

Appendix F

Wastewater Treatment and Waste Disposal Supplemental Information

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Appendix F. Wastewater Treatment and Waste Disposal Supplemental Information

1 This appendix provides additional information for context and background to support the
2 discussions of hydraulic fracturing wastewater management and treatment in Chapter 8 of the
3 Hydraulic Fracturing Drinking Water Assessment. Information in this appendix includes: estimates
4 compiled for several states for volumes of wastewater generated in regions where hydraulic
5 fracturing is occurring; an overview of the technologies that can be used to treat hydraulic
6 fracturing wastewater; calculations of estimated treatment process effluent concentrations for
7 example constituents; a description of the different discharge options for centralized waste
8 treatment plants; and the water quality needed for wastewater to be reused for hydraulic
9 fracturing. Discussion is also provided on difficulties that can arise during treatment of hydraulic
10 fracturing wastewaters: the potential impacts of hydraulic fracturing wastewater on biological
11 treatment processes; and an overview of the formation of disinfection byproducts.

F.1. Estimates of Wastewater Production in Regions where Hydraulic Fracturing is Occurring

12 Table F-1 presents estimated wastewater volumes for several states in areas with hydraulic
13 fracturing activity. These data were compiled from production data available on state databases
14 and were tabulated by year. For California, data were compiled for Kern County, where about 95%
15 of hydraulic fracturing is taking place ([CCST, 2015](#)). Production records from Colorado, Utah, and
16 Wyoming include the producing formation for each well reported; data from these states were
17 filtered to select data from formations indicated in the literature as targets for hydraulic fracturing.
18 Data presented for these three states include statewide estimates as well as estimates for selected
19 basins. Data from New Mexico are available from the states in files for three basins as well as for the
20 state; these data were not filtered further.

21 Results in Table F-1 illustrate some of the challenges associated with obtaining estimates of
22 hydraulic fracturing wastewater volumes, especially using publicly available data. Some of the
23 values likely include reported values from conventional wells (wells that may not be hydraulically
24 fractured, and are typically not subject to modern, high volume hydraulic fracturing). For example,
25 the well counts for California, Colorado, Utah, and Wyoming were in the thousands or tens of
26 thousands at least as early as 2000, several years before the surge of modern hydraulic fracturing
27 began in the mid-2000s. The data used for California were from Kern County but are not specific to
28 hydraulic fracturing activity. Where producing formations are provided, the accuracy of the
29 estimates will depend upon correct selection of hydraulically fractured formations. Thus, both
30 underestimation and overestimation may be possible because of a lack of clear indication of which
31 wells were hydraulically fractured.

Table F-1. Estimated volumes (millions of gallons) of wastewater based on state data for selected years and numbers of wells producing fluid.

State	Basin	Principal lithologies	Data type	2000	2004	2008	2010	2011	2012	2013	2014	Comments
California	San Joaquin ^a	Shale, unconsolidated sands	Produced water	46,000	48,000	58,000	65,000	71,000	75,000	74,000	-	Data from CA Department of Conservation, Oil and Gas Division. ^a Produced water data compiled for Kern County. Data may also represent contributions from production without hydraulic fracturing.
			Wells	33,695	39,088	46,519	49,201	51,031	51,567	52,763	-	
Colorado	All basins with hydraulically fractured formations	-	Produced water	7,300	11,000	21,000	14,000	12,000	12,000	7,700	-	Data from CO Oil and Gas Conservation Commission. ^b Produced water includes flowback. Data filtered for formations indicated in literature as undergoing hydraulic fracturing and matched to corresponding basins. Example counties selected for presentation as well as estimated state total.
			Wells	11,264	14,934	28,282	33,929	35,999	38,371	37,618	-	
	Denver	Sandstone, shale	Produced water	140	160	170	160	160	150	110	-	
			Wells	1,829	1,511	1,277	1,204	1,193	1,131	1,072	-	
	Piceance	Sandstone	Produced water	3,500	5,800	9,300	6,900	6,500	6,800	4,300	-	
			Wells	1,134	2,478	6,486	9,105	10,057	10,868	10,954	-	

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State	Basin	Principal lithologies	Data type	2000	2004	2008	2010	2011	2012	2013	2014	Comments	
Colorado, cont.	Raton	Coalbed methane	Produced water	2,400	4,100	8,900	4,300	3,200	2,700	2,100	-		
			Wells	681	1,634	2,795	2,734	2,778	2,710	2,545	-		
	San Juan	Coalbed methane	Produced water	1,000	1,100	1,300	2,000	1,200	1,100	650	-		
			Wells	1,183	1,605	1,975	2,220	2,308	2,328	2,333	-		
New Mexico	Permian	Shale, sandstone	Produced water	-	-	-	-	-	31,000	31,000	20,000	Data from New Mexico Oil Conservation Division. ^c Data provided by the state by basin and for the entire state. Unclear how much contribution from production without hydraulic fracturing. Produced water includes flowback.	
			Wells	-	-	-	-	-	29,839	30,386	30,287		
	Raton	Coalbed methane	Produced water	-	-	-	-	-	510	540	310		
			Wells	-	-	-	-	-	1,495	1,502	1,526		
	San Juan	Coalbed methane	Produced water	-	-	-	-	-	1,700	2,000	1,100		
			Wells	-	-	-	-	-	22,492	22,349	22,076		
	Total	-		Produced water	-	-	-	-	-	33,000	34,000	22,000	
				Wells	-	-	-	-	-	53,826	54,237	53,889	

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State	Basin	Principal lithologies	Data type	2000	2004	2008	2010	2011	2012	2013	2014	Comments	
Utah	All basins with hydraulically fractured formations	-	Produced water	1,200	1,200	2,300	2,400	2,700	2,900	3,400	2,800	Data from State of Utah Oil and Gas Program. ^d Produced water includes flowback. Data filtered by formation indicated in the literature as hydraulically fractured and matched to basins. Data presented for selected basins as well as for all formations likely to be hydraulically fractured.	
			Wells	3,080	4,377	7,409	8,432	9,101	10,075	10,661	10,900		
	Kaiparowits/ Uinta	Coalbed methane	Produced water	860	740	1,300	1,400	1,800	2,000	2,400	1,900		
			Wells	1,718	2,517	3,761	4,329	4,838	5,538	6,046	6,334		
	San Juan/ Uinta	Coalbed methane	Produced water	2	49	350	270	240	230	190	120		
			Wells	62	223	910	933	959	951	867	870		
	Uinta	Shale/sandstone	Produced water	350	420	560	680	700	640	830	790		
			Wells	1,067	1,396	2,282	2,745	2,888	3,115	3,257	3,223		
	Wyoming	All basins with hydraulically fractured formations	-	Produced water	1,300	1,400	1,300	1,500	1,600	1,700	1,600	1,800	Data from Wyoming Oil and Gas Conservation Commission. ^e Produced water may include flowback. Data filtered by formation indicated in the literature as hydraulically fractured and matched to basins. Data presented for selected basins as well as for all formations likely to be hydraulically fractured.

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State	Basin	Principal lithologies	Data type	2000	2004	2008	2010	2011	2012	2013	2014	Comments
Wyoming, cont.			Wells	3,470	3,378	3,585	3,620	3,728	3,843	4,030	4,213	
	Big Horn	Sandstone	Produced water	380	350	350	380	430	440	420	440	
			Wells	365	359	387	397	412	414	407	403	
	Denver	Sandstone	Produced water	54	44	49	59	76	90	97	170	
			Wells	142	118	124	140	167	204	230	278	
	Green River	Sandstone/ shale	Produced water	0	1	2	8	5	5	9	15	
			Wells	44	44	60	67	67	59	64	67	
	Powder River	Coalbed methane	Produced water	690	630	620	660	700	840	970	1,100	
			Wells	1,953	1,900	2,001	2,028	2,119	2,207	2,352	2,565	
	Wind River/ Powder River	Sandstone/ shale	Produced water	130	330	330	400	420	290	110	41	
			Wells	966	957	1,013	988	963	959	977	900	

^a California Department of Conservation, Oil and Gas Division. Oil & Gas – Online Data. Monthly Production and Injection Databases: ftp://ftp.consrv.ca.gov/pub/oil/new_database_format/.

^b Colorado Oil and Gas Conservation Commission. Data: Downloads: Production Data: <http://cogcc.state.co.us/data2.html#/downloads>.

^c New Mexico Oil Conservation Division. Production Data. Production Summaries: All Wells Data: http://gotech.nmt.edu/gotech/Petroleum_Data/allwells.aspx.

^d Utah Department of Natural Resources. Division of Oil, Gas, and Mining. Data Research Center. Database Download Files: http://oilgas.ogm.utah.gov/Data_Center/DataCenter.cfm#production.

^e Wyoming Oil and Gas Conservation Commission. Production files by county and year: <http://wogcc.state.wy.us/productioncountyyear.cfm?Oops=#oops#&RequestTimeOut=6500>.

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F.2. Overview of Treatment Processes for Treating Hydraulic Fracturing Wastewater

1 Treatment technologies discussed in this appendix are classified as basic or advanced. Basic
2 treatment technologies are ineffective for reducing total dissolved solids (TDS) and are typically not
3 labor intensive. Advanced treatment technologies can remove TDS and/or are complex in nature
4 (e.g., energy- and labor-intensive).

F.2.1. Basic Treatment

5 Basic treatment technologies include physical separation, coagulation/oxidation,
6 electrocoagulation, sedimentation, and disinfection. These technologies are effective at removing
7 total suspended solids (TSS), oil and grease, scale-forming compounds, and metals, and they can
8 minimize microbial activity. Basic treatment is typically incorporated in a permanent treatment
9 facility (i.e., fixed location) but can also be part of a mobile unit for onsite treatment applications.

F.2.1.1. Physical Separation

10 The most basic treatment need for oil and gas wastewaters, including those from hydraulic
11 fracturing operations, is separation to remove suspended solids, and oil and grease. The separation
12 method largely depends on the type of resource(s) targeted by the hydraulic fracturing operation.
13 Down-hole separation techniques, including mechanical blocking devices and water shut-off
14 chemicals to prevent or minimize water flow to the well, may be used during production in shale
15 plays containing greater amounts of liquid hydrocarbons. To treat water at the surface, separation
16 technologies such as hydrocyclones, dissolved air or induced gas flotation systems, media (sand)
17 filtration, and biological aerated filters can remove suspended solids and some organics from
18 hydraulic fracturing wastewater.

19 Media filtration can also remove hardness and some metals if chemical precipitation (i.e.,
20 coagulation, lime softening) is also employed ([Boschee, 2014](#)). An example of a centralized waste
21 treatment facility (CWT) that uses chemical precipitation and media filtration to treat hydraulic
22 fracturing waste is the Water Tower Square Gas Well Wastewater Processing Facility in
23 Pennsylvania (see Table 8-7). One or more of these technologies is typically used prior to advanced
24 treatment such as reverse osmosis (RO) because advanced treatment processes foul, scale, or
25 otherwise do not operate effectively in the presence of TSS, certain organics, and/or some metals
26 and metalloid compounds ([Boschee, 2014](#); [Drewes et al., 2009](#)). The biggest challenge associated
27 with use of these separation technologies is solids disposal from the resulting sludge ([Igunnu and](#)
28 [Chen, 2014](#)).

F.2.1.2. Coagulation/Oxidation

29 Coagulation is the process of agglomerating small, unsettleable particles into larger particles to
30 promote settling. Chemical coagulants such as alum, iron chloride, and polymers can be used to
31 precipitate TSS, some dissolved solids (except monovalent ions such as sodium and chloride), and
32 metals from hydraulic fracturing wastewater. Adjusting the pH using chemicals such as lime or
33 caustic soda can increase the potential for some constituents, including dissolved metals, to form
34 precipitates. Chemical precipitation is often used in industrial wastewater treatment as a

1 pretreatment step to decrease the pollutant loading on subsequent advanced treatment
2 technologies; this strategy can save time, money, energy consumption and the lifetime of the
3 infrastructure.

4 Processes using advanced oxidation and precipitation have been applied to hydraulic fracturing
5 wastewaters in on-site and mobile systems. Hydroxyl radicals generated by cavitation processes
6 and the addition of ozone can degrade organic compounds and inactivate micro-organisms. The
7 process can also aid in the precipitation of elements, which cause hardness and scaling in the
8 treated water (e.g. calcium, magnesium). The process can also reduce sulfate and carbonate
9 concentrations in the treated water. This type of treatment can be very effective for on-site reuse of
10 wastewater ([Ely et al., 2011](#)).

11 The produced solid residuals from coagulation/oxidation processes typically require further
12 treatment, such as de-watering ([Duraisamy et al., 2013](#); [Hammer and VanBriesen, 2012](#)).

F.2.1.3. Electrocoagulation

13 Electrocoagulation (EC) (Figure F-1) combines the principles of coagulation and electrochemistry
14 into one process ([Gomes et al., 2009](#)). An electrical current added to the wastewater produces
15 coagulants that then neutralize the charged particles, causing them to destabilize, precipitate, and
16 settle. EC may be used in place of, or in addition to, chemical coagulation. EC can be effective for
17 removal of organics, TSS, and metals, but it is less effective for removing TDS and sulfate. Although
18 it is still considered an emerging technology for unconventional oil and gas wastewater treatment,
19 EC has been used in mobile treatment systems to treat hydraulic fracturing wastewaters
20 ([Halliburton, 2014](#); [Igunnu and Chen, 2014](#)). Limitations with this technology are the potential for
21 scaling, corrosion, and bacterial growth ([Gomes et al., 2009](#)).



Figure F-1. Electrocoagulation unit.

Source: [Dunkel \(2013\)](#).

F.2.1.4. Sedimentation

1 Treatment plants may include sedimentation tanks, clarifiers, or some other form of settling basin
2 to allow larger particles to settle out of the water where they can eventually be collected,
3 dewatered, and disposed of. These types of tanks/basins all serve the same purpose – to reduce the
4 amount of solids going to subsequent processes (i.e., overload the media filters).

F.2.1.5. Disinfection

5 Some hydraulic fracturing applications may require disinfection to kill bacteria after treatment and
6 prior to reuse. Chlorine is a common disinfectant. Chlorine dioxide, ozone, or ultraviolet light can
7 also be used. This is an important step for reused water because bacteria can cause problems for
8 further hydraulic fracturing operations by multiplying rapidly and causing build-up in the well
9 bore, which decreases gas extraction efficiency.

F.2.2. Advanced Treatment

10 Advanced treatment technologies consist of membranes (reverse osmosis (RO), nanofiltration,
11 ultrafiltration, microfiltration, electrodialysis, forward osmosis, and membrane distillation),
12 thermal distillation technologies, crystallizers, ion exchange, and adsorption. These technologies
13 are effective for removing TDS and/or targeted compounds. They typically require pretreatment to
14 remove solids and other constituents that may damage or otherwise impede the technology from
15 operating as designed. Advanced treatment technologies can be energy intensive and are typically
16 employed when a purified water effluent is necessary for direct discharge, indirect discharge, or
17 reuse. In some instances, these water treatment technologies can make use of methane generated
18 by the gas well as an energy source. Some advanced treatment technologies can be made mobile for
19 on-site treatment.

F.2.2.1. Membranes

20 Pressure-driven membrane processes including microfiltration, ultrafiltration, nanofiltration, and
21 RO (Figure F-2) are being used in some settings to treat oil and gas wastewater. These processes
22 use hydraulic pressure to overcome the osmotic pressure of the influent waste stream, forcing clean
23 water through the membrane ([Drewes et al., 2009](#)). Microfiltration and ultrafiltration processes do
24 not reduce TDS but can remove TSS and some metals and organics ([Drewes et al., 2009](#)). RO and
25 nanofiltration are capable of removing TDS, including anions and radionuclides. RO, however, may
26 be limited to treating TDS levels of approximately 40,000 mg/L TDS ([Shaffer et al., 2013](#); [Younos
27 and Tulou, 2005](#)).



Figure F-2. Photograph of reverse osmosis system.

Source: Thinkstock.

F.2.2.2. Electrodialysis

1 Electrodesialysis relies on positively and negatively charged particles and coated membranes to
2 separate contaminants from the water (Figure F-3). Electrodesialysis has been considered for use by
3 the shale gas industry, but it is not currently widely utilized ([ALL Consulting, 2013](#)). TDS
4 concentrations above 15,000 mg/L are difficult to treat by electrodesialysis ([ALL Consulting, 2013](#)),
5 and oil and divalent cations (e.g. Ca, Fe, Mg) can foul the membranes ([Hayes and Severin, 2012b](#);
6 [Guolin et al., 2008](#)).



Figure F-3. Picture of mobile electro dialysis units in Wyoming.

Source: [DOE \(2006\)](#). Permission: ALL Consulting.

F.2.2.3. Forward Osmosis/Membrane Distillation

1 Forward osmosis, an emerging technology for treating hydraulic fracturing wastewater, uses an
2 osmotic pressure gradient across a membrane to draw the contaminants from a low osmotic
3 solution (the feed water) to a high osmotic solution ([Drewes et al., 2009](#)). The selection of the
4 constituents for the draw solution is very important as the constituents should be more easily
5 removed from solution than the compounds (e.g. salts) in the feed. Alternatively, draw solutions can
6 contain components that are more easily reused or recycled. Another emerging technology,
7 membrane distillation, relies on a thermal gradient across a membrane surface to volatilize pure
8 water and capture it in the distillate ([Drewes et al., 2009](#)).

F.2.2.4. Thermal Distillation

9 Thermal distillation technologies, such as mechanical vapor recompression (MVR) (Figure F-4) and
10 dewvaporation, use liquid-vapor separation by applying heat to the waste stream, vaporizing the
11 water to separate out impurities, and condensing the vapor into distilled water ([Drewes et al.,
12 2009](#); [LEau LLC, 2008](#); [Hamieh and Beckman, 2006](#)). MVR and dewvaporation can treat high-TDS
13 waters and have been proven in the field as effective for treating oil and gas wastewater ([Hayes and
14 Severin, 2012b](#); [Drewes et al., 2009](#)). Like RO, these processes are energy intensive and are used
15 when the objective is very clean water (i.e., TDS less than 500 mg/L) for direct/indirect discharge
16 or if clean water is needed for reuse. As with membrane processes, scaling is an issue with these
17 technologies, and scale inhibitors may be needed for them to operate effectively ([Igunnu and Chen,
18 2014](#)).



Figure F-4. Picture of a mechanical vapor recompression unit near Decatur, Texas.

Source: [Drewes et al. \(2009\)](#). Permission provided.

- 1 CWTs such as the Judsonia Central Water Treatment Facility in Arkansas, and the Casella-Altela
- 2 Regional Environmental Services and Clarion Altela Environmental Services, both in Pennsylvania,
- 3 have NPDES permits and use MVR or thermal distillation for TDS removal. Figure F-5 shows a
- 4 diagram of the treatment train at another facility, the Maggie Spain facility in Texas, which uses
- 5 MVR in its treatment of Barnett Shale wastewater ([Hayes and Severin, 2012a](#)).

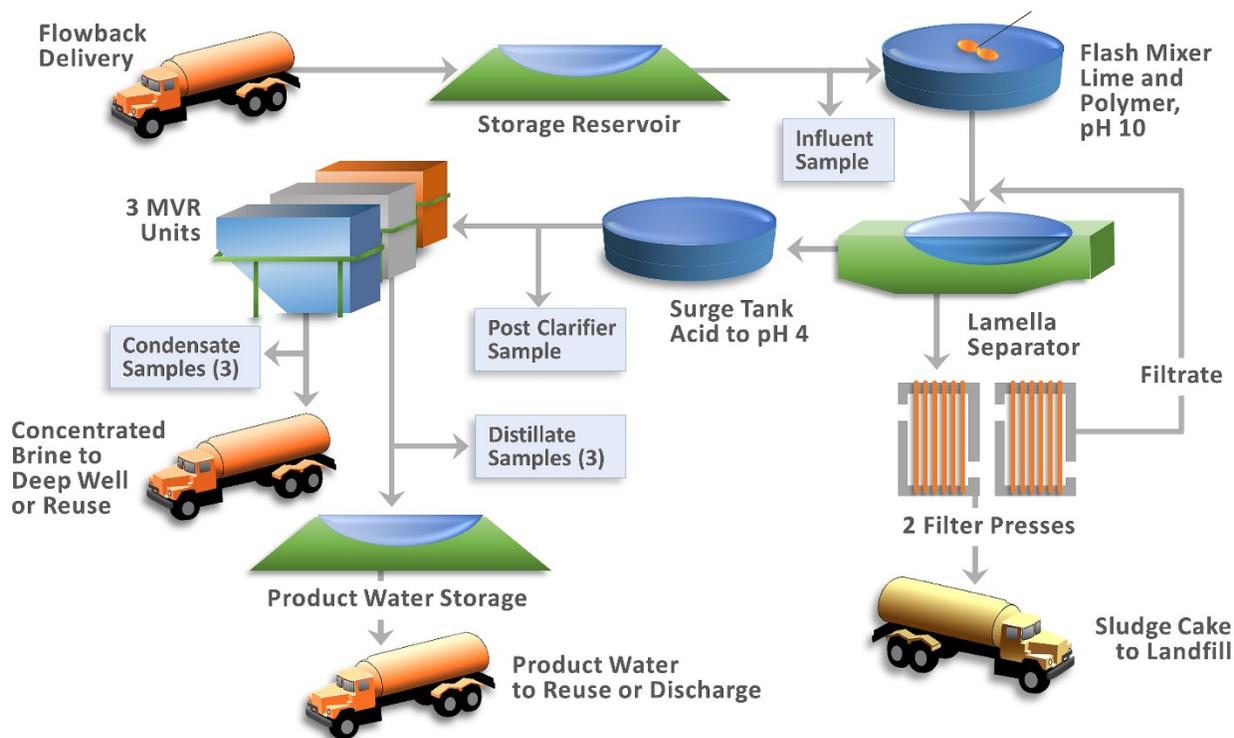


Figure F-5. Mechanical vapor recompression process design – Maggie Spain Facility.

Adapted from: [Hayes and Severin \(2012a\)](#).

- 1 Crystallizers can be employed at CWTs to treat high-TDS waters or to further concentrate the waste
- 2 stream from a distillation process, reducing residual waste disposal volumes. The crystallized salt
- 3 can be landfilled, deep-well injected, or used to produce pure salt products that may be salable
- 4 ([Ertel et al., 2013](#)).
- 5 Another thermal method, freeze-thaw evaporation, involves spraying wastewater onto a freezing
- 6 pad, allowing ice crystals to form, and the brine mixture that remains in solution to drain from the
- 7 ice ([Drewes et al., 2009](#)). In warmer weather, the ice thaws and the purified water is collected. This
- 8 technology cannot treat waters with high methanol concentrations and is only suitable for areas
- 9 where the temperature is below freezing in the winter months ([Igunnu and Chen, 2014](#)). In
- 10 addition, freeze-thaw evaporation can only reduce TDS concentrations to approximately 1,000
- 11 mg/L, which is higher than the 500 mg/L TDS surface water discharge limit required by most
- 12 permits ([Igunnu and Chen, 2014](#)).

F.2.2.5. Ion Exchange and Adsorption

- 13 Ion exchange (Figure F-6) is the process of exchanging ions on a media referred to as resin for
- 14 unwanted ions in the water. Ion exchange is used to treat for target ions that may be difficult to
- 15 remove by other treatment technologies or that may interfere with the effectiveness of advanced
- 16 treatment processes.



Figure F-6. Picture of a compressed bed ion exchange unit.

Source: [Drewes et al. \(2009\)](#). Permission provided.

- 1 Adsorption is the process of adsorbing contaminants onto a charged granular media surface.
- 2 Adsorption technologies can effectively remove organics, heavy metals, and some anions ([Igunnu](#)
- 3 [and Chen, 2014](#)). With ion exchange and adsorption processes, the type of resin or adsorptive
- 4 media used (e.g., activated carbon, organoclay, zeolites) dictates the specific contaminants that will
- 5 be removed from the water ([Drewes et al., 2009](#); [Fakhru'l-Razi et al., 2009](#)).

- 6 Because they can be easily overloaded by contaminants, ion exchange and adsorption treatment
- 7 processes are generally used as a polishing step following other treatment processes or as a unit
- 8 process in a treatment train rather than as stand-alone treatment ([Drewes et al., 2009](#)). Stand-alone
- 9 units require more frequent regeneration and/or replacement of the spent media making these
- 10 technologies more costly to operate ([Igunnu and Chen, 2014](#)). Figure F-7 shows a schematic of the
- 11 Pinedale Anticline Water Reclamation Facility located in Wyoming, which uses an ion exchange unit
- 12 with boron-selective resin as a polishing step to treat hydraulic fracturing wastewater specifically
- 13 for boron ([Boschee, 2012](#)).

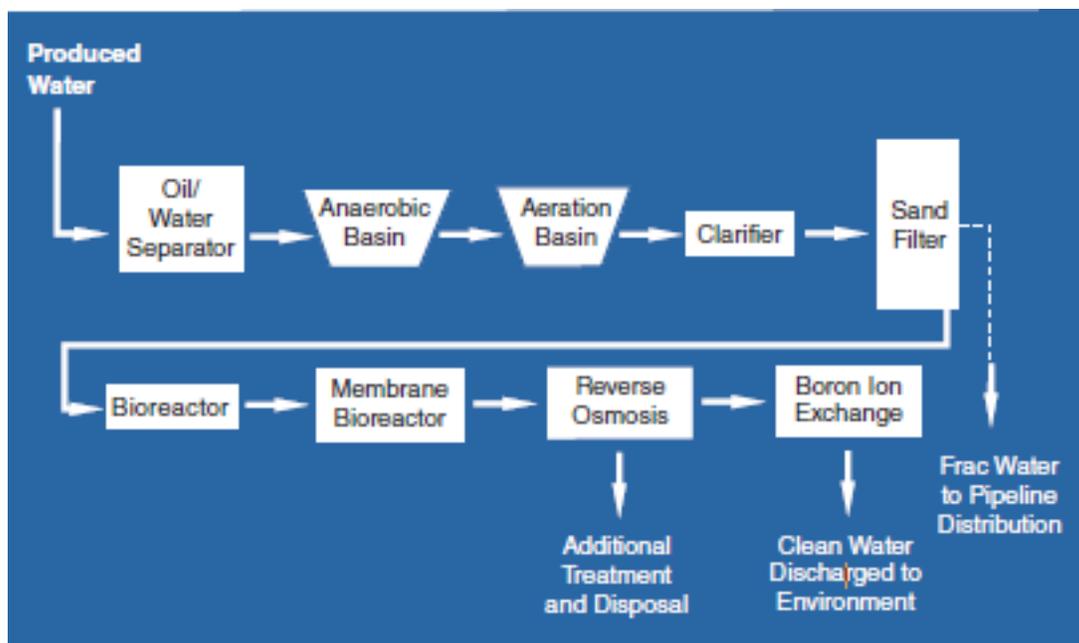


Figure F-7. Discharge water process used in the Pinedale Anticline field.

Source: [Boschee \(2012\)](#).

F.3. Treatment Technology Removal Capabilities

1 Table F-2 provides removal efficiencies for common hydraulic fracturing wastewater constituents
 2 by treatment technology. With the exception of TSS and TDS, the studies cited demonstrate removal
 3 for a subset of constituents in a category (e.g., [Gomes et al., 2009](#)) reported that electro dialysis was
 4 an effective treatment for oil and grease, not all organics). The removal efficiencies include ranges
 5 of 1 to 33% (denoted by +), 34% to 66% (denoted by ++), and greater than 66% removal (denoted
 6 by +++). Cells denoted with "--" indicate that the treatment technology is not suitable for removal of
 7 that constituent or group of constituents. If a particular treatment technology only lists removal
 8 efficiencies for TDS, it can be assumed that in some cases, cations and anions would also be
 9 removed by that technology; therefore, where specific results were not provided in literature, cells
 10 denoted with "Assumed" refer to cations and anions that comprise TDS.

Table F-2. Removal efficiency of different hydraulic fracturing wastewater constituents using various wastewater treatment technologies.^a

Treatment Technology	Hydraulic Fracturing Wastewater Constituents					
	TSS	TDS	Anions	Metals	Radio-nuclides	Organics
Hydrocyclones	+++ (Duraisamy et al., 2013)	--	--	--	--	++ (Duraisamy et al., 2013)
Evaporation (freeze-thaw evaporation)	+++ (Igunnu and Chen, 2014 ; Drewes et al., 2009)	+++ (Igunnu and Chen, 2014 ; Drewes et al., 2009 ; Arthur et al., 2005)	Assumed	+++ (Igunnu and Chen, 2014 ; Drewes et al., 2009 ; Arthur et al., 2005)	--	+++ (Igunnu and Chen, 2014 ; Duraisamy et al., 2013 ; Drewes et al., 2009)
Filtration (granular media)	+++ (Barrett, 2010)	--	--	+++ ^b (Duraisamy et al., 2013)	--	+++ (Shafer, 2011 ; Drewes et al., 2009)
Chemical precipitation	+++ (Fakhru'l-Razi et al., 2009)	--	--	+++ (Fakhru'l-Razi et al., 2009 ; AWWA, 1999)	+++ ^c (Zhang et al., 2014)	+++ (Fakhru'l-Razi et al., 2009)
Sedimentation (clarifier)	++ (NMSU DACC WUTAP, 2007)	--	--	--	--	--
Dissolved air flotation	+++ (Shammas, 2010)	--	--	--	--	++/+++ (Duraisamy et al., 2013 ; Fakhru'l-Razi et al., 2009)
Electro-coagulation	+++ (Igunnu and Chen, 2014 ; Bukhari, 2008)	--	--	+ (Igunnu and Chen, 2014)	--	+++ (Igunnu and Chen, 2014 ; Duraisamy et al., 2013 ; Fakhru'l-Razi et al., 2009)
Advanced oxidation and precipitation	--	+ (Abrams, 2013)	--	+ /+++ (Abrams, 2013)	--	+++ ^d (Duraisamy et al., 2013) (Fakhru'l-Razi et al., 2009)

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Treatment Technology	Hydraulic Fracturing Wastewater Constituents					
	TSS	TDS	Anions	Metals	Radio-nuclides	Organics
Reverse osmosis	--	++/+++ ^e (Alzahrani et al., 2013 ; Drewes et al., 2009)	+++ (Alzahrani et al., 2013) (Arthur et al., 2005)	++/+++ ^f (Alzahrani et al., 2013) (Drewes et al., 2009 ; AWWA, 1999)	+++ (Drewes et al., 2009)	+//+/+++ ^g (Drewes et al., 2009 ; Munter, 2000)
Membrane filtration (UF/MF)	+++ (Arthur et al., 2005)	--	--	+++ (Fakhru'l-Razi et al., 2009)	--	++/+++ (Duraismy et al., 2013 ; Fakhru'l-Razi et al., 2009 ; Hayes and Arthur, 2004 ; AWWA, 1999) ^h
Forward osmosis	--	+++ (Drewes et al., 2009)	Assumed	Assumed	--	--
Distillation, including thermal distillation (e.g., mechanical vapor recompression (MVR))		+++ ⁱ (Hayes et al., 2014 ; Bruff and Jikich, 2011 ; Drewes et al., 2009)	+++ (Bruff and Jikich, 2011 ; Drewes et al., 2009)	+++ (Hayes et al., 2014 ; Bruff and Jikich, 2011 ; Drewes et al., 2009)	+++ (Bruff and Jikich, 2011 ; Drewes et al., 2009)	+//+/+++ (Hayes et al., 2014 ; Duraismy et al., 2013 ; Drewes et al., 2009 ; Fakhru'l-Razi et al., 2009)
Ion exchange	--	--	+++ (Drewes et al., 2009)	+++ (Drewes et al., 2009 ; Arthur et al., 2005)	+++ (Drewes et al., 2009)	+//+/+++ (Fakhru'l-Razi et al., 2009 ; Munter, 2000) ^j
Crystallization	--	+++ (ER, 2014)	Assumed	Assumed	--	--
Electrodialysis	--	+++ ^k (Drewes et al., 2009 ; Gomes et al., 2009 ; Arthur et al., 2005)	++/+++ (Banasiak and Schäfer, 2009)	+//+/+++ (Banasiak and Schäfer, 2009)	--	+++ (Gomes et al., 2009)
Capacitive deionization (emerging technology)	--	+++ ^l (Drewes et al., 2009)	--	--	--	--

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Treatment Technology	Hydraulic Fracturing Wastewater Constituents					
	TSS	TDS	Anions	Metals	Radio-nuclides	Organics
Adsorption ^m	--	--	+ /++ /+++ ⁿ (Habuda-Stanic et al., 2014)	+++ (Igunnu and Chen, 2014 ; Drewes et al., 2009)	--	+ /++ /+++ (Arthur et al., 2005 ; Hayes and Arthur, 2004 ; Munter, 2000)
Biological treatment	+++ (Igunnu and Chen, 2014 ; Drewes et al., 2009)	--	--	--	--	+ /++ /+++ (Igunnu and Chen, 2014 ; Drewes et al., 2009 ; Fakhru'l-Razi et al., 2009)
Constructed wetland/reed beds	++ /+++ (Manios et al., 2003)	+ (Arthur et al., 2005)	--	++ /+++ (Fakhru'l-Razi et al., 2009)	--	+ /+++ (Fakhru'l-Razi et al., 2009 ; Arthur et al., 2005)

^a To the extent possible, removal efficiencies are based on an individual treatment technology that does not assume extensive pretreatment or combined treatment processes. However, it should be noted that some processes cannot effectively operate without pretreatment (e.g., RO, media filtration, sedimentation).

^b Pretreatment (pH adjustment, aeration, solids separation) required.

^c Radium co-precipitation with barium sulfate.

^d The Fenton process.

^e Typically requires pretreatment. Not a viable technology if TDS influent >50,000 mg/L.

^f Iron and manganese oxides will foul the membranes.

^g Some organics will foul the membranes (e.g., organic acids).

^h Ultrafiltration membrane was modified with nanoparticles.

ⁱ Can typically handle high TDS concentrations.

^j Resin consisted of modified zeolites that targeted removal of BTEX.

^k Influent TDS for this technology should be <8,000 mg/L.

^l Specific technology was an electronic water purifier which is a hybrid of capacitive deionization. Influent TDS for this technology should be <3,000 mg/L.

^m Typically polishing step, otherwise can overload bed quickly with organics.

ⁿ Removal efficiency is dependent on the type of adsorbent used and the water quality characteristics (e.g., pH).

- 1 Given the variety of properties among classes of organic constituents, different treatment processes
- 2 may be required depending upon the types of organic compounds needing removal. Table F-3 lists
- 3 treatment processes and the classes of organic compounds they can treat.

Table F-3. Treatment processes for hydraulic fracturing wastewater organic constituents.

Treatment processes	Organic compounds removed	References
Adsorption with activated carbon	Soluble organic compounds	Fakhru'l-Razi et al. (2009)
Adsorption with organoclay media	Insoluble organic compounds	Fakhru'l-Razi et al. (2009)
Aeration	Volatile organic compounds	Tchobanoglous et al. (2013)
Dissolved air flotation	Volatile organic compounds, dispersed oil	Drewes et al. (2009)
Freeze/thaw evaporation ^a	TPH, volatile organic compounds, semi-volatile organic compounds	Duraisamy et al. (2013) ; Drewes et al. (2009)
Ion exchange (with modified zeolites)	BTEX, chemical oxygen demand, biochemical oxygen demand	Hayes et al. (2014) ; Duraisamy et al. (2013) ; Drewes et al. (2009) ; Fakhru'l-Razi et al. (2009) ; Munter (2000)
Distillation	BTEX, polycyclic aromatic hydrocarbons (PAHs)	Hayes et al. (2014) ; Duraisamy et al. (2013) ; Drewes et al. (2009) ; Fakhru'l-Razi et al. (2009) .
Chemical precipitation	Oil & grease	Drewes et al. (2009) ; Fakhru'l-Razi et al. (2009)
Chemical Oxidation	Oil & grease	Drewes et al. (2009) ; Fakhru'l-Razi et al. (2009)
Media filtration (walnut shell media or sand)	Oil & grease	Drewes et al. (2009) ; Fakhru'l-Razi et al. (2009)
Microfiltration	Oil & grease	Drewes et al. (2009) ; Fakhru'l-Razi et al. (2009)
Ultrafiltration	Oil & grease, BTEX	Drewes et al. (2009) ; Fakhru'l-Razi et al. (2009)
Reverse osmosis ^b	Dissolved organics	Drewes et al. (2009) ; U.S. EPA (2005)
Electrocoagulation	Chemical oxygen demand, Biochemical oxygen demand	Fakhru'l-Razi et al. (2009)
Biologically aerated filters	Oil & grease, TPH, BTEX	Fakhru'l-Razi et al. (2009)
Reed bed technologies	Oil & grease, TPH, BTEX	Fakhru'l-Razi et al. (2009)
Hydrocyclone separators	Dispersed oil	Drewes et al. (2009)

^a Technology cannot be used if the methanol concentration in the hydraulic fracturing wastewater exceeds 5%.

^b RO will remove specific classes of organic compounds with removal efficiencies dependent on the compound's structure and the physical and chemical properties of the hydraulically fractured wastewater. Organoacids will foul membranes.

- 1 Table F-4 presents estimated effluent concentrations that could be produced by a variety of unit
 2 treatment processes for several example constituents and for various influent concentrations. This

1 analysis uses treatment process removal efficiencies from literature used to develop Table F-2 and
2 average wastewater concentrations of several constituents presented in Chapter 7 and Appendix E.
3 These estimates were done to illustrate the combined effects of influent wastewater composition
4 and treatment process choice on achievable effluent concentrations. The removal efficiencies
5 represent a variety of studies, primarily at bench and pilot scale, and done with either conventional
6 or hydraulic fracturing wastewater. Removal efficiency for a given treatment process can vary due
7 to a number of factors, and constituent removal may be different in a full-scale facility that uses
8 several processes. Thus, the calculations shown in Table F-4 are intended to be rough
9 approximations for illustrative purposes.

Shale/ Sandstone Play	Contaminant	MCL	Avg. Influent Conc.	Units	Freeze-Thaw Evaporation	Media Filtration	Chemical Precipitation	Flotation (DAF)	Electro-coagulation	Advanced Oxidation and precipitation	Reverse osmosis	Membrane Filtration (UF/MF)	Distillation	Ion exchange	Electrodialysis	Adsorption	Biological Treatment (bioreactors, BAFs)	Constructed Wetland
Devonian Sandstone	Radium 226	--	2400	pCi/L			120 - 1700				24		24 - 71	170				
Marcellus	Radium 228	--	120	pCi/L			6.2 - 85				1.2		1.2 - 3.6	8.4				
Marcellus	Total Radium	5	2500	pCi/L			130 - 1800				25		25 - 76	180				
Barnett	TOC	--	9.8	mg/L								0.2				0.98 - 2.9	2.1 - 4	1
Marcellus	TOC	--	160	mg/L								3.2				16 - 48	35 - 58	16
Cotton Valley	TOC	--	200	mg/L								4				20 - 59	44 - 71	20
Barnett	BOD	--	580	mg/L					58					290 - 440			29 - 87	47
Marcellus	BOD	--	40	mg/L					4					20 - 30			2 - 6	3.2
Barnett	O&G	--	160	mg/L		16						16			8	1.6	43	9.8
Marcellus	O&G	--	74	mg/L		7.4						7.4			3.7	0.74	19	4.4
Barnett	Benzene	5	680	µg/L	68							310	6.8			110		ND
Marcellus	Benzene	5	360	µg/L	36							170	3.6			58		ND
Barnett	Toluene	1,000	760	µg/L	76							350				84		ND
Marcellus	Toluene	1,000	1100	µg/L	110							510				120		ND
Barnett	Ethylbenzene	700	29	µg/L	2.9											3.2		ND
Marcellus	Ethylbenzene	700	150	µg/L	15											17		ND
Barnett	Xylenes	10,000	360	µg/L	36							170				14		ND
Marcellus	Xylenes	10,000	1300	µg/L	130							600				52		ND
Barnett	BTEX	--	1800	µg/L	180				7.3				91	270 - 550	3.7 - 91			

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Shale/ Sandstone Play	Contaminant	MCL	Avg. Influent Conc.	Units	Freeze-Thaw Evaporation	Media Filtration	Chemical Precipitation	Flotation (DAF)	Electro-coagulation	Advanced Oxidation and precipitation	Reverse osmosis	Membrane Filtration (UF/MF)	Distillation	Ion exchange	Electrolysis	Adsorption	Biological Treatment (bioreactors, BAFs)	Constructed Wetland
Marcellus	BTEX	--	2900	µg/L	290					12			150	440 - 870		5.8 - 150		
Barnett	Naphthalene	--	240	µg/L						0.95								
Marcellus	Naphthalene	--	360	µg/L						1.4								
Barnett	1,2,4- Trimethyl- benzene	--	170	µg/L						0.69								
Marcellus	1,2,4- Trimethyl- benzene	--	430	µg/L						1.7								
Barnett	1,2,4- Trimethyl- benzene	--	59	µg/L						0.24								
Marcellus	1,2,4- Trimethyl- benzene	--	310	µg/L						1.2								

ND = Non-detect

F.4. Centralized Waste Treatment Facilities and Waste Management Options

1 CWTs are designed to treat for site-specific wastewater constituents so that the effluent meets the
2 requirements of the designated disposal option(s) (i.e., reuse, direct/indirect discharge). The most
3 basic treatment processes that a CWT might use include ([Easton, 2014](#); [Duhon, 2012](#)):

- 4 • Physical treatment technologies such as dissolved air or gas flotation technologies, media
5 filtration, hydrocyclones, and clarification;
- 6 • Chemical treatment technologies such as chemical precipitation and chemical oxidation;
7 and
- 8 • Biological treatment technologies such as biological aerated filter systems and reed beds.

9 While these technologies are effective at removing oil and grease, suspended solids, scale-forming
10 compounds, and some heavy metals, if TDS should be reduced as required by the intended disposal
11 option, advanced processes such as RO, thermal distillation, or evaporation are necessary.

F.4.1. Discharge Options for CWTs

12 Direct discharge CWTs are allowed to discharge treated wastewater directly to surface waters
13 under the NPDES permit program. Discharge limitations may be based on water quality standards
14 in the NPDES and technology-based effluent limitation guidelines under 40 CFR Part 437. In
15 addition, permitting authorities have permitted facilities for discharge under 40 CFR 435, Subpart
16 E. Judsonia Central Water Treatment Facility in Sunnydale, Arkansas is permitted to directly
17 discharge treated effluent from produced and flowback waters from the Fayetteville Shale play to
18 Byrd pond located on the property. Pinedale Anticline Field Wastewater Treatment Facility in
19 Wyoming, WY, originally designed to treat produced water from tight gas plays in the Pinedale
20 Anticline Field to levels suitable for reuse, was upgraded to include RO treatment for discharge to a
21 local river. CWTs with NPDES discharge permits may also opt to treat oil and gas wastewater for
22 reuse. Some facilities have the ability to treat wastewater to different qualities (e.g., with or without
23 TDS removal), which they might do to target various reuse water quality criteria. Both the Judsonia
24 facility and Pinedale facility discussed above have the ability to employ either TDS- or non-TDS-
25 removal treatment depending on the customers' needs.

26 Indirect discharge CWTs may treat hydraulic fracturing wastewater and then discharge the treated
27 wastewater effluent to a POTW. Discharge to the POTW is controlled by an Industrial User
28 mechanism, which incorporates pretreatment standards established in 40 CFR Part 437. Two
29 facilities located in Pennsylvania (Eureka Resources) and Ohio (Patriot Water Treatment) include
30 indirect discharge as an option in wastewater treatment. The Eureka-Williamsport facility accepts
31 wastewater (primarily from the Marcellus Shale play) and either treats it for reuse or discharges it
32 to the local POTW. The Patriot facility offers services to hydraulic fracturing operators in the
33 Marcellus and Utica Shale plays for removal of solids and metals using chemical treatment. As of
34 March 2015, however, the Patriot facility is limited by the Ohio Environmental Protection Agency in
35 accepting only "low salinity" (<50,000 mg/L TDS) produced water and may only discharge 100,000
36 gallons (380,000 L) per day to the Warren Ohio POTW.

1 Zero-discharge CWTs do not discharge treated wastewater; instead, the wastewater is treated and
 2 reused in subsequent hydraulic fracturing operations. [WVWRI \(2012\)](#) state that this practice
 3 reduces potential effects on surface drinking water sources by reducing both direct and indirect
 4 discharges. Zero-discharge facilities may offer different levels of treatment including minimal
 5 treatment (for example, filtration), low-level treatment (chemical precipitation), and/or advanced
 6 treatment (evaporation, crystallization). Reserved Environmental Services (RES) Mt. Pleasant,
 7 Pennsylvania, is a zero liquid discharge facility permitted by PA DEP to treat wastewater from the
 8 Marcellus Shale play for reuse. Residual solids are dewatered and sent to a landfill. Treated
 9 wastewater effluent is stored, monitored, and chlorinated for reuse ([ONG Services, 2015](#)).

F.5. Water Quality for Reuse

10 As of 2015, there is no consensus on the water quality requirements for reuse of wastewater for
 11 hydraulic fracturing, and operator opinions vary on the minimum standards for the water quality
 12 needed for fracturing fluids ([Vidic et al., 2013](#); [Acharya et al., 2011](#)). Table F-5 provides a list of
 13 constituents and the recommended or observed target concentrations for reuse applications. The
 14 wide concentration ranges for many constituents (e.g., TDS ranges from 500 to 70,000 mg/L),
 15 suggest that water quality requirements for reuse are dictated by operation-specific requirements,
 16 including operator preference and selection of fracturing fluid chemistry.

Table F-5. Water quality requirements for reuse.

Source: [U.S. EPA \(2015g\)](#).

Constituent	Reasons for Limiting Concentrations	Recommended or observed base fluid target concentrations (mg/L, after blending) ^b
TDS	Fluid stability	500 – 70,000
Chloride	Fluid stability	2,000 – 90,000
Sodium	Fluid stability	2,000 – 5,000
<i>Metals</i>		
Iron	Scaling	1 – 15
Strontium	Scaling	1
Barium	Scaling	2 – 38
Silica	Scaling	20
Calcium	Scaling	50 – 4,200
Magnesium	Scaling	10 – 1,000
Sulfate	Scaling	124 – 1,000
Potassium	Scaling	100 – 500
Scale formers ^a	Scaling	2,500

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Constituent	Reasons for Limiting Concentrations	Recommended or observed base fluid target concentrations (mg/L, after blending) ^b
Other		
Phosphate	Not Reported	10
TSS	Plugging	50 – 1,500
Oil	Fluid stability	5 – 25
Boron	Fluid stability	0 – 10
pH (S.U.)	Fluid stability	6.5 – 8.1
Bacteria (counts/mL)	Bacterial growth	0 – 10,000

^a Includes total of barium, calcium, manganese, and strontium.

^b Unless otherwise noted.

1 Wastewater quality can be managed for reuse by either blending it with freshwater and allowing
 2 dilution to bring the concentrations of problematic constituents to an acceptable range or through
 3 treatment ([Veil, 2010](#)). Treatment, if needed, can be conducted at facilities that are mobile, semi-
 4 permanent modular systems, or fully permanent CWTs ([Nicot et al., 2012](#)). At a minimum, hydraulic
 5 fracturing service providers generally prefer that the wastewater be treated to remove TSS,
 6 microorganisms, and constituents that form scale or inhibit crosslinking in gelled fluid systems
 7 ([Boschee, 2014](#)). Figure F-8 shows a schematic of a treatment system to treat wastewater for reuse
 8 that can remove suspended solids, hardness, and organic constituents.

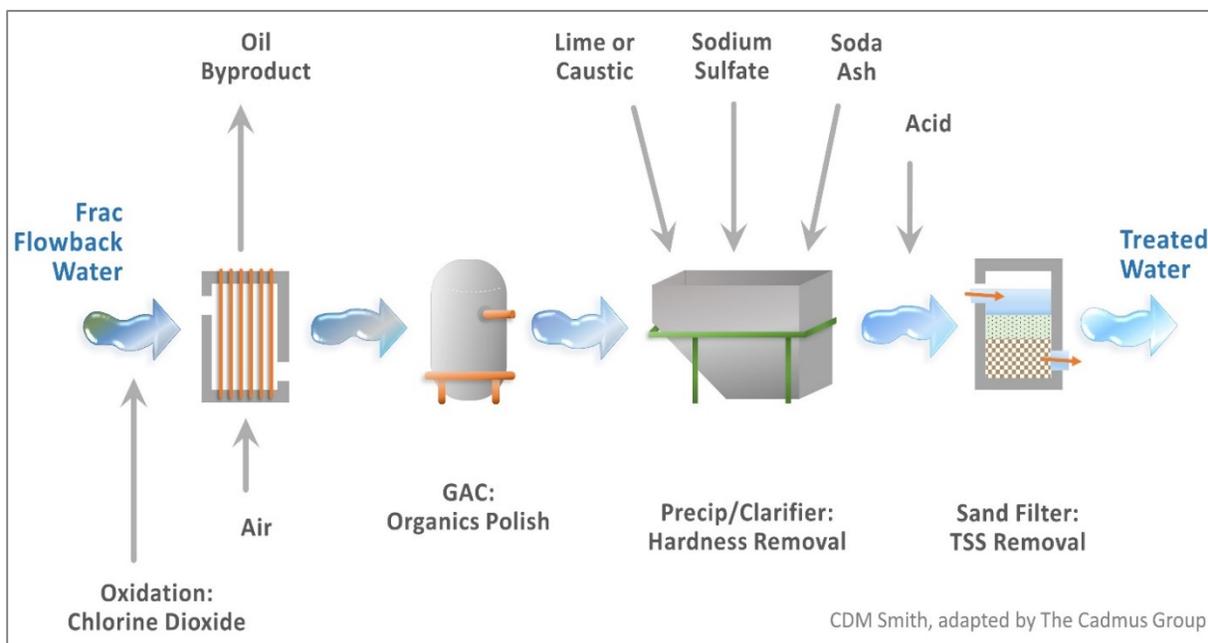


Figure F-8. Diagram of treatment for reuse of flowback and produced water.

Source: [Kimball \(2010\)](#).

- 1 In the Marcellus, the wastewater to be reused is first generally treated with oil/gas-water
 2 separation, filtration, and dilution ([Ma et al., 2014](#)). Although many Marcellus treatment facilities
 3 only supply basic reuse treatment that removes oil and solids, advanced treatment facilities that
 4 use techniques such as RO or distillation methods are also in operation ([Veil, 2010](#)).
- 5 Reuse concerns can vary with the type of hydraulic fracturing fluid used (e.g., slickwater, linear gel,
 6 crosslinked gel, foam) ([Wasylishen and Fulton, 2012](#)) and the anticipated changes in water
 7 chemistry over time (transition from flowback to produced water) ([Hammer and VanBriesen,
 8 2012](#)). Elevated TDS is a concern, but residual constituents from previous fluid mixtures (e.g.,
 9 breakers) may also cause difficulties when reusing water for subsequent fracturing operations
 10 ([Montgomery, 2013](#); [Walsh, 2013](#)).
- 11 *On-Site Treatment for Reuse*
- 12 On-site systems that treat produced water for reuse can reduce potential impacts to drinking water
 13 resources associated with transportation and disposal and facilitate the logistics of reuse by
 14 preparing the water close to well sites. These systems sometimes consist of mobile units containing
 15 one or more treatment processes that can be moved from site to site to treat waters in newly
 16 developed sites that are not yet producing at full-scale. Semi-permanent facilities that serve a
 17 specific area also exist ([Halldorson, 2013](#); [Boschee, 2012](#)).
- 18 Treatment systems are typically tailored for site-specific produced water chemical concentrations
 19 and desired water quality treatment goals, including whether significant TDS removal is needed. If

1 low TDS water is needed, more advanced treatment will be required (see Section 8.5 of Chapter 8),
2 which can increase the treatment costs to three to four times higher than for treatment systems
3 that do not remove TDS ([Halldorson, 2013](#)). On-site facilities may be warranted where truck
4 hauling or seasonal accessibility to and from a central facility is an issue ([Boschee, 2014](#); [Tiemann
et al., 2014](#)). Operators may also consider on-site facilities if they have not fully committed to an
5 area and the well counts are initially low. In those instances, they can later decide to add or remove
6 units based on changing production volumes ([Boschee, 2014](#)).
7

F.6. Hydraulic Fracturing Impacts on POTWs

F.6.1. Potential Impacts on Treatment Processes

8 Wastewater treatment processes used by POTWs are generally not designed or operated for
9 wastewater containing high salt concentrations (>0.1-5% salt). Four basic problems for biological
10 treatment of saline water have been described ([Woolard and Irvine, 1995](#)): 1) microbes in
11 conventional treatment systems tend to be sensitive to changes in ionic strength, 2) microbial
12 metabolic functions are disrupted leading to decreased degradation of carbon compounds, 3)
13 effluent suspended solids are increased due to cell lysis and/or a reduction in organisms that
14 promote flocculation, and 4) the extent of salt acclimation is limited in conventional systems.

15 Biological pre-treatment may be beneficial as an added process in pre-treatment (e.g. prior to
16 indirect discharge from a CWT to a POTW) for removal of organic contaminants. Specialized
17 treatment systems using salt-tolerant bacteria may be beneficial as an additional level of treatment
18 for pre-treating (or polishing) wastewaters in centralized treatment systems. (These processes
19 differ from conventional biological processes in standard wastewater treatment, which are not
20 suitable for large volumes of UOG wastewater.) In particular, membrane bioreactors (MBRs) have
21 been examined for the treatment of oil and gas wastewater ([Dao et al., 2013](#); [Kose et al., 2012](#);
22 [Miller, 2011](#)). MBRs provide advantages over conventional aeration basin processes as they can be
23 implemented into existing treatment trains more easily and have a much smaller footprint than
24 aeration basins.

25 Because sudden increases in chloride concentration, above 5-8 g/L, may cause problems for
26 wastewater treatment ([Ludzack and Noran, 1965](#)). POTWs planning to accept indirect discharge in
27 the future may find it valuable to restrict influent salt concentrations to a level that will not disturb
28 existing biological treatment processes.

F.7. Hydraulic Fracturing and DBPs

F.7.1.1. Disinfection By-Products

29 This section provides background information on disinfection by-products (DBPs) and their
30 formation to support the discussion in Section 8.6.1 of Chapter 8 regarding impacts on surface
31 waters and downstream drinking water utilities due to elevated bromide and iodide in hydraulic
32 fracturing wastewaters.

1 Regulated DBPs are a small subset of the full spectrum of DBPs that include other chlorinated and
2 brominated DBPs as well as nitrogenous and iodated DBPs. Some of the emerging unregulated
3 DBPs may be more toxic than their regulated counterparts ([Harkness et al., 2015](#); [McGuire et al.,
4 2014](#); [Parker et al., 2014](#)). Of the many types of DBPs that can form when drinking water is
5 disinfected, SDWA's Stage 1 and Stage 2 DBP Rules regulate four total trihalomethanes (TTHMs),
6 five haloacetic acids (HAA5s), bromate, and chlorite ([U.S. EPA, 2006](#)).

7 Most brominated DBPs form when water containing organic material and bromide reacts with a
8 disinfectant such as chlorine during drinking water treatment. Parameters that affect DBP
9 formation include concentration and type of organic material, disinfectant concentration, pH, water
10 temperature, and disinfectant contact time. In addition, many studies have found that elevated
11 bromide levels correlate with increased DBP formation ([Singer, 2010](#); [Obolensky and Singer, 2008](#);
12 [Matamoros et al., 2007](#); [Hua et al., 2006](#); [Yang and Shang, 2004](#)). Some studies found similar results
13 for iodide as well ([McGuire et al., 2014](#); [Parker et al., 2014](#)). [Pope et al. \(2007\)](#) reported that
14 increased bromide levels are the second best indicator of DBP formation, with pH being the first.

15 In addition, research finds that higher levels of bromide and iodide contribute to increased
16 concentrations of the brominated and iodated forms of DBPs (both regulated and unregulated),
17 which tend to be more cytotoxic, genotoxic, and carcinogenic than chlorinated species ([McGuire et
18 al., 2014](#); [Parker et al., 2014](#); [States et al., 2013](#); [Krasner, 2009](#); [Richardson et al., 2007](#)). Studies
19 generally report that the ratios of halogen incorporation into DBPs reflect the ratio of halogen
20 concentrations in the source water ([Criquet et al., 2012](#); [Jones et al., 2012](#); [Obolensky and Singer,
21 2008](#)).

22 From a regulatory perspective, elevated bromide levels create difficulties in meeting drinking water
23 MCLs. When the TTHMs are predominately in the form of brominated DBPs, the higher molecular
24 weight of bromide (79.9 g/mol) relative to chloride (35.5 g/mol) causes the overall mass of the
25 TTHM sum to increase. This can lead to elevated concentrations of TTHM, in turn potentially
26 leading to violations of the TTHM MCL for the drinking water utility ([Francis et al., 2009](#)).

27 High bromide levels are also cited as causing formation of nitrogenous DBP N-
28 nitrosodimethylamine (NDMA) in water disinfected with chloramines ([Luh and Mariñas, 2012](#)).
29 Although NDMA is not regulated by the EPA as of early 2015, it is listed as a priority toxic pollutant,
30 and the EPA is planning to evaluate NDMA and other nitrosamines as candidates for regulation
31 during the six-year review of the Microbial and Disinfection Byproducts (MDBP) rules ([U.S. EPA,
32 2014a](#)).

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