Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2019: Updates Under Consideration for Produced Water Emissions

This memorandum discusses updates under consideration for EPA's 2021 *Inventory of U.S. Greenhouse Gas Emissions and Sinks* (GHGI) for produced water emissions within the natural gas and petroleum systems production sectors. The memorandum provides background and current methodology, available data, analysis of available data, regional variability and time series considerations, and updated methodology considerations and national emissions estimates.

1 Background and Current GHGI Methodology

EPA's definition of produced water is: "the water (brine) brought up from the hydrocarbon-bearing strata during the extraction of oil and gas, and can include formation water, injection water, and any chemicals added downhole or during the oil/water separation process".[1] Produced water is the largest wastewater source by volume generated during oil and gas extraction. The ratio of produced water to recovered hydrocarbon is extremely variable across the U.S. ranging from less than 1:1 to more than 100:1.[2] Produced water is also referred to as "production salt water" – the specific salinity of produced water is quite variable and is dependent upon the formation's geochemistry. The Bakken and Marcellus shale formations can have produced waters that have 10 times the salinity of seawater, while other areas may have produced water that is considerably less saline than seawater.[3,4]

The current GHGI emission calculation methodology for emissions from produced water in the Natural Gas Systems sector is limited to two individual coal bed methane (CBM) formations: Powder River Basin (in Wyoming) and Black Warrior Basin (in Alabama). The current emission calculation methodology uses relevant activity data multiplied by emission factors.

1.1 Activity Data

For the Powder River Basin, EPA obtained produced water production data from the Wyoming Oil and Gas Conservation Commission (WOGCC) in units of barrels per month.[5]

For the Black Warrior Basin, EPA obtained monthly producing well counts (beginning in April 1996) from the Alabama Oil and Gas Board (AOGB).[6] From the monthly data, EPA calculated annual average well counts beginning in 1996. EPA obtained annual well counts for the Black Warrior Basin for 1990 and 1994 from a Gas Research Institute (GRI) technical document.[7] EPA then developed annual well count estimates for 1991, 1992, 1993, and 1995 by scaling the 1994 annual well count with coalbed methane production. EPA used 2013 data as proxy data for all subsequent years (i.e., 2014 through 2018).

Table 1 presents the applicable activity data for the Powder River Basin and the Black Warrior Basin, for select years from the current methodology. Appendix A (Table A-1) provides the complete time series of activity data for each basin.

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[1] 40 CFR §435.11(bb).

[2] *Summary of Input on Oil and Gas Extraction Wastewater Management Practices Under the Clean Water Act*. Final Report. EPA-821-S19-001. U.S. Environmental Protection Agency, Engineering and Analysis Division, Office of Water. Washington, D.C. May 2020.

[3] "What is produced water?" American Geosciences Institute. Internet address: https://www.americangeosciences.org/critical-issues/faq/what-produced-water

[4] *Natural Produced Waters Geochemical Database.* U.S. Geological Survey (USGS). Internet address: https://eerscmap.usgs.gov/pwapp/

[5] Wyoming Oil and Gas Conservation Commission (WOGCC). Internet address: http://pipeline.wyo.gov/coalbedchart.cfm

[6] Alabama Oil and Gas Board (AOGB). Internet address: https://www.ogb.state.al.us/

[7] *A Guide to Coalbed Methane Reservoir Engineering*. GRI-94/0397. Gas Research Institute. 1996

Table 1. Current GHGI Produced Water Activity Data

Basin	1990	2005	2014	2015	2016	2017	2018
Powder River (10^6 gallons produced water)	25	23,422	12,670	12,670	12,670	12,670	12,670
Black Warrior (wells)	1,300	4,246	5,480	5,480	5,480	5,480	5,480

1.2 Emission Factors

For the Powder River Basin, the current GHGI applies a base emission factor (EF) of 2.0522×10^{-9} Gg CH_4/gallon of water drainage. For the Black Warrior Basin, the current GHGI applies a base EF of 2.0694×10^{-3} Gg CH_4/well. These values were developed using an assumed methane concentration in water of 542.9 mg/l (or 0.19 lbs/bbl) at 700 foot well depth. Additional details on these EFs are unavailable. The EFs are then adjusted by the year-specific methane contents for the Rocky Mountain and Gulf Coast regions, respectively.

Table 2 shows the EFs for the Powder River Basin and the Black Warrior Basin, for select years. Appendix A (Table A-2) provides the complete time series of EFs for each basin.

Table 2. Produced Water Emission Factors

Basin	1990	2005	2014	2015	2016	2017	2018
Powder River (Gg CH_4/ gallon water)	1.744×10^{-9}	2.135×10^{-9}	2.313×10^{-9}	2.328×10^{-9}	2.373×10^{-9}	2.373×10^{-9}	2.373×10^{-9}
Black Warrior (Gg/well)	2.096×10^{-3}	2.327×10^{-3}	2.334×10^{-3}	2.334×10^{-3}	2.335×10^{-3}	2.335×10^{-3}	2.335×10^{-3}

1.3 Emissions

Combining the produced water activity data (presented in Section 1.1) with the produced water emission factors (presented in Section 1.2) results in the emissions for the Powder River Basin and the Black Warrior Basin, for select years as shown in Table 3. Appendix A (Table A-3) provides the complete time series of emissions for each basin.

Table 3. Produced Water CH_4 Emissions (metric tons)

Basin	1990	2005	2014	2015	2016	2017	2018
Powder River	43	50,005	47,638	47,957	48,877	48,877	48,877
Black Warrior	2,724	9,879	12,790	12,788	12,796	12,796	12,796
Total	**2,768**	**59,884**	**60,428**	**60,745**	**61,674**	**61,674**	**61,674**

2 Analysis of Available Data

The details of available data for the update under consideration (i.e., both activity data and emission factors) are described below.

2.1 Activity Data

EPA reviewed the 2017 Nonpoint Oil and Gas Emission Estimation Tool (2017 Oil and Gas Tool)[8] to assess produced water activity data. For the 2017 Oil and Gas Tool, EPA developed source category emission estimation methodologies for 19 individual source categories; one of these source categories is produced water tanks. The activity parameter used for the produced water tanks source category was produced water production at oil wells and produced water production at gas and CBM wells; produced water production quantities are in units of barrels per year (bbl/year).

The primary data source in the 2017 Oil and Gas Tool for produced water production quantities is Enverus DrillingInfo data, but additional data sources are used for some states. The 2017 Oil and Gas Tool used the following sources of produced water activity data:

- Enverus DrillingInfo – 27 states (i.e., Alabama, Alaska, Arizona, Arkansas, California, Colorado, Florida, Kentucky, Louisiana, Michigan, Mississippi, Missouri, Montana, Nebraska, Nevada, New Mexico, New York, North Dakota, Ohio, Oklahoma, Oregon, South Dakota, Tennessee, Texas, Utah, Virginia, and Wyoming)
- State oil and gas commissions – 3 states (i.e., Idaho, Indiana, and Pennsylvania)
- State environmental agencies – 1 state (i.e., Kansas)
- Multiple sources – 3 states (i.e., Illinois [state oil and gas commission and EIA], Maryland [Enverus DrillingInfo and Energy Information Administration], and West Virginia [Enverus DrillingInfo and state environmental agency])

In general, the sources of produced water roughly parallel the sources of well counts used in the annual GHGI.

Table 4 presents the "Current Values" (i.e., year 2017 volumes) for produced water and the "Previous Values" (i.e., year 2014 volumes) for produced water, as shown in the Production Module of the 2017 Oil and Gas Tool[9]:

Table 4. 2017 NEI Production Water Volumes (bbl)

Well Type	Previous Value (Year 2014)	Current Value (Year 2017)
CBM Wells	512,318,013	378,446,711
Gas Wells	973,980,331	1,113,855,869
Oil Wells	15,545,896,708	15,858,915,589

Compared to the "Previous Values" (i.e., year 2014 volumes) for produced water from the 2017 Oil and Gas Tool Production Module, the year 2017 total produced water quantities increased by 1.9% (i.e., CBM decreased by 26.2%, gas increased by 14.4%, and oil increased by 2.0%).

For the update under consideration, EPA is assessing Enverus DrillingInfo data and the other datasets to estimate produced water volumes over the GHGI time series. EPA is also considering not distinguishing between gas wells and CBM wells, thereby combining the data to develop a single produced water volume applicable to all gas wells.

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[8] *2017 Nonpoint Oil and Gas Emission Estimation Tool, Version 1.2.* Prepared for U.S. Environmental Protection Agency by Eastern Research Group, Inc. (ERG), Morrisville, North Carolina. October 2019.
[9] See Footnote 8.

2.2 Emission Factors

There are a number of documents that address produced water emissions; however, the EFs used in all of these documents all ultimately trace back to a 1996 Gas Research Institute (GRI)/EPA study.[10] Table 5 is an extract of Table 5.5 from that document which presents methane emissions from production salt water (i.e., produced water) tanks. The emission estimates were estimated using an ASPEN PLUS process simulation, rather than actual measurements. Three key assumptions used in this simulation are as follows:

- The natural gas industry produces 497 million barrels of salt water annually, including approximately 100 million barrels from coal bed methane wells.[11]
- 70 percent of the water from gas wells is reinjected with the remaining 30 percent stored in atmospheric tanks.[12]
- Hydrocarbon composition is 100 percent methane.

Table 5. Salt Water Tank Emissions from 1996 GRI/EPA Study

Salt Content (Wt %)	Pressure (psi)	Methane Emissions (10^6 lb/yr)
20	50	1.6
	250	10.8
	1000	38.8
10	250	16.4
	1000	58.7
2	250	19.4
	1000	69.5

More recently, the 1996 GRI/EPA study produced water EFs shown in Table 5 were incorporated into the API *Compendium of Greenhouse Gas Emissions Methodologies for the Oil and Natural Gas Industry*.[13] Within the API *Compendium* (Table 5-10), the EFs were rearranged and the units were converted from units of million pounds per year to units of metric tons per thousand barrels, based upon the annual total of 497 million barrels of produced water cited in the 1996 GRI/EPA study. In addition, average EFs were calculated for each pressure (i.e., 50, 250, and 1,000 psi). Table 6 reproduces the EFs from the API *Compendium* (Table 5-10). This identical table is also included in a guidance document developed by The Climate Registry.[14]

Table 6. Produced Salt Water Tank Methane Flashing Emission Factors from API *Compendium*

Separator Pressure (psi)	Produced Water Salt Content (%)	EF (GRI/EPA initial units – 10^6 lb CH_4/year)	Converted EF (metric tons/ 1000 bbl produced water)[a]
50	20	1.6	0.0015
250	20	10.8	0.00986
	10	16.4	0.0150
	2	19.4	0.0177
	Average[b]	–	0.0142

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[10] *Methane Emissions from the Natural Gas Industry, Volume 6: Vented and Combustion Source Summary, Final Report*. GRI-94/0257.23 and EPA-600/R-96-080f. Gas Research Institute and U.S. Environmental Protection Agency. June 1996.

[11] *Atlas of Gas Related Produced Water for 1990*. 95/0016. Produced by Energy Environmental Research Center, University of North Dakota, and ENSR Consulting and Engineering for Gas Research Institute. May 1995.

[12] See Footnote 11.

[13] *Compendium of Greenhouse Gas Emissions Methodologies for the Oil and Natural Gas Industry*. Produced by URS Corporation for American Petroleum Institute. August 2009

[14] *Oil & Gas Production Protocol, Annex II to the General Reporting Protocol*, Version 1.0. The Climate Registry. February 2010.

Separator Pressure (psi)	Produced Water Salt Content (%)	EF (GRI/EPA initial units – 10^6 lb CH_4/year)	Converted EF (metric tons/ 1000 bbl produced water)[a]
1000	20	38.8	0.0354
	10	58.7	0.0536
	2	69.5	0.0634
	Average[b]		0.0508

[a] Converted EFs calculated based on 497 million barrels of produced water generated annually.
[b] Average EFs calculated based on a simple average of EFs for 2, 10, and 20 percent produced water salt content.

An early oil and gas emission inventory that included produced water emissions was the 2011 CenSARA Oil and Gas Emission Inventory.[15] The 2011 CenSARA inventory cited the produced water emission factors included in The Climate Registry document.

The Production Module of the 2017 Oil and Gas Tool[16] cited the average produced water EFs used in the 2011 CenSARA Oil and Gas Emission Inventory. The average EFs were converted to units of pounds CH_4/barrel produced water and assigned to specific well types. Table 7 summarizes the produced water EFs used in the 2017 Oil and Gas Tool. The 2017 Oil and Gas Tool applies the "low pressure oil wells" EF to oil wells that require an artificial lift to increase production. Most counties in the 2017 Oil and Gas Tool used a default average of 73 percent of oil wells using an artificial lift; this average is based on CenSARA data.

Table 7. Produced Water Emission Factors, by Well Type, from 2017 Oil and Gas Tool

Well Type	Separator Pressure (psi)	Average CH_4 EF (lb/bbl)
Low Pressure Oil Wells	50	0.0033
Regular Pressure Oil Wells	250	0.0313
Gas and CBM Wells	1000	0.112

Finally, various recent technical analyses of the U.S. oil and gas supply chain[17,18,19] cite the produced water EFs described above.

For the update under consideration, EPA is considering applying the average EFs presented in Table 7. To estimate gas well produced water emissions for the update under consideration, EPA would apply the "gas and CBM wells" EF of 0.112 lb/bbl. For comparison, the current GHGI EF (applied only to certain CBM formations) is 0.22 lb/bbl. To estimate oil well produced water emissions for the update under consideration, EPA would apply the "regular pressure oil wells" EF of 0.0.0313 lb/bbl and the "low pressure oil wells" EF of 0.0033 lb/bbl, based on the estimated population of wells that require an artificial lift. Data on the population of oil wells at various well pressures are unavailable.

3   Time Series Considerations

In general, produced water data for the entire time series are obtainable from the same datasets cited in the 2017 Oil and Gas Tool Production Module. In particular, Enverus DrillingInfo data are available over the time

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[15] *2011 Oil and Gas Emission Inventory Enhancement Project for CenSARA States*. Produced by ENVIRON International Corporation and Eastern Research Group, Inc. (ERG) for Central States Air Resources Agencies (CenSARA). December 2012.

[16] *Instructions for Using the 2017 EPA Nonpoint Oil and Gas Emissions Estimation Tool, Production Module*. Produced by Eastern Research Group, Inc. (ERG) for U.S. Environmental Protection Agency. October 2019.

[17] D. Zavala-Araiza et al., "Super-emitters in natural gas infrastructure are caused by abnormal process conditions". *Nature Communications*. January 16, 2017.

[18] R.A. Alvarez et al., Supplementary Materials for "Assessment of methane emissions from the U.S. oil and gas supply chain". *Science*. June 21, 2018.

[19] J. Littlefield et al., *Life Cycle Analysis of Natural Gas Extraction and Power Generation*. DOE/NETL-2019/2039. National Energy Technology Laboratory. April 19, 2019.

series. However, those states that rely on non-Enverus DrillingInfo data (i.e., Idaho, Illinois, Indiana, Kansas, Maryland, Pennsylvania, and West Virginia) may not have produced water volumes readily available each year. For missing data in the middle of the time series, linear interpolation will be used for gap filling. For missing data at the beginning of the time series, EPA is considering applying data from the earliest available year as a proxy value.

4   Preliminary National Emissions Estimates

EPA calculated preliminary national CH_4 emissions estimates for year 2017[20] using the following equation and by applying the produced water volumes in Table 4, the EFs in Table 7, and a default average of 73 percent of oil wells use artificial lifts (see Section 2.2). Table 8 summarizes the resulting 2017 emissions estimates.

$$Emissions_w = PW_w \times EF_w \times \left(\frac{453.6\ g}{1\ lb}\right) \times \left(\frac{1\ metric\ ton}{10^6\ g}\right)$$

Where:

Emissions$_w$	=	Annual produced water emissions from well type w (mt);
PW$_w$	=	Annual produced water quantities from well type w (bbl); and
EF$_w$	=	Emission factor for produced waste emissions from well type w (lb/bbl).

Table 8. Year 2017 Produced Water National CH$_4$ Emissions Estimates (metric tons)

Well Type	Produced Water Volume (bbl)	EF (lb/bbl)	Year 2017 Emissions (mt)
Oil Wells – Low Pressure	11,577,008,380	0.0033	17,329
Oil Wells – Regular Pressure	4,281,907,209	0.0313	60,793
Gas Wells	1,492,302,580	0.112	75,813
Total			**153,936**
Current GHGI			*61,674*
Powder River	*490,393,575*	*0.22*	*48,877*
Black Warrior	*131,591,163*	*0.21*	*12,796*

The EFs presented in Section 2.2, including the Table 7 EFs used in the preliminary estimates, rely on an assumption from the 1996 GRI/EPA study that 30 percent of generated produced water is stored in a tank and undergoes tank flashing (see the assumptions underlying the emissions data at the beginning of Section 2.2). As a result, EPA's preliminary emissions estimates implicitly assume that 30 percent of produced water undergoes tank flashing and the remaining 70 percent of produced water does not have emissions. EPA found minimal data to adjust this assumption and seeks stakeholder feedback regarding this assumption. If additional data are available regarding the percent of produced water that releases emissions (either through tank flashing emissions or evaporation in a pond), EPA will consider adjusting the EFs (i.e., increase the EF to remove the assumption that 30 percent of produced water undergoes tank flashing) and adjusting the activity data to account for the portion of produced water with emissions. The 2017 Oil and Gas Tool Production Module includes a tank storage fraction (the fraction of produced water stored in tanks based upon surveys for each state); however, most of the tank storage fraction values are defaulted to a value of 1.

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[20] Year 2017 emissions are estimated because produced water volumes from the 2017 NEI Oil and Gas Tool are readily available for that year. EPA is currently developing produced water volume estimates for the time series.

A previous survey study[21] indicated the following distribution of produced water management practices in 2012:

- Injection for enhanced oil recovery – 45.1%
- Injection for disposal – 38.9%
- Surface discharge – 5.4%
- Evaporation – 3.4%
- Offsite commercial disposal – 6.7%
- Beneficial reuse – 0.6%

Based on these produced water management practices, it is not clear what fraction of produced water actually is stored in tanks and undergoes flashing. For example, the survey study does not indicate whether produced water that is injected is stored in tanks first (in which case there would be flashing emissions) or if it is handled by other means (e.g., piping) and does not have emissions.

5   Requests for Stakeholder Feedback

EPA seeks stakeholder feedback on the update under consideration discussed in this memo and the questions below.

1. EPA seeks feedback on the fraction of oil wells that are low pressure, including whether it is reasonable to apply an average of 73 percent of oil wells using artificial lifts.
2. EPA seeks feedback on the percent of produced water that releases emissions (e.g., through tank flashing or evaporation in a pond), including whether the assumption that 30 percent of produced water undergoes tank flashing is reasonable.
3. EPA seeks feedback on updating the current GHGI EF for gas wells, currently applied to only certain CBM formations, to instead use the updated EF for all gas well produced water.

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[21] *U.S. Produced Water Volumes and Management Practices in 2012.* Produced by Veil Environmental, LLC for the Ground Water Protection Council. April 2015. Available at http://www.gwpc.org/sites/default/files/Produced%20Water%20Report%202014-GWPC_0.pdf

Appendix A: Activity Data, Emission Factors, and Emission Estimates from Current GHGI Methodology

Table A-1. Current GHGI Produced Water Activity Data

Year	Powder River Basin (gallons produced water)	Black Warrior Basin (wells)
1990	24,833,340	1,300
1991	76,253,310	1,704
1992	253,637,580	2,230
1993	258,413,526	2,581
1994	395,441,592	2,706
1995	731,194,212	2,731
1996	850,452,960	2,768
1997	1,895,693,394	2,774
1998	3,032,900,388	2,838
1999	6,429,856,860	2,873
2000	15,783,545,946	2,928
2001	21,506,423,610	3,143
2002	24,318,956,382	3,357
2003	23,791,158,888	3,669
2004	22,599,925,656	3,963
2005	23,421,598,326	4,246
2006	28,423,070,466	4,493
2007	27,554,638,356	4,764
2008	28,802,976,384	5,026
2009	23,883,321,966	5,191
2010	22,368,432,828	5,296
2011	20,596,530,150	5,462
2012	15,730,043,952	5,517
2013	12,669,783,252	5,480
2014	12,669,783,252	5,480
2015	12,669,783,252	5,480
2016	12,669,783,252	5,480
2017	12,669,783,252	5,480
2018	12,669,783,252	5,480

Table A-2. Current GHGI Produced Water Emission Factors

Year	Powder River Basin (Gg CH$_4$/gallon produced water)	Black Warrior Basin (Gg CH$_4$/well)
1990	1.744×10^{-9}	2.096×10^{-3}
1991	1.800×10^{-9}	2.104×10^{-3}
1992	1.858×10^{-9}	2.172×10^{-3}
1993	1.911×10^{-9}	2.209×10^{-3}
1994	1.966×10^{-9}	2.249×10^{-3}
1995	2.021×10^{-9}	2.289×10^{-3}
1996	1.938×10^{-9}	2.328×10^{-3}
1997	1.952×10^{-9}	2.328×10^{-3}
1998	1.966×10^{-9}	2.328×10^{-3}
1999	1.961×10^{-9}	2.328×10^{-3}
2000	1.989×10^{-9}	2.328×10^{-3}
2001	2.055×10^{-9}	2.328×10^{-3}
2002	2.097×10^{-9}	2.327×10^{-3}
2003	2.120×10^{-9}	2.327×10^{-3}
2004	2.128×10^{-9}	2.327×10^{-3}
2005	2.135×10^{-9}	2.326×10^{-3}
2006	2.151×10^{-9}	2.326×10^{-3}
2007	2.253×10^{-9}	2.327×10^{-3}
2008	2.246×10^{-9}	2.325×10^{-3}
2009	2.260×10^{-9}	2.323×10^{-3}
2010	2.260×10^{-9}	2.319×10^{-3}
2011	2.290×10^{-9}	2.316×10^{-3}
2012	2.282×10^{-9}	2.315×10^{-3}
2013	2.295×10^{-9}	2.334×10^{-3}
2014	2.313×10^{-9}	2.334×10^{-3}
2015	2.328×10^{-9}	2.334×10^{-3}
2016	2.373×10^{-9}	2.335×10^{-3}
2017	2.373×10^{-9}	2.335×10^{-3}
2018	2.373×10^{-9}	2.335×10^{-3}

Table A-3. Current GHGI Produced Water Emissions

Year	Powder River Basin (metric tons CH$_4$)	Black Warrior Basin (metric tons CH$_4$)	Total (metric tons CH$_4$)
1990	43	2,724	2,768
1991	137	3,585	3,722
1992	471	4,844	5,315
1993	494	5,701	6,195
1994	778	6,085	6,862
1995	1,478	6,251	7,729
1996	1,648	6,445	8,093
1997	3,700	6,456	10,156
1998	5,964	6,605	12,569
1999	12,612	6,688	19,300
2000	31,387	6,817	38,203
2001	44,186	7,318	51,504
2002	50,997	7,813	58,810
2003	50,432	8,538	58,970
2004	48,098	9,220	57,318
2005	50,005	9,879	59,884
2006	61,128	10,453	71,581
2007	62,082	11,087	73,169
2008	64,705	11,686	76,391
2009	53,988	12,060	66,048
2010	50,563	12,283	62,846
2011	47,173	12,648	59,822
2012	47,008	12,775	59,782
2013	47,260	12,787	60,047
2014	47,638	12,790	60,428
2015	47,957	12,788	60,745
2016	48,877	12,796	61,674
2017	48,877	12,796	61,674
2018	48,877	12,796	61,674