

Analysis of regulatory framework for produced water management and reuse in major oil and gas producing regions in the United States

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Table S1. General Permit WMGR123 Appendix A (39 constituents) from Pennsylvania.

Constituent	Limit
Aluminum (mg/L)	0.2
Ammonia (mg/L)	2
Arsenic (µg/L)	10
Barium (mg/L)	2
Benzene (µg/L)	0.12
Beryllium (µg/L)	4
Boron (mg/L)	1.6
Bromide (mg/L)	0.1
Butoxyethanol (mg/L)	0.7
Cadmium (µg/L)	0.16
Chloride (mg/L)	25
Chromium (µg/L)	10
COD (mg/L)	15
Copper(µg/L)	5
Ethylene glycol (µg/L)	13
Gross Alpha (pCi/L)	15
Gross Beta (pCi/L)	1000
Iron (mg/L)	0.3
Lead (µg/L)	1.3
Magnesium (mg/L)	10
Manganese (mg/L)	0.2
MBAS (surfactants)	0.5
Methanol (mg/L)	3.5
Molybdenum (mg/L)	0.21
Nickel (mg/L)	0.03
Nitrite-nitrate nitrogen (mg/L)	2

Oil & grease (mg/L)	ND
pH	6.5-8.5
Radium (pCi/L)	5
Selenium (µg/L)	4.6
Silver (µg/L)	1.2
Sodium (mg/L)	25
Strontium (mg/L)	4.2
Sulfate (mg/L)	25
TDS (mg/L)	500
Toluene (Methylbenzene) (mg/L)	0.33
TSS (mg/L)	45
Uranium (µg/L)	30
Zinc (mg/L)	0.065

Table S2. Alternative screening matrix for the produced water reuse in Oklahoma, prepared by the Produced Water Working Group.

Scenario	Water Use	County	Potential User(s)	Volume of Water Needed (BPD)	Volume of Water Produced in the county (BPD)	Treatment required	Regulatory Challenges	Selected for Economic Evaluation
1.a	Agriculture/ Irrigation	Texas	Heimsoth Partners	217,739	149,403	Y	Y	N
1.b		Texas	Russell Family Partnership	449,499	149,403	Y	Y	N
1.c		Texas	Fischer Family Farms LP	227,681	149,403	Y	Y	N
1.d		Texas	Stephens Land & Cattle Co Inc.	195,477	149,403	Y	Y	N
1.e		Texas	Chemical Spray for Agriculture/ Irrigation	<10,000	149,403	Y	Y	N
2.a	Power	Pawnee	Oklahoma Gas and Electric Company	1,550,729	93,787	Y	Y	Y
2.b		Oklahoma	Oklahoma Gas and Electric Company	203,617	191,323	Y	Y	N
2.c		Seminole	Oklahoma Gas and Electric Company	743,499	329,065	Y	Y	Y

3.a	Mining	Dewey	Kauk Mike and LaDena	223,199	122,762	Y	Y	N
4.a	Industrial	Muskogee	Georgia-Pacific Consumer Products (Manufacturing of Consumer Products, Tissue)	752,741	4,108	Y	Y	N
4.b		Kay	Phillips Refinery	131,748	173,719	Y	Y	N
4.c		Garfield	Koch (Chemical Manufacturing)	238,095	146,793	Y	Y	N
4.d		Grant	Medford OK Natural Gas Liquids Fractionator	30,000	109,502	Y	Y	Y
5.a	Reuse Clean Brine- oil and Gas	Alfalfa to Blaine	Oil and Gas - Transfer Produced Water from Mississippi Lime to Stack Play	250,000	600,560	Y	Y	Y
6.a	Aquifer Storage and Recovery- Oil and Gas	Alfalfa	Oil and Gas - Store treated produced water in saline aquifer	NA	600,560	Y	Y	N
7.a	Surface Water Discharge	Beckham	Irrigation - Lugert-Altus Irrigation District	1,819,025	22,323	Y	Y	Y
7.b		Grant	Salt Fork Arkansas River (downstream of Great Salt Plains Lake)	NA	109,502	Y	Y	Y

BPD: barrel per day.

NA: not available.

Table S3. Cost estimates for ten produced water use scenarios in Oklahoma, prepared by the Produced Water Working Group.

Case	Case Description	Total Capital (\$Millions)	Capacity BWPD	County	Assumed water TDS (mg/L)	Normalized \$/BW
1	Typical Source and Disposal- STACK &SCOOP	NA	NA	Central OK	NA	1.09
2	Oil and gas reuse (treatment cost only)	NA	NA	State-wide	NA	0.57
3	Clean Brine Transfer & treatment	208	200,000	Alfalfa	213,000	1.03
4	Evaporation - low TDS (SCOOP & STACK)	NA	20,000+	Blaine	17,000	1.66
5	Evaporation - high TDS (Miss. Lime)	NA	20,000+	Alfalfa	213,000	1.79
6	Desalination for Surface Discharge	22	15,000	Beckham	9,000	3.58
7	Desalination for Power Use	88	130,000	Pawnee	125,000	4.37
8	Desalination for Power Use	95	230,000	Seminole	180,000	4.43
9	Desalination for Industrial Use	35	30,000	Grant	227,000	7.41
10	Desalination for Surface Discharge	38	30,000	Grant	227,000	7.49

BW: barrel water. BWPD: barrel of water per day.

Table S4. Recommended Irrigation Water Risk-Based Comparison (RBC) Levels (mg/L) in California.

Inorganics		Organics	
Arsenic	0.1	Acetone	20,000
Barium	2,000	Benzene	0.7
Boron	70	Ethylbenzene	6
Cadmium	70	Ethylene Glycol	5000
Chromium (VI)	0.4	Methylene Chloride	2
Fluoride	700	Naphthalene	200
Mercury	20	PAHs	0.02
Thallium	10	Toluene	500
Zinc	2,000	Total Petroleum Hydrocarbons	200
		Trimethylbenzene	200
		Xylenes	1000

Table S5. Oil and Gas wells permitting in Colorado Division of Water Resources

Extraction only			Beneficial Use after Extraction	
	Tributary	Non-tributary	Tributary	Non-tributary
CBM well	Permit required	Permit required	Permit required	Permit required
	Replace depletion*	No replace depletion	Replace depletion	No replace depletion
Non-CBM	No permit required	No permit required	Permit required	Permit required
	Replace depletion	No replace depletion	Replace depletion	No replace depletion

* Replace depletions that impact an over-appropriated stream.

Table S6. Groundwater standards in Colorado

Inorganic		Organic Compounds	
Contaminants	Concentration	Contaminants	Concentration µg/L
TDS	< 1.25x background	Benzene	5
Chloride	< 1.25x background	Toluene	560-1000
Sulfate	< 1.25x background	Ethylbenzene	700
		Xylenes (Total)	1400-10,000
		Liquid hydrocarbons, including condensate and oil	Below detection level

Table S7. Soil quality criteria for road spreading of produced water in Colorado.

Inorganic		Organic Compounds	
Contaminants	Concentration mg/kg	Contaminants	Concentration mg/kg
Arsenic	0.39	TPH	500
Barium (Total)	15,000	Benzene	0.17
Boron	2 mg/L	Toluene	85
Cadmium	70	Ethylbenzene	100
Chromium (III)	120,000	Xylenes (total)	175
Chromium (VI)	23	Acenaphthene	1000
Copper	3100	Anthracene	1000
Lead	400	Benz(a)anthracene	0.22
Mercury	23	Benzo(b)fluoranthene	0.22
Nickel (soluble)	1600	Benzo(k)fluoranthene	2.2
Selenium	390	Liquid hydrocarbons including condensate and oil	Below detection level
Silver	390		
Zinc	23,000		
pH	6-9		
SAR	<12		
EC	<4 mS/cm or 2x background		

Table S8. Regulatory guidelines for road application of waste and wastewater in Wyoming.

Testing criteria	Limit
pH	6-9
TDS	-
Radium 226	60 pCi/L
Toxicity Characteristic Leaching Procedure (TCLP) for solids and sludges	
Total for water samples	
Benzene	0.5 mg/L
TOX	0.13 mg/L
Arsenic	5 mg/L
Barium	100 mg/L
Cadmium	1 mg/L
Chromium	5 mg/L
Lead	5 mg/L
Mercury	0.2 mg/L
Selenium	1 mg/L
Silver	5 mg/L
%Solids	N/A
%TPH	N/A
%Water	N/A
TPH	N/A
(Method 418.1)	
TPH (Cumulative)	1.5 lbs/ft ²

Note: The WOGCC will allow a total constituent analysis (TOX) to be substituted for the halogenated organics listed in the TCLP constituents provided the following conditions are met:

1. The TOX test has a detection level of 0.1 mg/l;
2. The TOX test is run on a fluid extracted in accordance with the TCLP procedure;
3. If the TOX concentration exceeds any one of the appropriate individual constituent regulatory levels an analysis will be required for all individual TCLP constituents; and
4. The analysis of non-halogenated constituents may be required by the WOGCC, as necessary.

Table S9. CBM permitting guideline for discharges to irrigated drainages of the Powder River Basin, Wyoming.

	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Outfall	<p>Monitor: Flow, EC, SAR, pH, HCO₃</p> <p>Threshold: EC >7500 µS/cm pH=6.5-9.0</p> <p>Effluent limits: downstream class 2&3 water protection</p> <p>Corrective Action: DEQ enforcement action</p>	<p>Monitor: Same as Scenario 1.</p> <p>Threshold: EC >7500 µS/cm pH=6.5-9.0; Effluent limits: downstream class 3 water protection.</p> <p>Corrective Action: Same as Scenario 1.</p>	<p>Monitor: Same as Scenario 1.</p> <p>Threshold: EC limit (published soil EC threshold value /1.5. Limit SAR (3-10) to < 6.67 x EC (dS/m) -3.33</p> <p>If smectite soils, additional SAR restrictions.</p> <p>Corrective Action: Same as Scenario 1; If exceedance of E.C. or SAR: curtail direct discharge quantity</p>	<p>Monitor: Same as Scenario 1.</p> <p>Threshold: Effluent limits calculated using waste load allocation, discharge limits calculated using historic median streamflow during irrigation season.</p> <p>Corrective Action: Same as Scenario 1.</p>
Reservoir	<p>Monitor: EC, SAR, pH, HCO₃, water elevation & volume</p> <p>Threshold: E.C.>150% outfall E.C.; USDA soil EC/1.5; SAR: Hanson 2006</p> <p>Additional E.C. for smectite clays*</p> <p>Corrective Action: If flowing seep found, cease discharge, repair, or close reservoir. E.C.>150% outfall E.C., cease discharge or scenario 2</p>	<p>Monitor: Same as Scenario 1.</p> <p>Threshold: Flowing seep visibly below reservoir</p> <p>Corrective Action: If flowing seep appears below reservoir, then cease discharge at outfall, repair, or close reservoir.</p>	N/A	N/A
Ephemeral Channel	<p>Monitor: Flow, pH, E.C., Ca, Mg, Na, K, SO₄, HCO₃, carbon isotopes</p> <p>Threshold: N/A</p>	N/A	<p>(Becoming perennialized Stream Channel)</p> <p>Monitor: Same as Scenario 1</p>	Same as Scenario 3

	Corrective Action: N/A		Threshold: Same as Outfall in Scenario 3.	
			Corrective Action: exceeded over multiple months, adjust outfall limits downward, or eliminate contributing discharges.	
Groundwater	<p>Monitor: Water level, pH, E.C., Ca, Mg, Na.</p> <p>Intensified monitor: additional K, SO₄, HCO₃, Cl, carbon isotopes</p> <p>Threshold: Lateral migration into stream channels, groundwater flow to irrigated fields.</p> <p>Corrective Action: If CBM causes groundwater elevation, cease outfall discharges.</p>	Same as Scenario 1	N/A	N/A
Shallow Groundwater	<p>Monitor: Same as groundwater.</p> <p>Threshold: First threshold groundwater < 6 feet.</p> <p>Second threshold < 3 feet</p> <p>Corrective Action: If first met, detect cause & corrective action; If the second met, cease discharges</p>	N/A	Same as Scenario 1	N/A
Soils	<p>Monitor: For initial, texture, clay mineralogy, ESP, pH, E.C., SAR, SO₄, HCO₃, lime, O.C., N, P, K. For ongoing: pH, E.C., SAR, SO₄, HCO₃, Cl.</p>	N/A	Same as Scenario 1	Same as Scenario 1

	<p>Threshold: EC/SAR increase >15% or >40% annually; ESP > 10% or EC > 4,000 μS/cm.</p> <p>Corrective Action: Reduce discharges, change discharge locations, improved drainage chemical amendments to fields</p>			
Crops/ Forage	<p>Monitor: yield (tons/acre), crude protein (C.P.), Ca, P, K (annually); Se (Bi-annually).</p> <p>Threshold: Statistically significant decrease in yield or quality</p> <p>Corrective Action: Reclamation of any damaged fields.</p>	N/A	Same as Scenario 1	Same as Scenario 1

Table S10. Wyoming Department of Environmental Quality parameter list for produced water for beneficial use for land application.

pH	4.5 - 9.0 s.u.	4,6-dinitro-o-cresol	1.5 µg/L
TDS	480.0 mg/L	2,4-dinitrophenol	39 µg/L
Electrical Conductivity (EC)	750 micromhos/cm@25°C	2-nitrophenol	ND
Sodium Adsorption Ratio (SAR)	8 -10	4-nitrophenol	300 µg/L
Chloride (Cl)	100 mg/L	p-chloro-m-cresol	1.4 mg/L
Sulfates (SO ₄ 2-)	192 mg/L	pentachlorophenol	1 µg/L
Bicarbonates (HO ₃ -)	Not greater than 50 percent of the total anion concentration in meq/L	phenol	11 mg/L
Aluminum (Al)	5 mg/L	2,4,6-trichlorophenol	4.1 µg/L
Ammonia (NH ₃ -N)	30 mg/L	acenaphthene	2 mg/L
Antimony	0.006 mg/L	acenaphthylene	1 mg/L
Arsenic (As)	0.01 mg/L	anthracene	10 mg/L
Barium (Ba)	2 mg/L	benzidine	0.00039 µg/L
Beryllium (Be)	0.1 mg/L	benzo(a)anthracene	ND
Boron (B)	0.6 mg/L	benzo(a)pyrene	0.2 µg/L
Cadmium (Cd)	0.01 mg/L	3,4-benzofluoranthene	ND
Chromium (Cr)	0.1 mg/L	benzo(g,h,i) perylene	ND
Cobalt (Co)	0.05 mg/L	benzo(k)fluoranthene	2.5 µg/L
Copper (Cu)	0.2 mg/L	bis(2-chloroethoxy) methane	59 µg/L
Cyanide (CN)	0.2 mg/L	bis(2-chloroethyl) ether	0.0816 µg/L
Fluoride (F)	4 mg/L	bis(2-chloroisopropyl) ether	ND
Hydrogen Sulfide(H ₂ S)	4.2 µg/L	bis (2-ethylhexyl) phthalate	6 µg/L
Iron (Fe)	5 mg/L	4-bromophenyl phenyl ether	ND
Lead (Pb)	5 mg/L	butylbenzyl phthalate	16 µg/L
Lithium (Li)	0.1 mg/L	2-chloronaphthalene	ND

Manganese (Mn)	0.2 mg/L	4-chlorophenyl phenyl ether	ND
Mercury (Hg)	2 µg/L	chrysene	89.7 µg/L
Molybdenum	0.2 mg/L	dibenzo(a,h)anthracene	0.012 µg/L
Nickel (Ni)	0.2 mg/L	1,2-dichlorobenzene	600 µg/L
Nitrate (NO ₃ -N)	10 mg/L	1,3-dichlorobenzene	3 mg/L
Nitrite (NO ₂ -N)	1 mg/L	1,4-dichlorobenzene	75 µg/L
(NO ₃ +NO ₂)-N	10 mg/L	3,3'-dichlorobenzidine	0.13 µg/L
Oil & Grease	10 mg/L	diethyl phthalate	30 mg/L
Phenol	11 mg/L	dimethyl phthalate	ND
Selenium (Se)	0.02 mg/L	di-n-butyl phthalate	ND
Silver (Ag)	0.2 mg/L	2,4-dinitrotoluene	67 µg/L
Strontium	20 mg/L	2,6-dinitrotoluene	33 µg/L
Thallium	0.002 mg/L	di-n-octyl phthalate	200 µg/L
Uranium	30 µg/L	1,2-diphenylhydrazine (as azobenzene)	0.078 µg/L
Vanadium (V)	0.1 mg/L	fluroranthene	ND
Zinc (Zn)	2 mg/L	fluorene	1.33 mg/L
RSC	1.25 meq/L	hexachlorobenzene	1 µg/L
Combined Total Radium 226 and Radium 228	5 pCi/L	hexachlorobutadiene	10 µg/L
"Gross alpha particle radioactivity (including Radium 226 but excluding Radon and Uranium)"	15 pCi/L	hexachlorocyclopentadiene	50 µg/L
Volatile Organic Compounds, Semi-Volatile Organic Compounds, Polyaromatic Hydrocarbons		hexachloroethane	40 µg/L
acrolein	17 µg/L	indeno(1,2,3-cd) pyrene	897 µg/L
acrylonitrile	0.17 µg/L	isophorone	7 mg/L
benzene	5 µg/L	N-nitrosodimethylamine	0.11 µg/L
bromoform	80 µg/L	N-nitrosodi-n-propylamine	0.00128 µg/L
carbon tetrachloride	5 µg/L	N-nitrosodiphenylamine	18.3 µg/L

chlorobenzene	100 µg/L	naphthalene	700 µg/L
chlorodibromomethane	80 µg/L	phenanthrene	1 mg/L
chloroethane	21 mg/L	pyrene	1 mg/L
chloroethylvinyl ether	ND	toluene	1 mg/L
chloroform	80 µg/L	1,2,4-trichlorobenzene	70 µg/L
dichlorobromomethane	ND	tetrachloroethylene	5 µg/L
1,1-dichloroethane	ND	Pesticides	
1,2-dichloroethane	5 µg/L	aldrin	1 µg/L
1,1-dichloroethylene	0.7 µg/L	alpha-BHC	2 µg/L
1,2-dichloropropane	5 µg/L	beta-BHC	0.050 µg/L
1,3-dichloropropylene (1,3-dichloropropene)	1 mg/L	gamma-BHC	0.2 µg/L
1,4-dioxane	1 mg/L	delta-BHC	0.2 µg/L
ethylbenzene	700 µg/L	chlordane	2 µg/L
ethylene glycol	70 mg/L	4,4'-DDT	0.264 µg/L
2-ethyl 1-hexanol	0.83 µg/L	4,4'-DDE	0.264 µg/L
MBAS (Surfactants)	0.5 mg/L	4,4'-DDD	0.374µg/L
methyl bromide	47 µg/L	dieldrin	2 µg/L
methyl chloride	ND	alpha-endosulfan	ND
methylene chloride	5 µg/L	beta-endosulfan	ND
nitrobenzene	0.7 mg/L	endosulfan sulfate	110 µg/L
1,1,2,2-tetrachloroethane	0.5 µg/L	endrin	2 µg/L
tetrachloroethylene	5 µg/L	endrin aldehyde	2 µg/L
toluene	1 mg/L	heptachlor	2 µg/L
1,2-trans-dichloroethylene	1 µg/L	heptachlor epoxide	0.2 µg/L
1,1,1-trichloroethane	0.2 mg/L	PCB-1242	0.5 µg/L
1,1,2-trichloroethane	5 µg/L	PCB-1254	0.5 µg/L
trichloroethylene	5 µg/L	PCB-1221	0.5 µg/L
vinyl chloride	2 µg/L	PCB-1232	0.5 µg/L
2-chlorophenol	0.2 mg/L	PCB-1248	0.5 µg/L

2,4-dichlorophenol	0.1 mg/L	PCB-1260	0.5 µg/L
2,4-dimethylphenol	667 µg/L	PCB-1016	0.5 µg/L
		toxaphene	3 µg/L

Note:

1. Laboratory analysis of treated produced water must be conducted according to test procedures approved under 40 CFR Part 136 unless other test procedures have been authorized in writing by the department.
2. Laboratory results for cations, anions and metals are to be reported as Total Recoverable.
3. Where laboratory methods are not capable of achieving detection at, or below the permissible limit, a result of non-detectable will be accepted provided that the method used is capable of achieving the lowest detection limit.
4. Pesticide analyses are required unless it is documented that one or more have not been used.
5. µg/L-micrograms per liter
6. mg/L-milligrams per liter
7. ND - non-detect
8. meq/L-milliequivalents per liter
9. pCi/L -picocuries per liter
10. s.u. - standard unit