negative velocity value indicates that these particles will rise to the surface rather than settle to the bottom. This theory outlines the basic principle of separation between oil, solids, and water using gravity, where oil naturally rises to the top, and solids settle to the bottom. Skimmer tanks and API separators operate on this principle. These separators work well with relatively large particles. Smaller particles (that is, particles with a smaller R) have a slower settling (or rising) velocity. Thus, to separate these particles, some assistance may be needed. This assistance may come in the form of increased settling forces (that is, increased g) imparted by a hydrocyclone or centrifuge, or induced coalescence. Coalescers are built so that particles hit an object (for example, a flat or corrugated plate), accumulate there, and are bombarded by other particles. When the particles hit each other, they coalesce into larger particles that can be separated using gravity. Enhanced coalescence may take advantage of chemical additives to induce precipitation or a filter.

Oil droplets may also be removed using gas flotation. In gas flotation, bubbles are forced through the water. Because oil droplets stick to the bubbles, the oil is

[13] The density of a material is its mass divided by its volume. For example, water has a density of approximately 1 g/cm^3.

[14] The specific gravity of a material is its density divided by the density of a reference material. The reference material often used for solids and liquids is water.

carried up by the bubbles to the top of the reactor. The foam on the top of the reactor (created by bubbles and oil) is skimmed off the surface. The efficiency of this process may be enhanced by using coagulants, polyelectrolytes, or demulsifiers to destabilize the particles suspended in the water, increasing their ability to stick to each other.

If, for a use like EOR, further particle removal is needed, filtration may be employed. Media filters use sand, anthracite coal, or nutshells. The suspended particles intercept the media particles as the produced water is forced through the media. Periodically, the media must be cleaned to remove the accumulated particles. In some cases, polymeric or ceramic ultrafiltration or even nanofiltration membranes may be used to filter water (Ashaghi et al. 2007). Membranes offer an advantage over media filtration because they can offer a high degree of particle removal with less chemical addition, they occupy a smaller footprint, and they have relatively low energy cost.

Although the technologies described above effectively remove oil and suspended solids, further treatment is required to remove dissolved solids and degrade or remove potentially harmful organic contaminants. Although these treatment processes are not widespread in the field, they are currently under development for produced water treatment applications, and they would be required if that water were to be used in non-industrial applications. (An extreme example of this would be treated produced water used for drinking water.) Dissolved solids removal is accomplished using desalination. Desalination approaches include evaporation, multi-stage flash, multi-effect distillation and mechanical vapor recompression. Most assisted evaporation technologies are very energy intensive while solar evaporation requires large land area. Some membrane processes, including forward osmosis (Coday et al. 2014) and membrane distillation (Duong et al. 2015), show promise for treating high concentration TDS produced water because they use a concentration and temperature gradient, respectively, rather than a pressure gradient to purify water. Processes such as reverse osmosis, which require very high pressures to treat high salinity water, will be limited in their application for produced water treatment (Shaffer et al. 2013), although some have used lower-pressure nanofiltration to remove divalent ions, including calcium and sulfate. Several technologies are being studied to remove potentially harmful organic chemicals from produced water. Oxidation and photocatalysis can degrade these chemicals. Chemicals may also be adsorbed onto carbon-based adsorbents, organoclays, polymers, or zeolites (Fakhru'l-Razi et al. 2009).

Removal of dissolved solids, including potentially harmful contaminants, will be necessary for non-industrial beneficial reuse applications. The applicability of these advanced produced water treatment technologies will vary by location. Desalination of produced water will likely prove more expensive than conventional treatment of freshwater and will thus probably only be applicable in regions prone to water shortages.

11.6.2 Trends in Recycling

Recycling of produced water in Pennsylvania has grown enormously in the past decade (Fig. 11.3). The primary driver for recycling in Pennsylvania is financial and driven by disposal costs, as discussed previously. However, the incentive for produced water recycling in Texas is quite different. Texas, is a more arid state than Pennsylvania, especially in the western region where the Permian Basin and Eagle Ford Shale are located. To decrease water demand for hydraulic fracturing, the Texas Legislature has encouraged operators to tap unconventional sources of water, including brackish groundwater and recycled produced water. Recycling additionally reduces water transportation costs, decreases traffic on rural roads, and thus reduces noise and wear and tear on roads. Thus, companies have a financial and regulatory incentive for water reuse (and water reuse is good for publicity). Chesapeake claims to reuse 870 m^3 per well in the Barnett Shale (Mantell 2011). In the Haynesville Shale in East Texas, where produced water is high in total dissolved solids, the company prefers to reuse the lower salinity drilling wastewater. They state that reusing produced water reduces the overall cost of operations. Fasken Oil and Ranch and Apache Corporation both limit the amount of freshwater they withdraw for hydraulic fracturing, targeting instead brackish groundwater and recycled produced water (Midland Reporter Telegram 2015). A representative of the Apache Corp. said the company treated 1.6 million m^3 of produced water in 2014, enough to fill 80,000 trucks (Boyd 2015). Although widely-available produced water recycling data is limited, the consensus from the industry and officials is that regulations (discussed below) are facilitating reuse of produced water and helping to lessen the industry's impact on water demand.

11.6.3 Regulatory Framework for Recycling

Produced water recycling is assumed to be legal throughout the U.S., though many states have yet adopted regulations with respect to the practice (Richardson et al. 2013). Of the six oil and gas producing states examined in this chapter, for example, Wyoming has no regulations governing recycling. The regulations in other states are summarized in Table 11.2 below. As indicated there, most require recycling operations to be permitted, typically by the state oil and gas regulator. The permitting requirements are intended to enhance state oversight of recycling to ensure that it is conducted safely and does not endanger public health or the environment. They may, however, have the unintended consequence of discouraging recycling by leading to burdensome and/or time-consuming reviews. Recognizing this, a number of states have recently taken steps to streamline the permitting process. One example is Pennsylvania, wherein regulations require all recycling operations to be permitted by the PDEP.[15] In 2012, the PDEP issued a general permit authorizing the recycling

[15] The PDEP is authorized to issue general permits under 25 Pa. Code § 287.612.

Table 11.2 Regulation of produced water recycling in major oil and gas producing states

State	Regulation of produced water recycling	
	Non-commercial recycling	Commercial recycling
Texas	***Authorized*** without a permit if the recycled fluid will be used as make-up water in a fracking fluid treatment or as another type of oil field fluid. In all other circumstances, a permit is required from the RRC	***Authorized*** at a commercial recycling facility that has been permitted by the RRC
North Dakota	***Authorized*** with a permit from the North Dakota industrial commission	
Pennsylvania	***Authorized*** with a permit from the PDEP. A general permit has been issued for the recycling of oil and gas liquid waste to develop or fracture a well. Persons wishing to operate under the general permit must obtain a registration from the PDEP	
Ohio	***Authorized*** with a permit from the Ohio Department of Natural Resources	
Colorado	***Authorized*** without a permit if recycling occurs at the well site. Recycling may occur off-site, at a non-commercial centralized waste management facility, that holds a permit from the Colorado oil and gas conservation commission	***Authorized*** at a facility that has been registered with the Department of Public Health and Environment
Wyoming	No state regulations	

of oil and gas liquid waste for re-use in developing or fracturing a well (PDEP 2012).[16] Oil and gas producers recycling waste for use in future operations do not, therefore, have to be permitted on an individual basis and need only register with the PDEP under the general permit (PDEP 2012, p. 2).

In half of the six oil and gas producing states, regulations differentiate between commercial and non-commercial recycling operations, with less stringent requirements applied to the latter. Texas, for example, has established a simplified permitting process for non-commercial operations. Until 2013, Texas regulations required all recycling facilities to be permitted. Although this requirement continues to apply to commercial facilities, in March 2013, state regulations were amended to allow certain non-commercial recycling without a permit. Under the amended regulations, a permit is not required for the recycling of flowback fluid at a drilling site if the recycled fluid will be used "as make-up water for a hydraulic fracturing fluid treatment(s), or as another type of oilfield fluid to be used in the wellbore of an oil, gas, geothermal, or service well" (16 Texas Administrative Code § 3.8(d)(7)(B)).

These and other similar policies should, in theory, encourage increased recycling of produced water by lowering the costs faced by oil and gas operators. Their practical effect is, however, difficult to assess as most operators do not report on the extent to which they recycle. While there is some anecdotal evidence that recycling is increasing, in many areas, the bulk of produced water is simply disposed of. This is

[16] Oil and gas liquid waste is defined to include "liquid wastes from the drilling, development and operation of oil and gas wells and transmission facilities" (PDEP 2012, p. 2).

likely due to economic factors, with studies finding that recycling is generally more expensive than disposal, particularly through underground injection (Cook et al. 2015). Operators are, therefore, unlikely to recycle wastewater absent regulatory mandates or other incentives.

To our knowledge, no state has mandated recycling. Of the six oil and gas producing states examined in this chapter, only Texas has actively sought to encourage recycling through tax incentives. Texas legislation exempts "tangible personal property specifically used to process, reuse, or recycle wastewater that will be used in fracturing work performed at an oil and gas well" from state sales, excise, and use taxes (Texas Tax Code § 151.355(7)). The Texas Legislature has also considered providing tax credits to oil and gas producers who use recycled wastewater and/or other alternatives to fresh water in their operations (H.B. 4021, 84th Legislature, Regular Session (2015)).

Texas has considered imposing restrictions on produced water disposal to encourage increased recycling. A bill introduced in the Texas Legislature in 2013 would have prohibited the disposal of produced water from wells subject to hydraulic fracturing "unless [it] is incapable of being treated to a degree that would allow [it] to be: (1) used to perform a hydraulic fracturing treatment on another oil or gas well; (2) used for another beneficial purpose; or (3) discharged into or adjacent to water in the state" (H.B. 2992, 83rd Legislature, Regular Session (2013)). Another bill, also introduced in 2013, would have imposed a fee 0.06 USD/m^3 "on oil and gas waste disposed of by injection in a commercial well" (H.B. 379, 83rd Legislature, Regular Session (2013)). Neither bill passed.

11.7 Conclusion

Increasing produced water recycling will minimize the impact of future oil and gas operations on water resources. While there is currently some recycling of produced water for EOR and industrial uses in the U.S., this and other reuse remains fairly limited in most oil and gas regions, likely due to the cost and complexity of treating produced water. Produced water is often contaminated with oil, solids, salts, metals, and hydrocarbons which must be removed or substantially reduced prior to reuse in oil and gas and/or other applications. The cost of treatment may discourage recycling if other financial incentives—such as a relatively high cost of disposal—are absent. Recycling rates may also be impacted by the regulatory framework governing produced water disposal. In Pennsylvania, for example, regulatory restrictions on surface discharge have led to increased recycling by oil and gas operators. Recycling is less common in other states, likely due to the widespread availability of disposal wells for underground injection and a permissive regulatory framework.

There have recently been a few recycling success stories in Texas. This is likely due, at least in part, to changes in the regulation of recycling. The changes removed regulatory barriers to recycling by streamlining the permitting process. Texas' experience thus suggests that states wishing to increase recycling should take steps to simplify their regulatory frameworks. Care should, however, be taken to ensure that any simplification does not compromise environmental protections. The experience of Pennsylvania, where water resources were contaminated by improperly treated produced water, highlights the need for careful oversight of produced water handling.

Pennsylvania's experience also suggests that restrictions on disposal may encourage increased recycling. While in Pennsylvania the restrictions are largely a result of geology, which limits the sites suitable for underground injection, other states could achieve similar results through regulatory action. States could, for example, adopt regulations limiting the amount or type of produced water that may be disposed of through underground injection, surface discharge, or land application. Such regulatory action seems unlikely, however, particularly in major oil and gas producing states. In those states, restricting produced water disposal could have economic impacts, leading to a slowdown in oil and gas production (i.e., due to the higher cost of recycling). This is also likely to discourage the tightening of federal disposal regulations, for example, to treat oil and gas waste as hazardous under the RCRA. In the absence of regulation, recycling is likely to remain limited, at least for the foreseeable future.

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