STATE OF NEW MEXICO
DEPARTMENT OF ENERGY, MINERALS AND NATURAL RESOURCES

OIL CONSERVATION COMMISSION

IN THE MATTER OF PROPOSED
AMENDMENTS TO THE COMMISSION'S

RULES ON PRODUCED WATER
19.15.2, 19.15.16, and 19.15.34 NMAC   CASE NO. 21281

<u>**PRE-HEARING STATEMENT OF WILDEARTH GUARDIANS**</u>

This Pre-Hearing Statement is submitted on behalf of WildEarth Guardians (Guardians)

through its undersigned counsel, as required by NMAC 19.15.3.11.B.

I.   INTRODUCTION

The Produced Water Act, as enacted through House Bill (HB) 546, authorizes the Oil

Conservation Division (OCD) to promulgate rules regulating the "disposition, handling,

transport, storage, recycling, treatment and disposal of produced water during, or for reuse in, the

exploration, drilling, production, treatment or refinement of oil or gas, including disposal by

injection pursuant to authority delegated under the federal Safe Drinking Water Act, in a manner

that protects public health, the environment and fresh water resources." NMSA 1978, § 70-2-

12.B(15). But instead of adopting scientifically-based regulations with specific, measurable

standards and practices to protect public health, the environment, and fresh water resources from

the serious threat posed by produced water, OCD's proposal simply maintains the division's

current hands-off, de-regulatory approach to managing the largest source of toxic waste in the

state. OCD's bare-bones effort to promulgate tooth-less rules falls so dramatically short of the

legislature's objective for these rules that its rulemaking effort must be suspended.

II.   BACKGROUND ON PRODUCED WATER

A. Produced Water Poses a Toxic Threat to Public Health and the Environment.

OCD's de-regulatory approach appears to assume that produced water is a relatively benign byproduct of oil and gas production. To the contrary, scientific studies show that produced water can be highly toxic, radioactive, and a clear threat to public health, the environment, and fresh water resources.

As the EPA has acknowledged, produced water contains "salts, metals, radioactive materials, dissolved organic compounds, and hydraulic fracturing [fracking] chemicals and their transformation products (the result of reactions of these chemicals in the subsurface)."[1] Produced water from shale formations "typically contains high levels of TDS (salinity) and associated ionic constituents (bromide, calcium, chloride, iron, potassium, manganese, and sodium)."[2] Studies in the New Mexico portion of the Permian Basin have shown average salinity levels of more than 89,000 mg/L in produced water, some 2.5 times higher than the 35,000 mg/L characteristic of seawater.[3] With such high salinity levels, researchers have concluded that the basin has a "Low" potential for treatment, as desalination technologies required to render produced water safe for most uses is likely to be cost-prohibitive.[4]

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[1] EPA, Hydraulic Fracturing for Oil and" Gas: Impacts from the Hydraulic Fracturing Water Cycle on Drinking Water Resources in the United States, EPA-600-R-16-236Fa at 7-1 (Dec. 2016), available at: www.epa.gov/hfstudy (attached as WildEarth Guardians Exhibit 1)

[2] *Id*. at 7-42 (Ex. 1)

[3] Benko, K.L. & J.E. Drewes, Produced Water in the Western United States: Geographical Distribution, Occurrence, and Composition, 25 Envtl. Engineering Science No. 2, 239, 243 tbl.3 (2008) (attached as WildEarth Guardians Exhibit 2)

[4] *Id*. (Ex. 2).

Further, "[p]roduced water can also contain toxic materials, including barium, cadmium, chromium, lead, mercury, nitrate, selenium, and BTEX," as well as acetone, ethylene glycol (anti-freeze), phthalates, polypropylene glycols, and dozens of other toxic chemicals.[5] Such toxics can have significant adverse impacts on human health including causing cancer[6] and disrupting the endocrine system.[7] According to EPA, the presence of volatile organic compounds (VOCs) in produced water indicates a potential for releases to the surrounding air, but due to a dearth of scientific information quantifying air pollutant emissions from produced water, EPA has been unable to draw conclusions "about the magnitude or frequency of these releases."[8] Notably, VOCs are a primary precursor pollutant leading to the formation of ozone.[9] With the two primary oil- and gas-producing regions of New Mexico experiencing significant ozone pollution problems – including the Carlsbad region, which is already out of compliance with the federal ambient air quality standard for ozone based on air monitoring data[10] – additional VOC emissions from produced water storage ponds represents an unaddressed public health threat.

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[5] EPA, *supra* note 1, at 7-4, 7-22 to -23 (Ex. 1).

[6] E.G. Elliott, Unconventional Oil and Gas Development and Risk of Childhood Leukemia: Assessing the Evidence, Science of the Total Environment 138 (2017) (attached as WildEarth Guardians Exhibit 3).

[7] C.D. Kassotis et al., Endocrine-Disrupting Chemicals and Oil and Natural Gas Operations: Potential Environmental Contamination and Recommendations to Assess Complex Environmental Mixtures, 124 Environmental Health Perspectives 3, at 256 (Mar. 2016), available at: https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4786988/pdf/ehp.1409535.pdf (attached as WildEarth Guardians Exhibit 4).

[8] EPA, Management of Exploration, Development and Production Wates: Factors Informing a Decision on the Need for Regulatory Action, at 5-29 (April 2019), available at: https://www.epa.gov/sites/production/files/2019-04/documents/management_of_exploration_development_and_production_wastes_4-23-19.pdf.

[9] New Mexico Envt. Dep't, Ozone Attainment Initiative at 5 (September 26, 2019), available at: https://www.env.nm.gov/air-quality/o3-initiative/ (last accessed July 16, 2020) (attached as WildEarth Guardians Exhibit 5).

[10] *Id*. at 7, 10, 11 (Ex. 5).

Oil- and gas-bearing geologic formations also often contain naturally radioactive

materials, which can be concentrated in fracking waste, such as produced water.[11] According to

the EPA, radionuclides commonly found in produced water include "radium, radon, uranium,

potassium and thorium,"[12] and produced water from shale formations in the Permian Basin has

been shown to contain "significant levels of uranium."[13] The extraction, storage, transportation,

recycling, and reuse of produced water thus poses a serious threat of widespread radioactive

contamination. As the EPA has acknowledged, "[o]nce oil and gas have been extracted from the

formation, workers and members of the public may be exposed to radionuclides that are brought

to the surface."[14] As a British radiation biologist has stated, "All oil-field workers are radiation

workers."[15] They just don't know it. "Tanks, filters, pumps, pipes, hoses, and trucks that

[produced water] brine touches can all become contaminated, with the radium building up" and

concentrating into a hardened and highly radioactive "scale."[16] Experts have attributed a slew of

cancers among oil workers in Louisiana to on-the-job radiation exposure with 99 percent

certainty.[17] Yet radioactive produced water is – even today – being piped and trucked across

New Mexico's oil fields without testing, without adequate protective equipment for exposed

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[11] EPA Radiation Waste Material from Oil and Gas Drilling, https://www.epa.gov/radtown/radioactive-waste-material-oil-and-gas-drilling (last accessed July 10, 2020) (attached as WildEarth Guardians Exhibit 6).

[12] *Id*. (Ex. 6).

[13] EPA, *supra* note 1, at 7-20 (Ex. 1).

[14]14 EPA, *supra* note 11 (Ex. 6).

[15] J. Nobel, America's Radioactive Secret at 6, Rolling Stone (Jan. 21, 2020), available at: https://www.rollingstone.com/politics/politics-features/oil-gas-fracking-radioactive-investigation-937389/ (attached as WildEarth Guardians Exhibit 7).

[16] *Id*. (Ex. 7).

[17] *Id*. at 9-10 (Ex. 7).

workers, and without a regulatory scheme designed to protect against this dire public health and environmental threat.

Perhaps even more concerning, of more than a thousand chemicals found by scientists in produced water samples, only 14% have established toxicity values for risk assessment in the United States.[18] In other words, the toxicity of *86%* of the chemicals found in produced water has never been studied.[19] Moreover, less than one-quarter of the nearly 1,200 chemicals identified in produced water can *even be detected* through standard analytical methods, a huge barrier to fully understand the public health and environmental impacts of produced water reuse.[20] Because of this massive data gap, in 2019, EPA found that it lacked the data necessary to quantitatively evaluate "the potential risks associated with releases to the environment" of produced water."[21]

B. OCD's Current Regulatory Scheme is Inadequate to Protect Public Health and the Environment.

In light of the clear public health and environmental risks poses by toxic, radioactive produced water, the industry's track record of managing this largely-unregulated hazardous waste is troubling to say the least. Produced water is routinely leaked and spilled, with produced water spills documented as a result of "human error, equipment or container failure (for instance, pipeline, tank or storage pit leaks), accidents, and storms," resulting in produced water spills of

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[18] C. Danforth et al., An Integrative Method for Identification and Prioritization of Constituents of Concern in Produced Water from Onshore Oil and Gas Extraction, Environment International 134, at 8 (2020) (attached as WildEarth Guardians Exhibit 8).

[19] *Id*. (Ex. 8).

[20] *Id*. at 9 (Ex. 8). *See also* EPA, supra note 1, at 7-12 (Ex. 1) (explaining that studies have shown that "standard analytical methods are not adequate for detecting and quantifying the numerous organic chemicals, both naturally occurring and anthropogenic, that are now known to occur in produced water," and "advanced analytical techniques are needed to detect or quantify some analytes.")

[21] EPA, *supra* note 8, at 5-29.

up to 2.9 million gallons and long-term impacts to soil, groundwater, and surface water.[22] EPA

data show that from 2010 to 2015, for every 100 active oil and gas wells, there were between

five to seven produced water spills *each year*.[23]

New Mexico's oil and gas industry is no outlier. OCD records show more than 7,000

documented releases of produced water within the state since July 2010, approximately two a

day.[24] Within the first six months of 2020 alone, there have been 325 reported spills of produced

water, including 171 *major* spills, as defined by OCD.[25] The EPA has connected produced water

leaks to volatile organic compound (VOC) contamination of groundwater near the Duncan Oil

Field.[26] And with a documented correlation between new oil and gas wells in the Permian Basin

and rural commercial vehicle crashes, the risk of produced water being released as a result of a

trucking accident cannot be ignored.[27]

While OCD's rulemaking authority is limited to regulating produced water reuse within

the oil industry, NMSA 1978, § 70-2-12.B.(15), the risks posed by produced water are not

simply industrial risks. Because New Mexico's oil fields are located in and around existing

communities, the storage, transportation, and reuse of produced water – even where confined to

the oil fields – still jeopardizes the health and safety of tens of thousands of New Mexicans each

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[22] EPA, supra note 1, at 7-1 (Ex. 1).

[23] *Id*. at 7-31 (Ex. 1).

[24] New Mexico Oil Conservation Division, OCD Permitting, Spill Search Database,
https://wwwapps.emnrd.state.nm.us/ocd/ocdpermitting/Data/Spills/Spills.aspx,
 last accessed (July 14, 2020).

[25] Search Results, New Mexico Oil Conservation Division, OCD Permitting, Spill Search Database,
(search parameters for Incident Date Range January 1, 2020 – June 30, 2020; Spill Material: Produced
Water (attached as WildEarth Guardians Exhibit 9).

[26] EPA, *supra* note 1, at 7-28 (Ex. 1).

[27] *Id*. at 7-40 to -41 (Ex. 1).

day, with real-world consequences. For example, earlier this year, a family home in Otis, Eddy County, was drenched after a produced water pipeline burst 200 yards away.[28] Awakened in the middle of the night by a loud pop and the sound of rushing water, the family ran outside to the smell of gas and their home, their yard and livestock, and even their bodies being soaked by a toxic rain of produced water. Yet OCD's proposed rules would do *absolutely nothing* to protect against similar incidents in the future.

III.   OCD'S PROPOSED RULES

The legislature authorized OCD to promulgate produced water regulations to protect "public health, the environment and fresh water resources" from the serious risks of toxic contamination from the vast quantities of produced water generated by the oil and gas industry. Instead of taking this charge seriously, however, OCD has rolled out the red carpet for the oil and gas industry and completely abdicated its responsibility for protecting the health and welfare of New Mexicans and the environment of the state. Despite the legislature's clear charge to develop rules to protect public health and the environment, OCD's proposed new rules provide no regulatory requirements, including measurable standards and practices, governing reuse of produced water "for drilling, completion, producing or enhanced recovery of oil or natural gas or plugging of wells," but would simply allow such uses to proceed unabated without any permitting or notice requirements. Moreover, OCD proposes to continue to allow the reuse of produced water in the treatment or refinement of oil or gas fails based on indeterminate future "[a]pproval requirements [as] will be determined by the district office based upon the proposed

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[28] K. Chamberlain, 'It was Raining on Us': Family Awoken By Produced Water Pipe Burst Near Carlsbad, NM Political Report (Jan. 24, 2020), available at: https://nmpoliticalreport.com/2020/01/24/it-was-raining-on-us-family-awoken-by-produced-water-pipe-burst-near-carlsbad/ (attached as WildEarth Guardians Ex. 10).

use." Such a kick-the-can approach fails to provide an adequate level of detail or certainly regarding future approval requirements needed to ensure that any such future uses will be conducted "in a manner that protects public health, the environment and fresh water sources." NMSA 1978, § 70-2-12.B(12).

At its core, OCD's regulatory proposal would merely align the definition of produced water with the statutory definition from the Produced Water Act and add a new reporting requirement for produced water and actual water used in fracking operations. But these minor tweaks do not provide the effective regulatory program that the New Mexico Legislature contemplated when it authorized OCD to adopt rules "to regulate" the use of produced water within the oil and gas fields "in a manner that protects public health, the environment and fresh water sources." NMSA 1978, § 70-2-12.B(12). To meet the Legislature's protection goals, OCD must regulate produced water using specific, measurable standards and practices.

OCD's vague statement that produced water shall be handled and stored "in a manner that protects public health, the environment and fresh water resources" merely repeats statutory language, but fails to detail any specific requirements or measurable standards and practices needed to effectively regulate produced water usage within the oil and gas industry. Moreover, the new reporting requirement – while a small step towards gathering information needed to fully understand the magnitude of the produced water problem – provides no new regulatory protections for public health or the environment.

Based on its proposed regulations, OCD appears either unable or unwilling to provide the robust regulatory oversight of produced water that is needed to protect public health and the environment. OCD has completely ignored the legislature's charge to adopt regulations that protect human health and the environment from the substantial risks from produced water.

Fundamentally, OCD's proposed rules lack any effective requirements or measurable standards and practices governing the safe handling and transport of produced water, of particular concern given the toxic, radioactive nature of fracking waste and the regulatory limbo that has allowed the oil and gas industry a free pass from complying with federal hazardous waste regulations.[29]

In light of the fundamental absence of effective regulatory requirements in the division's proposed rule, this rulemaking effort must be suspended until OCD has developed the internal technical competency necessary to develop scientifically-based, prescriptive regulations that actually govern the safe handling, transport, recycling, and reuse of produced water. For example, new rules should specify the manner in which produced water is to be stored to avoid environmental contamination and worker exposure; define specific worker training and certification requirements to ensure that workers handling or transporting produced water are able to safely manage this toxic waste; and regulate the manner in which produced water is to be transported. New rules should further be used to develop a produced water tracking system to ensure that the division has the means necessary to readily track the movement of produced water from the well-head to its ultimate disposition through re-use or disposal; and such rules should mandate routine water quality testing of produced water to promote better scientific understanding regarding the toxicity of produced water and to ensure the protection of public health and the environment. Instead, however, OCD's proposed rules continue the Division's de-regulatory approach to managing produced water, allowing the oil and gas industry free reign to

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[29] EPA, Exemption of Oil and Gas Exploration and Production Wastes from Federal Hazardous Waste Regulations (Oct. 2002), available at: https://yosemite.epa.gov/oa/eab_web_docket.nsf/Attachments%20By%20ParentFilingId/945EF425FA4A9B4F85257E2800480C65/$FILE/28%20-%20RCRA%20E%26P%20Exemption.pdf (attached as WildEarth Guardians Exhibit 11).

operate without oversight, contrary to the New Mexico legislature's expressed intent that OCD regulate this toxic waste product in an effective manner that "protects public health, the environment and fresh water resources," as intended by the New Mexico Legislature.

IV.   WILDEARTH GUARDIANS' PROPOSED MODIFICATIONS

Guardians fundamentally believes that it is premature to finalize new OCD rules governing produced water at this time. In light of the COVID-19 pandemic, the ability of the public to fully engage in these proceedings has been dramatically restricted. Moreover, the bare-bones proposal from OCD illustrates an apparent lack of technical competency to craft rules that ensure that produced water recycling and re-use does not threaten public health, the environment, or fresh water resources. It is incumbent that OCD take the time necessary to craft a real regulatory system that takes seriously the division's legislative charge to protect public health and the environment from toxic fracking waste, including produced water.

However, if the OCC is committed to promulgating new rules at this time, Guardians proposes the modifications detailed in red-line as Appendix A. These modifications are intended to provide a reasonable regulatory structure that meets the dual legislative purposes of protecting public health and the environment while encouraging recycling and reuse of produced water within the oil and gas industry, including the following:

- Establishment of a permitting or registration system for produced water re-use;

- Establishment of a tracking system for produced water;

- Establishment of hazardous waste training requirements for workers handling produced water;

- Establishment of requirements that ensure the safe and environmentally-protective handling and transport of produced water;

- Encouragement of produced water re-use through prohibition of the use of fresh water with total dissolved solid levels below 1,000 mg/L for fracking;

- Establishment of requirement for water quality control commission regulations to protect surface and groundwater from possible produced water contamination;

- Acknowledgment of statutory prohibition on re-use of produced water outside the oil and gas industry absent approval of such uses by the water quality control commission, and elimination of proposed language that anticipates future authorization of such non-oil field uses as a foregone conclusion.

V.   GUARDIANS' PARTICIPATION AT THE RULEMAKING HEARING

Guardians does not intend to present testimony from any technical witnesses at the hearing. Pursuant to 19.15.3.11.B.(1) NMAC, 19.15.3.12.A.2(b), (e) NMAC, and 19.15.3.12.B(3) NMAC, Guardians does request an opportunity to provide an opening statement (10 minutes) and closing statement (10 minutes), and to cross-examine witnesses at the hearing (time required dependent upon witnesses).

Respectfully submitted this 17th day of July, 2020

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Exhibits:

Exhibit 1: EPA, Hydraulic Fracturing for Oil and" Gas: Impacts from the Hydraulic Fracturing Water Cycle on Drinking Water Resources in the United States, EPA-600-R-16-236Fa (Dec. 2016), available at: www.epa.gov/hfstudy.

Exhibit 2: Benko, K.L. & J.E. Drewes, Produced Water in the Western United States: Geographical Distribution, Occurrence, and Composition, 25 Envtl. Engineering Science No. 2, 239 (2008) .

Exhibit 3: E.G. Elliott, Unconventional Oil and Gas Development and Risk of Childhood Leukemia: Assessing the Evidence, Science of the Total Environment 138 (2017).

Exhibit 4: C.D. Kassotis et al., Endocrine-Disrupting Chemicals and Oil and Natural Gas Operations: Potential Environmental Contamination and Recommendations to Assess Complex Environmental Mixtures, 124 Environmental Health Perspectives 3, at 256 (Mar. 2016), available at: https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4786988/pdf/ehp.1409535.pdf.

Exhibit 5: New Mexico Envt. Department, Ozone Attainment Initiative at 5 (September 26, 2019), available at: https://www.env.nm.gov/air-quality/o3-initiative/ (last accessed July 16, 2020).

Exhibit 6: EPA Radiation Waste Material from Oil and Gas Drilling, https://www.epa.gov/radtown/radioactive-waste-material-oil-and-gas-drilling (last accessed July 10, 2020).

Exhibit 7: J. Nobel, America's Radioactive Secret, Rolling Stone (Jan. 21, 2020), available at: https://www.rollingstone.com/politics/politics-features/oil-gas-fracking-radioactive-investigation-937389/.

Exhibit 8: C. Danforth et al., An Integrative Method for Identification and Prioritization of Constituents of Concern in Produced Water from Onshore Oil and Gas Extraction, Environment International 134 (2020).

Exhibit 9: Search Results, New Mexico Oil Conservation Division, OCD Permitting, Spill Search Database, (search parameters for Incident Date Range January 1, 2020 – June 30, 2020; Spill Material: Produced Water.

Exhibit 10: K. Chamberlain, 'It was Raining on Us': Family Awoken By Produced Water Pipe Burst Near Carlsbad, NM Political Report (Jan. 24, 2020), available at: https://nmpoliticalreport.com/2020/01/24/it-was-raining-on-us-family-awoken-by-produced-water-pipe-burst-near-carlsbad/

Exhibit 11: EPA, Exemption of Oil and Gas Exploration and Production Wastes from Federal Hazardous Waste Regulations (Oct. 2002), available at: https://yosemite.epa.gov/oa/eab_web_docket.nsf/Attachments%20By%20ParentFilingId/945EF425FA4A9B4F85257E2800480C65/$FILE/28%20-%20RCRA%20E%26P%20Exemption.pdf

APPENDIX A

PROPOSED AMENDMENTS BY WILDEARTH GUARDIANS TO THE OIL CONSERVATION DIVISION'S RULEMAKING PROPOSAL

STATE OF NEW MEXICO
ENERGY MINERALS AND NATURAL RESOURCES DEPARTMENT
OIL CONSERVATION COMMISSION

IN THE MATTER OF PROPOSED
AMENDMENTS TO THE COMMISSION'S
RULES ON PRODUCED WATER,
19.15.2, 19.15.16, AND 19.15.34 NMAC

PROPOSED AMENDMENTS BY WILDEARTH GUARDIANS TO THE
OIL CONSERVATION DIVISION'S RULEMAKING PROPOSAL

WildEarth Guardians offers the following amendments to the Oil Conservation Division's (the "division's" or OCD's") rulemaking proposal.[1]

Title 19   NATURAL RESOURCES AND WILDLIFE
CHAPTER 15   OIL AND GAS
PART 2   GENERAL PROVISIONS FOR OIL AND GAS OPERATIONS

19.15.2.7   DEFINITIONS
      P.   Definitions beginning with the letter "P".
      (10)   "Produced water" means a fluid that is an incidental byproduct from drilling for or the production of oil and gas. **Produced water shall maintain its character as produced water, irrespective of subsequent treatment, dilution, recycling, or re-use, and any water that is commingled with produced water shall thereafter be considered and regulated as produced water.**

Title 19   NATURAL RESOURCES AND WILDLIFE
CHAPTER 15   OIL AND GAS
PART 16   DRILLING AND PRODUCTION

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[1] For clarity, these amendments are presented as if the changes proposed by the Oil Conservation Division ("OCD") have been adopted. Language to be added to the OCD proposal is underlined and in bold type, and language to be removed from the OCD proposal has been struck through.

19.15.16.21 WATER USE REPORT: For a hydraulically fractured well, an operator shall report, on form C-103 or C-105, the amount of water **and produced water** reported on the disclosure required by Subsection B of 19.15.16.19 NMAC and the breakdown of that amount by type~~s~~ of **fluid, including the following categories**~~water including~~ ~~produced water, nonpoatble water and potable water~~:

    A.   **produced water;**
    B.   **water other than produced water that has 1,000 or more mg/l TDS; and**
    C.   **water other than produced water that has less than 1,000 mg/l TDS.** ~~As used in 19.15.16.21 NMAC~~
    ~~A.~~   ~~"nonpotable water" means water, other than produced water, which contains 1,000 mg/l or more of TDS; and~~
    ~~B.~~   ~~"potable water" means water, other than produced water, which contains less than 1,000 mg/l of TDS.~~
    D.   **As soon as they are received by the Oil Conservation Division, all such reports shall be:**
        1.   **posted as separate reports in the data and statistics section of the Oil Conservation Division's website;**
        2.   **posted prominently on the Oil Conservation Division section of the New Mexico Energy, Minerals & Natural Resources website;**

    E.   **By March 31 of each year, the division shall prepare and make publicly available on the division's website an annual summary report describing the prior year's total usage of produced water, water other than produced water that has 1,000 or more mg/l TDS, and water other than produced water that has less than 1,000 mg/l TDS, as reported to the division. The division shall further break down the reported categories of usage by type of use, county of use, and other metrics, as may be appropriate.**

Title 19   **NATURAL RESOURCES AND WILDLIFE**
CHAPTER 15   **OIL AND GAS**
PART 34   **PRODUCED WATER, DRILLING FLUIDS AND LIQUID OIL FIELD WASTE**

19.15.34.2   SCOPE: 19.15.34 NMAAC applies to the transportation, disposal, recycling, re-use or the direct surface or subsurface disposition of produced water in connection with the development or production of oil or gas or both. 19.15.34 NMAC also applies to the transportation of drilling fluids and

liquid oil field waste. **19.15.34 does not authorize any transportation, disposal, recycling, re-use, or disposition of produced water that is not directly related to the exploration, development, production, treatment, or refinement of oil or gas.**

19.15.34.3   STATUTORY AUTHORITY: 19.15.34 NMAC is adopted pursuant to the Oil and Gas Act, Paragraph (15) of Subsection B of Section 70-2-12 NMSA 1978, which authorizes the division to regulate the disposition, handling, transport, storage, recycling, treatment and disposal of produced water during, or for reuse in, the exploration, drilling, production, treatment or refinement of oil or gas **in a manner that protects public health, the environment, and fresh water sources** and Paragraph (21) of Subsection B of Section 70-2-12 NMSA 1978 which authorizes the regulation of the disposition of nondomestic wastes from the exploration, development, production or storage of crude oil or natural gas.

19.15.34.6   OBJECTIVES: These regulations have four objectives of equal importance. They are:

A.   To prohibit for hydraulic fracturing (fracking) the use of surface or ground water that has less than 1,000 mg/l of TDS or that meets the U.S. Environmental Protection Agency standards for potable (or drinking) water.
B.   To ensure the protection of public health, the environment, and fresh water sources from any transportation, recycling, reuse and disposal of produced water, drilling fluids and other liquid oil field waste.
C.   To prohibit the use of produced water and the use of recycled produced water in any activities that are not directly related to the exploration, drilling, production, treatment, or refinement of oil and gas.
D.   To encourage the recycling or re-use of produced water in activities related to the exploration, drilling, production, treatment or refinement of oil and gas in a manner that protects public health, the environment and fresh water resources.

~~To encourage the recycling or re-use of produced water in a manner that protects public health, the environment and fresh water resources and establish procedures by which persons may transport, recycle, reuse and dispose of produced water, drilling fluids and other liquid oil field waste in activities related to the exploration, drilling, production, treatment or refinement of oil or gas.~~

19.15.34.7   DEFINITIONS: These definitions apply to 19.15.34.2 NMAC through 19.15.34.21 NMAC. See 19.15.2.7 for additional definitions.
          A.   "Recycling facility" is a stationary or portable facility used exclusively for the treatment, re-use or recycling of produced water. A recycling facility does not include oilfield equipment such as separators, heater treaters and scrubbers in which produced water may be used.

19.15.34.8   REQUIREMENTS FOR REUSE, RECYCLING OR DISPOSAL OF PRODUCED WATER:
          A.   Recycling or reuse of produced water.
          (1)   **Prior approval from the division by means of a** ~~No~~ permit or registration is required ~~from the division~~ for the reuse of produced water for drilling, completion, producing or enhanced recovery of oil or natural gas**,** ~~or~~ plugging of wells, or **any other reuse of produced water in the exploration, drilling, production treatment or refinement of oil or gas** ~~pursuant to 19.15.34 NMAC~~. **Prior to approval of any such permit or registration authorizing the reuse of produced water, the permittee must demonstrate to the division that the proposed reuse of produced water shall protect public health, the environment, and fresh water sources, and the division must issue a decision stating the basis for its finding that the proposed reuse shall protect public health, the environment, and freshwater sources.**
          (2)   **The division shall provide public notice of all produced water permit or registration approvals on the division's website within 5 days of any such approvals. Affected persons or persons who may be affected shall have the right to appeal the approval of any produced water permit or registration within 30 days of such public notice being provided. Such permit appeals shall proceed as adjudicatory hearings in accordance with the regulations at 19.15.4 NMAC.** ~~Any other reuse of produced water in the exploration, drilling, production, treatment or refinement of oil or gas requires prior approval by the appropriate division district office on form C-147. Approval requirements will be determined by the district office based upon the proposed use.~~
          (3)   Research using produced water is to be encouraged through pilot projects approved by the appropriate division district office. **Prior to the approval of any such pilot projects, the division shall provide public notice and a minimum of 30 days opportunity to comment on the proposed pilot project. Pilot project approval shall require the division to issue a decision stating the basis for its finding that the proposed pilot project shall protect public health, the environment, and freshwater resources. The division shall provide public notice of all such decisions and findings on the division's website within 5 days of any such approvals. Affected persons or persons who**

may be affected shall have the right to appeal the approval of any produced water pilot project within 30 days of such public notice being provided. Such permit appeals shall proceed as adjudicatory hearings in accordance with the regulations at 19.15.4 NMAC.

   (4) All produced water for recycling or reuse shall be handled and stored in a manner that protects public health, the environment and fresh water resources. **To ensure the protection of public health, the environment, and fresh water resources, at minimum:**

   (a) all produced water shall be handled, stored, and transported in a manner functionally equivalent to the appropriate handling, storage, and transportation of hazardous wastes, as defined and regulated at Title 20, Chapter 4, Part 1 NMAC 2020;

   (b) any person or entity handling, storing, treating, transporting, or disposing of produced water shall be required to have completed hazardous waste operations (HAZWOPER) training in accordance with federal regulations at 29 C.F.R. Section 1910.120(e), and shall maintain compliance with all applicable HAZWOPER certification requirements; and

   (c) any person or entity handling, storing, treating, transporting, or disposing of produced water shall be required to document and track the produced water from the original source of the produced water until the person's or entity's custody or control of the produced water shall cease. Such tracking documentation shall be provided to the division on at least a quarterly-annual basis, and shall be sufficiently detailed as to enable the division to track produced water from the well-head to its ultimate disposition through re-use or disposal.

   (5) All operations in which produced water is used shall be conducted in a manner consistent with hydrogen sulfide gas provisions in 19.15.11 NMAC or NORM provisions in 19.15.35 NMAC, as applicable.

   (6) All releases from the recycling and re-use of produced water shall be handled in accordance with 19.15.29 NMAC.

   (7) Any discharge, handling, transport, storage, recycling or treatment for the disposition of treated produced water~~, including disposition in road construction maintenance, roadway ice or dust control or other construction, or in the application of treated produced water to land,~~ for activities not directly related~~unrelated~~ to the exploration, drilling, production, treatment or refinement of oil or gas **shall be prohibited unless specifically authorized by** ~~is subject to~~ rules **that may be** adopted by the water quality control commission **pursuant to the Water Quality Act. Disposition in road construction or maintenance, roadway ice or dust control or other construction, or the application of treated produced water to land shall not be considered directly related to the**

exploration, drilling, production, treatment, or refinement of oil or gas, and shall be prohibited unless specifically authorized by rules that may be adopted by the water quality control commission pursuant to the Water Quality Act.

      B.   Disposal of produced water. Persons disposing of produced water shall use one of the following disposition methods:

            (1)   delivery to a produced water disposal well permitted pursuant to 19.15.26 NMAC, a surface waste management facility permitted pursuant to 19.15.36 NMAC, or a permanent pit permitted pursuant to 19.15.17 NMAC;

            (2)   recycling or reuse in accordance with 19.15.34 NMAC; or

            (3)   for uses regulated by the water quality control commission pursuant to the Water Quality Act, a person shall obtain a permit from the department of environment before using the produced water, recycled or treated water or treated product or any byproduct of the produced water.

      C.   **The use of water that has less than 1,000 mg/l of TDS or that meets the U.S. Environmental Protection Agency's standards for potable (drinking) water for hydraulic fracturing (fracking) is prohibited.**

19.15.34.9   RECYCLING FACILITIES:

      B.   In addition to other applicable rule requirements, registration of a recycling facility is required in the following circumstances:

            (3)   when the recycling facility is an addition to a produced water disposal well permitted under 19.15.26 NMAC;

19.15.34.13 OPERATIONAL REQUIREMENTS FOR RECYCLING CONTAINMENTS:

      C.   A recycling containment shall be deemed to have ceased operations if less than twenty percent of the total fluid capacity is used every six months following the first withdrawal of produced water for use. The operator must report cessation of operations to the appropriate division district office. The appropriate division district office may grant an extension to this determination of cessation of operations not to exceed six months.

## 19.15.34.14 CLOSURE AND SITE RECLAMATION REQUIREMENTS FOR RECYCLING CONTAINMENTS:

      F.   Reclamation of all disturbed areas no longer in use shall be considered complete when all ground surface disturbing activities at the site have been completed, and a uniform vegetative cover has been established that reflects a life-form ratio of plus or minus fifty percent of pre-disturbance levels and a total percent of plant cover of at least seventy percent of pre-disturbance levels, excluding noxious weeks.

19.15.34.18 DENIAL OF FORM C-133: the division may deny approval of a form C-133 if:

D. the applicant or officer, director or partner in the applicant, or a person with an interest in the applicant exceeding twenty-five percent, is or was within the past five years an officer, director or partner in the applicant, or a person with an interest in the applicant exceeding twenty-five percent in another entity that possesses or has possessed an approved form C-133 that has been cancelled or suspended, has a history of violating division or other state or federal environmental laws; is subject to a commission or division order, issued after notice an hearing, finding such entity to be in violation of an order requiring corrective action; or has a penalty assessment for violation of division or commission rules or orders that is unpaid more than 70 days after issuance of the order assessing the penalty.

WildEarth Guardians Exhibit 1

EPA, Hydraulic Fracturing for Oil and" Gas: Impacts from the Hydraulic Fracturing Water Cycle on Drinking Water Resources in the United States, EPA-600-R-16-236Fa (Dec. 2016), available at: www.epa.gov/hfstudy (excerpts).

Hydraulic Fracturing for Oil and Gas: Impacts from the Hydraulic Fracturing Water Cycle on Drinking Water Resources in the United States

Hydraulic Fracturing for Oil and Gas: Impacts from the Hydraulic Fracturing Water Cycle on Drinking Water Resources in the United States

Chapter 7. Produced Water Handling

Abstract

Produced water is a byproduct of hydrocarbon production and flows to the surface through the production well, along with oil and gas. Operators must store and dispose of (or in some cases treat) large amounts of non-potable produced water, either on site or off site, and spills or releases of produced water have the potential to impact drinking water resources. Unlike produced water from conventional oil and gas production, produced water generated following hydraulic fracturing initially contains returned hydraulic fracturing fluids. Much of the hydraulic fracturing fluid remains below ground; the median amount of fluid returned to the surface is 30% or less. Up to several million gallons of water can be produced from each well, with production generally decreasing with time.

Produced water contains several classes of constituents: salts, metals, radioactive materials, dissolved organic compounds, and hydraulic fracturing chemicals and their transformation products (the result of reactions of these chemicals in the subsurface). The concentrations of these constituents change with time, as the initially returning hydraulic fracturing fluid blends with formation water. Typically, this means that the produced water becomes more saline with time. Produced water composition and volume vary from well to well, both among different formations and within formations. A large number of organic compounds have been identified in produced water, many of which are naturally occurring petroleum hydrocarbons; some are known hydraulic fracturing chemicals. Only a few transformation products have been identified, and they include chlorinated organics.

Spills and releases of produced water with a variety of causes have been documented at different steps in the production process. The causes include human error, equipment or container failure (for instance, pipeline, tank or storage pit leaks), accidents, and storms. Unauthorized discharges may account for some releases as well. An estimated half of the spills are less than 1,000 gal (3,800 L). A small number of much larger spills has been documented, including a spill of 2.9 million gal (11 million L). Both short- and long-term impacts to soil, groundwater, and surface from spills have occurred. For many spills, however, the impacts are unknown. The potential of spills of produced water to affect drinking water resources depends upon the release volume, duration, and composition, as well as watershed and water body characteristics.

Data are lacking to characterize the severity and frequency of impacts on a nationwide scale. Suspected local-scale impacts often require an extensive multiple lines-of-evidence investigation to determine their cause. Further, when investigations do take place, the lack of baseline water quality data can make it difficult to determine the cause and severity of the impact. In such cases, additional data are necessary to determine the full extent of the impact of releases of produced water.

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7. Produced Water Handling

7.1   Introduction

Water is a byproduct of oil and gas production. After the hydraulic fracturing of the formation is completed, the injection pressure is reduced, and a possible inactive period where the well is "shut in" is completed, water is allowed to flow back from the well to prepare for oil or gas production.[1] This return-flow water may contain chemicals injected as part of the hydraulic fracturing fluid, chemicals naturally occurring in the formation, or the products of reactions that take place in the formation. Initially this water, sometimes called flowback, is mostly hydraulic fracturing fluid, but as time goes on, water chemistry becomes more similar to water associated with the formation. For formations containing saline water (brine), the salinity of the returned water increases as time passes as the result of increased contact time between the hydraulic fracturing fluid and the formation and inclusion of an increased portion of formation water. For this assessment, and consistent with industry practice, the term produced water is used to refer to any water flowing from the oil or gas well.

Produced water is piped directly to an injection well or stored and accumulated at the surface for eventual management by injection into disposal wells, transport to wastewater treatment plants, reuse, or in some cases, placement in evaporation pits or permitted direct discharge. See Text Box ES-11 and Section 8.4 for discussion of these management practices.

Produced water spills and releases can occur due to several causes, including events associated with pipelines, transportation, blowouts, and storage. Impacts to drinking water resources can occur if this released water enters surface water bodies or reaches groundwater. Such impacts may result in the water becoming unfit for consumption, either through obvious taste and odor considerations or the constituents in the water exceeding hazard levels (Chapter 9). Once released to the environment, transport of chemical constituents depends on the characteristics of the:

- Spill (volume, duration, concentration);
- Fluid (density as influenced by salinity);
- Chemicals (volatility, sorption, solubility); and
- Site-specific environmental characteristics (surface topography and location of surface water bodies, the type of the soil and aquifer materials, layering and heterogeneity of rocks, and the presence of dissolved oxygen and other factors needed to support biodegradation, and the presence of inorganic species that affect metal transport).

This chapter provides characterization of produced water and also provides background information for the coverage of wastewater disposal and reuse in Chapter 8. Chapter 7 addresses the characteristics of produced water including per-well generation of produced water. Chapter 8 considers management of this water, now called wastewater, at an aggregate level, and thus

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[1] There can be no shut-in period at all or it can last several weeks (Stepan et al., 2010).

discusses state, regional, and national estimates of treatment volumes. While Chapter 7 considers impacts from several types of unintentional releases, Chapter 8 focuses on impacts that are associated with wastewater management practices. One specific issue, leakage from pits and impoundments, is introduced in Chapter 7 as one of several avenues for accidental releases, with a more detailed exploration of the use of pits in wastewater management presented in Chapter 8.

Chapter 7 begins with a review of definitions for flowback and produced water in Section 7.1.1. Definitions are followed by a discussion in Section 7.2 of water volumes per well, first presenting data on the volume and percent of hydraulic fracturing fluid returned to the surface and then presenting data on the volume of water returned during production. These data all represent the response of individual wells. Because of the need to have aggregated volumes for estimating wastewater treatment loadings, estimates of total volumes are given in Section 8.2.

Chapter 7 continues with discussion of the chemical composition of produced water (Section 7.3). Because the composition of produced water is only known through analysis of samples, laboratory methods and their limitations are described in Section 7.3.1. Time-dependent changes in composition are discussed via three specific examples in Section 7.3.3, followed by discussion of five types of constituents: salts, metals, radioactive materials, organics, and known hydraulic fracturing additives in Section 7.3.4. The chemical and geological processes controlling the chemical composition of produced water are described in Appendix E. Spatial and temporal trends in the composition of produced water are illustrated with examples from the literature and data compiled for this report (Section 7.3.5).

The potential for impacts on drinking water resources of produced water releases and spills are described based on reported spill incidents (Section 7.4), and examples of spills from specific sources and data compilation studies are given in Section 7.4.2. The potential for impacts is described using contaminant transport principles in Section 7.6. The chapter concludes with a discussion of uncertainties and knowledge gaps, factors that influence the severity of impacts, and major findings (Section 7.7).

7.1.1   Definitions

Multiple definitions exist for the terms flowback and produced water. Appendix Section E.1 gives examples of definitions used by different organizations. These differing definitions reflect differing usage of the terms among various groups and that produced water reflects the continuously varying mixture between returning injection fluid and formation water. The majority of produced water definitions are fundamentally similar. The following definition is used in this report for produced water: any type of water that flows from the subsurface through oil and gas wells to the surface as a by-product of oil and gas production. Thus produced water can variously refer to returned hydraulic fracturing fluid, formation water alone, or a mixture of the two.

The term flowback has two major meanings. First is the process used to prepare the well for production by allowing excess liquids and proppant to return to the surface. The second use of the term is to refer to fluids predominantly containing hydraulic fracturing fluid that return to the surface. Because formation water can contact and mix with injection fluids, the distinction between returning hydraulic fracturing fluid and formation water is not clear. Definitions of flowback are

operational in the sense that they include some characteristic of the oil and gas operation (i.e., fluids returning within 30 days). These reflect that during the early phases of operation, a higher concentration of chemical additives is expected and later, water is characteristic of the formation. Because we use existing literature in our review, we do not introduce a preferred definition of flowback, and describe all water flowing from the well as produced water.

7.2   Volume of Hydraulic Fracturing Flowback and Produced Water

Veil (2015) estimated that, in 2012, all types (i.e., from conventional and unconventional reservoirs) of U.S. onshore and offshore oil and gas production generated 8.90 x 10^{11} gal (3.37 x 10^{12} L) of produced water. More details and state-level estimates are given in Section 8.2. This section presents information on flowback and produced water volume over various time scales, and where possible, on a per-well and per-formation basis, because characteristics and volume of flowback and produced water vary by well, formation, and time.

The amount of produced water from a well varies and depends on several factors, including production, formation, and operational factors. Production factors include the amount of fluid injected, the type of hydrocarbon produced (gas or liquid), and the location within the formation. Formation factors include the formation pressure, the interaction between the formation and injected fluid (capillary forces), and reactions within the reservoir. Operational factors include the volume of the fractured production zone that includes the length of well segments and the height and width of the fractures. Certain types of problems also influence water production, including possible loss of mechanical integrity and subsurface communication between wells, both of which can result in an unexpected increase in water production (U.S. GAO, 2012; Byrnes, 2011; DOE, 2011a; GWPC and ALL Consulting, 2009; Reynolds and Kiker, 2003).

The processes that allow gas and liquids to flow are related to the conditions along the faces of fractures. Byrnes (2011) conceptualized fluid flow across the fracture face as being composed of three phases. The first is characterized by forced imbibition of fluid into the reservoir and occurs during and immediately following fracture stimulation.[1] Second is fluid redistribution within the reservoir rock, due to capillary forces. Estimates have shown that 50% or more of fracturing fluid could be captured within the Marcellus shale if imbibition drives water 2 to 6 in (5 to 15 cm) into the formation (Engelder, 2012; Byrnes, 2011; He, 2011). In the last phase, water flows out of the formation when the well is opened and pressure is reduced in the wellbore and fractures. The purpose of this phase is to recover as much of the injected fluid as possible (Byrnes, 2011) to allow higher oil or gas flow rates. The length of the last phase and, consequently, the amount of water removed, depends on factors such as the amount of injected fluid, the permeability and relative permeability of the reservoir, capillary pressure properties of the reservoir rock, and the pressure near the fracture faces.[2] The well can be shut in for varying time periods depending on operator scheduling, surface facility construction and connection thereto, or other reasons.

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[1] The displacement of a non-wet fluid (i.e., gas) by a wet fluid (typically water). Adapted from Dake (1978).

[2] When multiple fluids (water, oil, gas) occupy portions of the pore space, the permeability to each fluid depends on the fraction of the pore space occupied by the fluid and the fluid's properties. As defined by Dake (1978), when this effective permeability is normalized by the absolute permeability, the resulting relationship is known as the relative permeability.

7.2.1 Flowback of Injected Hydraulic Fracturing Fluid

The amount of water produced by wells within the first few days following fracturing varies from formation to formation. Wells in the Mississippi Lime and Permian Basin can produce 1 million gal (3.8 million L) in the first 10 days of production. Wells in the Barnett, Eagle Ford, Granite Wash, Cleveland/Tonkawa Sand, Niobrara, Marcellus, and Utica Shales can produce 300,000 to 1 million gal (1.14 to 3.78 million L) within the first 10 days. Haynesville wells produce less, about 250,000 gal (950,000 L) (Mantell, 2013). Data show that the rate of water produced during the flowback period decreases as time passes (Ziemkiewicz et al., 2014; Hansen et al., 2013; Hayes, 2009).

It is not possible to specify precisely the amount of injected fluids that return in the flowback, because there is not a clear distinction between flowback and produced water, and the indicators (e.g., salinity and radioactivity, to name two) are not routinely monitored (GWPC and ALL Consulting, 2009). Rather, flowback estimates usually relate the amount of produced water measured at a given time after fracturing as a percentage of the total amount of injected fluid. Estimates of the fraction of injected hydraulic fracturing fluid that returns as flowback are highly variable (U.S. EPA, 2016d; Vengosh et al., 2014; Mantell, 2013; Vidic et al., 2013; Minnich, 2011; Xu et al., 2011). The maxima are less than 85% in all but one of the examples given in Table 7-1, Table 7-2, and Table 7-3, and most of the median values are less than 30%. In some cases, the amount of flowback is greater than the amount of injected hydraulic fracturing fluid, and the additional water comes from the formation (Nicot et al., 2014) or from a conductive pathway from an adjacent formation (Arkadakskiy and Rostron, 2013). See Appendix Section E.2.1 for more details.

Table 7-1. Data from one company's operations indicating approximate total water use and approximate produced water volumes within 10 days after completion of wells.
From Mantell (2013).

Formation	Approx. total average water use per well (million gal)	Produced water (flowback) within the first 10 days after completion		Produced water as a percentage of average water use per well	
		Low estimate (million gal)	High or only estimate (million gal)	Low estimate (% of total water use)	High or only estimate (% of total water use)
Gas shale plays (primarily dry gas)					
Barnett[a]	3.4	0.3	1.0	9%	29%
Marcellus[a]	4.5	0.3	1.0	7%	22%
Haynesville	5.4	--	0.25	--	5%
Liquid plays (gas, oil, condensate)					
Mississippi Lime	2.1	--	1.0	--	48%

Formation	Approx. total average water use per well (million gal)	Produced water (flowback) within the first 10 days after completion		Produced water as a percentage of average water use per well	
		Low estimate (million gal)	High or only estimate (million gal)	Low estimate (% of total water use)	High or only estimate (% of total water use)
Cleveland/ Tonkawa	2.7	0.3	1.0	11%	37%
Niobrara	3.7	0.3	1.0	8%	27%
Utica	3.8	0.3	1.0	8%	26%
Granite Wash	4.8	0.3	1.0	6%	21%
Eagle Ford	4.9	0.3	1.0	6%	20%

[a] Mantell (2011) reported produced water for the first 10 days at 500,000 to 600,000 gal for the Barnett, Fayetteville and Marcellus Shales.

Table 7-2. Additional short-, medium-, and long-term produced water estimates.

Location–formation	Produced water as percentage of injected fluid	Reference	Comment
Estimates without reference to a specific data set			
Unspecified Shale	5% – 35%	Hayes (2011)	
Marcellus Shale	10% – 25%	Minnich (2011)	Initial flowback
ND–Bakken	25%	EERC (2013)	
Estimates with reference to specific data evaluation			
Short duration			
Marcellus Shale	10%	Clark et al. (2013)	0 – 10 days
TX—Barnett	20%	Clark et al. (2013)	0 – 10 days
TX—Haynesville	5%	Clark et al. (2013)	0 – 10 days
AR—Fayetteville	10%	Clark et al. (2013)	0 – 10 days
Medium duration			
WV—Marcellus	8%	Hansen et al. (2013)	30 days
Marcellus Shale	24%	Hayes (2011, 2009)	Average from 19 wells, 90 days

Location–formation	Produced water as percentage of injected fluid	Reference	Comment
Long duration			
TX—Barnett	~100%[a]	Nicot et al. (2014)	72 months
WV—Marcellus	10% – 30%	Ziemkiewicz et al. (2014)	Up to 115 months
TX—Eagle Ford	<20%	Nicot and Scanlon (2012)	Lifetime
Unspecified duration			
PA—Marcellus	6%	Hansen et al. (2013)	

[a] Approximate median with large variability: 5th percentile of 20% and 90th percentile of 350%.

Table 7-3. Flowback water characteristics for wells in unconventional reservoirs.
Source: U.S. EPA (2016d). The formation-level data used to develop Tables 7-3 and 7-4 appear in Appendix Table E-1.

Resource type	Well type	Fracturing fluid (million gal)			Flowback (percent of fracturing fluid returned)		
		Weighted average	Range	Data points	Weighted average	Range	Data points
Shale	Horizontal	4.2	0.091–24	80,388	7%	0%–580%	7,377
	Directional	1.4	0.037–20	340	33%	1%–57%	36
	Vertical	1.1	0.015–19	5,197	96%	2%–581%	57
Tight	Horizontal	3.4	0.069–12	7,301	12%	0%–60%	75
	Directional	0.05	0.046–4	3,581	10%	0%–60%	342
	Vertical	1	0.016–4	10,852	4%	0%–60%	130

7.2.2 Produced Water Volumes

Mantell (2013, 2011) described the amount of produced water over the long term as high, moderate, or low for several formations. Wells in the Barnett Shale, Cleveland/Tonkawa Sand, Mississippi Lime, and the Permian Basin can produce more than 1,000 gal (3,800 L) of water per million cubic feet (MMCF) of gas. The most water-productive of these can be as high as 5,000 gal (19,000 L) per MMCF of gas. As a specific example, a high water producing formation in the western United States was described as producing 4,200 gal (16,000 L) per MMCF of gas for the life of the well (McElreath, 2011). The well was fractured and stimulated with about 4 million gal (15 million L) of water and returned 60,000 gal (230,000 L) per day in the first 10 days, followed by 8,400 gal (32,000 L) per day in the remainder of the first year. The Niobrara, Granite Wash, Eagle Ford, Haynesville, and Fayetteville Shales are relatively dry formations (with small amounts of naturally occurring formation water) and produce between 500 and 2,000 gal (1,900 to 7,600 L) of

produced water per MMCF of gas ([Mantell, 2013](#)). The Utica and Marcellus Shales are viewed as drier still and produce less than 200 gal (760 L) per MMCF of gas.

Wells producing in various formation show high produced water volume variability, including the Barnett Shale, which was attributed by [Nicot et al. (2014)](#) to a few wells with exceptionally high water production. Some of these wells produced more than the amount of injected fracturing fluid.

Wells in conventional and unconventional reservoirs produce differing amounts of water. Individual hydraulically fractured wells producing gas from the Marcellus Shale produced more water than hydraulically fractured wells in conventional wells in Pennsylvania ([Lutz et al., 2013](#)). However, on a per-unit of gas produced basis, wells producing from the Marcellus Shale generate less water (35%), than those in the conventional formations.

The EPA ([2016d](#)) reported characteristics of long-term produced water for hydraulically fractured shale and tight formations (Table 7-4). For shale, horizontal wells produced more water (1,100 gal/day; 4,200 L/day) than vertical wells (500 gal/day; 1,900 L/day). Typically, this would be attributed to the longer length of the production zone in horizontal laterals than in vertical wells.

Table 7-4. Long-term produced water generation rates (gal/day per well) for wells in unconventional reservoirs.
Source: [U.S. EPA (2016d)](#). The formation-level data used to develop Tables 7-3 and 7-4 appear in Appendix Table E-1.

Resource type	Well type	Long-Term Produced Water Generation Rates (gal per day per well)		
		Weighted average	Range	Data points
Shale	Horizontal	1,100	0–29,000	43,893
	Directional	820	0.83–12,000	1,493
	Vertical	500	4.8–51,000	12,551
Tight	Horizontal	980	10–120,000	4,692
	Directional	390	15–8,200	10,784
	Vertical	650	0.71–2100	34,624

In an example from the Pennsylvania Marcellus Shale, the EPA determined that, for vertical wells in unconventional reservoirs, 6% of water came from drilling, 35% from flowback, and 59% from long-term produced water; for horizontal wells, the corresponding numbers were 9%, 33%, and 58% ([U.S. EPA, 2016d](#)). This result agrees with the U.S. Department of Energy ([DOE, 2011a](#)) who concluded that the characteristic small amount of produced water from the Marcellus Shale was due either to its low water saturation or low relative permeability to water (see Section 6.3.2.1). For these dry formations, low shale permeability and high capillarity cause water to imbibe into the formation, where some is retained permanently.

7.2.2.1 Time Trends

High rates of water production (flowback) typically occur in the first few months after hydraulic fracturing, followed by rates reduced by an order of magnitude (e.g., Nicot et al., 2014). In many cases half of the total produced water from a well is generated in the first year. Similarly, the EPA (2016d) reported a general rule of thumb that, for unconventional reservoirs, the volume of flowback (which occurs over a short period of time) is roughly equal to the volume of long-term produced water. These trends in produced water volumes occur within the timeline of hydraulic fracturing activities (Section 3.3), and show that the large, initial return volumes of flowback last for several weeks, whereas the lower-rate produced water phase can last for years (Figure 7-1).
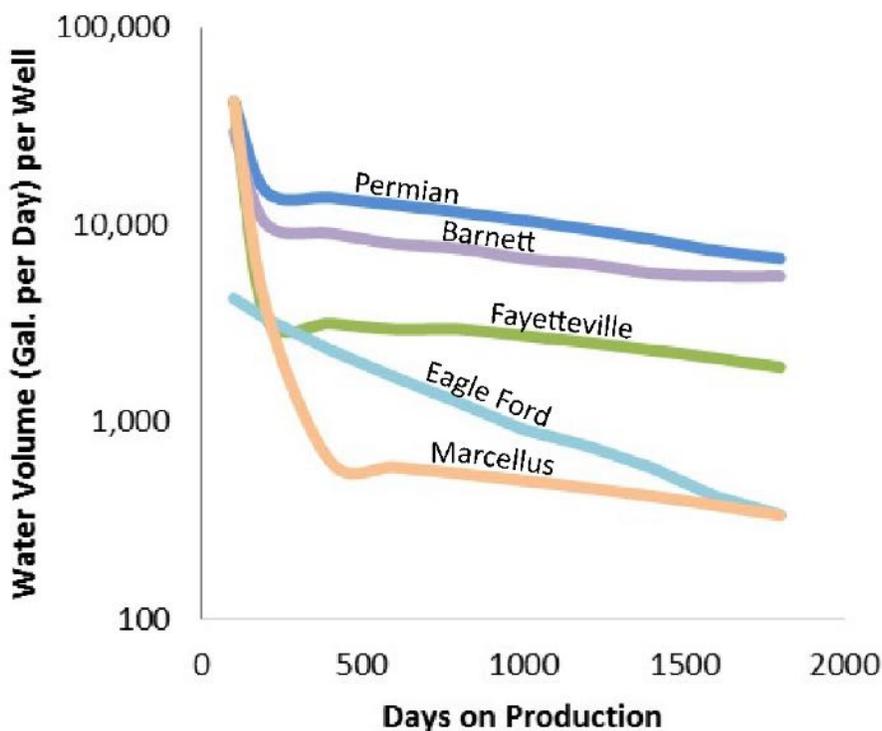

Figure 7-1. Generalized examples of produced water flow from five formations.
Actual produced water flows vary by location, play, basin, and amount of water used for hydraulic fracturing (EWI, 2015). Figure used with permission.

7.2.2.2 Coalbed Methane

Water is pumped from coal seams to reduce pressure so that gas adsorbed to the surface of the coal can flow to the production well (Guerra et al., 2011). Consequently, CBM tends to produce large volumes of water early on: more than conventional gas-bearing formations (U.S. GAO, 2012) (Figure 7-2). Within producing CBM formations, water production can vary for unknown reasons (U.S. GAO, 2012). As an example, data show that CBM production in the Powder River Basin produces 16 times more water than that in the San Juan Basin (U.S. GAO, 2012).
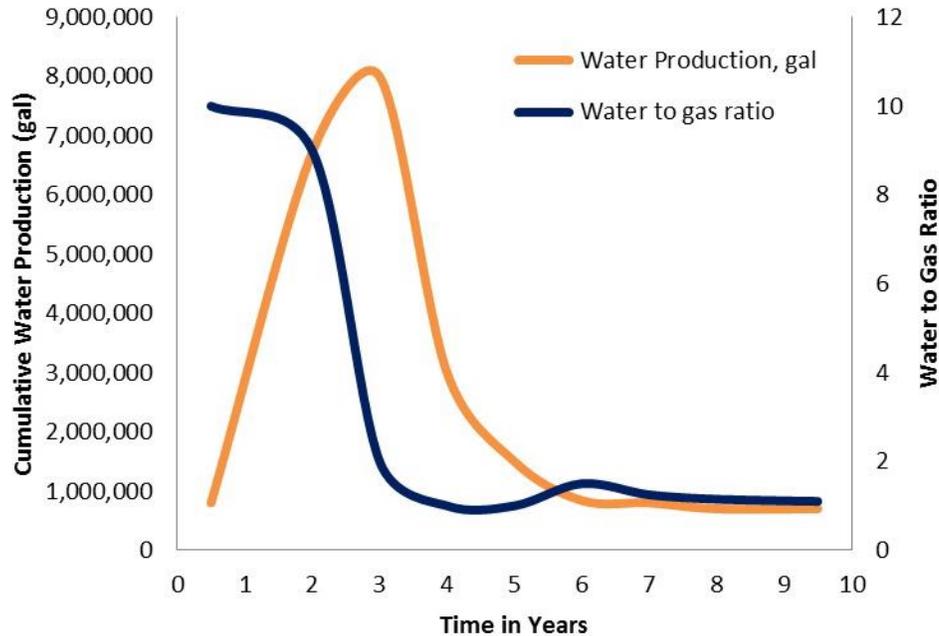
Figure 7-2. Typical produced water volume for a coal bed methane well in the western United States.
Source: Guerra et al. (2011).

7.3   Chemical Composition of Produced Water

For hydraulically fractured wells, the chemical composition of produced water changes from being similar to the injected hydraulic fracturing fluid to reflecting a mixture of hydraulic fracturing fluids, naturally occurring hydrocarbons, transformation products, and formation water. Initial produced water data show continuous changes in chemical composition and reflect processes occurring in the formation (Section 7.3.3). The data presented on longer-term produced water represent water that is primarily associated with the formation, rather than the hydraulic fracturing fluid (Section 7.3.4). Unlike the hydraulic fracturing fluid, the composition of which may be disclosed, compositional data on produced water comes from laboratory analysis of samples. Because of this reliance, we first discuss sampling and analysis of produced water, and especially note the limitations of existing analytical methods for organic chemicals and radionuclides.[1] It is important to note that the analytical methods can differ depending on the purpose of the analysis. Specifically, advanced laboratory methods have been used to identify unknown organic constituents of produced water (Section 7.3.1), routine methods are used for pre-drilling sampling, and a combination of methods may be needed for assessing environmental impacts (Section 7.4.2.5).

7.3.1   Determination of Produced Water Composition

Recent advances in analytical methods for produced water have allowed detection and quantification of a broad range of organic compounds, including those associated with hydraulic

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[1] Chemical components of produced water are described below.

fracturing fluid (Section 7.3.4.7 and Appendix E.3.5.). These studies make clear that standard analytical methods are not adequate for detecting and quantifying the numerous organic chemicals, both naturally occurring and anthropogenic, that are now known to occur in produced water (Lester et al., 2015; Maguire-Boyle and Barron, 2014; Thurman et al., 2014). Similarly, methods commonly applied for the analysis of radionuclides in drinking water may suffer from analytical interferences that result in poor data quality (Maxwell et al., 2016; Ying et al., 2015; Zhang et al., 2015b; Nelson et al., 2014; U.S. EPA, 2014i, 2004b). In these instances, alternative methods that have been developed to support the nuclear materials production and waste industry provide more reliable approaches to ensure adequate detection limits and avoid sample matrix interferences that are anticipated for the high salinity and concentrations of organic constituents that may be present in produced water samples.[1] Development of advanced or non-routine methods for both organics and inorganics (especially radium) suggests that data generated from earlier methods may be less reliable that those developed by the new methods (Nelson et al., 2014), and that advanced analytical techniques are needed to detect or quantify some analytes.

The compositional data that follow in this chapter and Appendix E rely on the analytical procedures used in measurement and were summarized as noted from numerous produced water studies or compilations, such as the U.S. Geological Survey (USGS) produced water database (Blondes et al., 2014).

7.3.2   Factors Influencing Produced Water Composition

Several interacting factors influence the chemical composition of produced water: (1) the composition of injected hydraulic fracturing fluids, (2) the targeted geological formation and associated hydrocarbon products, (3) the stratigraphic environment, and (4) subsurface processes and residence time (Barbot et al., 2013; Chapman et al., 2012; Dahm et al., 2011; Blauch et al., 2009).

The mineralogy and structure of a formation are determined initially by deposition, when rock grains settle out of their transporting medium (Marshak, 2004). Generally, shale forms from clays that were deposited in deep, oxygen-poor marine environments, and sandstone can form from sand deposited in shallow marine environments (Ali et al., 2010; U.S. EPA, 2004a). Coal forms when carbon-rich plant matter collects in shallow peat swamps. In the United States, coal formed in both freshwater (northern Rocky Mountains) and marginal-marine environments (Alabama's Black Warrior formation) (NRC, 2010; Horsey, 1981). Consequently, shale and sandstone produced water are expected to be saline, and CBM water may be much less so.

7.3.3   Produced Water Composition During the Flowback Period

The chemistry of produced water changes over time, especially during the first days or weeks after hydraulic fracturing. Generally, produced water concentrations of cations, anions, metals, naturally occurring radioactive material (NORM), and organics increase as time goes on (Barbot et al., 2013; Haluszczak et al., 2013; Chapman et al., 2012; Davis et al., 2012; Gregory et al., 2011; Blauch et al.,

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[1] For guidance in planning, implementing, and assessing projects that require laboratory analysis of radionuclides, see U.S. EPA (2004b).

2009). The causes include precipitation and dissolution of salts, carbonates, sulfates, and silicates; pyrite oxidation; leaching and biotransformation of organic compounds; and mobilization of NORM and trace elements. Concurrent precipitation of sulfates (e.g., $BaSO_4$) and carbonates (e.g., $CaCO_3$) alongside decreases in pH, alkalinity, dissolved carbon, and microbial abundance and diversity occur over time after hydraulic fracturing (Orem et al., 2014; Barbot et al., 2013; Murali Mohan et al., 2013; Davis et al., 2012; Blauch et al., 2009; Brinck and Frost, 2007). Leaching of organics appears to be a result of injected and formation fluids associating with shale and coal strata (Orem et al., 2014). Concentrations of organics in CBM produced water decrease with time, possibly due to the depletion of coal-associated water through formation pumping (Orem et al., 2007).

7.3.3.1 Total Dissolved Solids

Produced water total dissolved solids concentrations (TDS) increase by varying degrees because of the formation's geological origin. As an example, TDS concentrations increased to upper bound values in samples from four Marcellus Shale gas wells (Chapman et al., 2012) (Figure 7-3). The increased TDS was composed of increased sodium, calcium, and chloride (Chapman et al., 2012; Blauch et al., 2009). Similarly, TDS in flowback from the Westmoreland County wells started low and exceeded that of typical seawater (35,000 mg/L) within three days (Chapman et al., 2012). In a similar study, wells with hydraulic fracturing fluid containing less than 1,000 mg/L saw TDS concentrations increase above a median value of 200,000 mg/L within 90 days (Hayes, 2009).
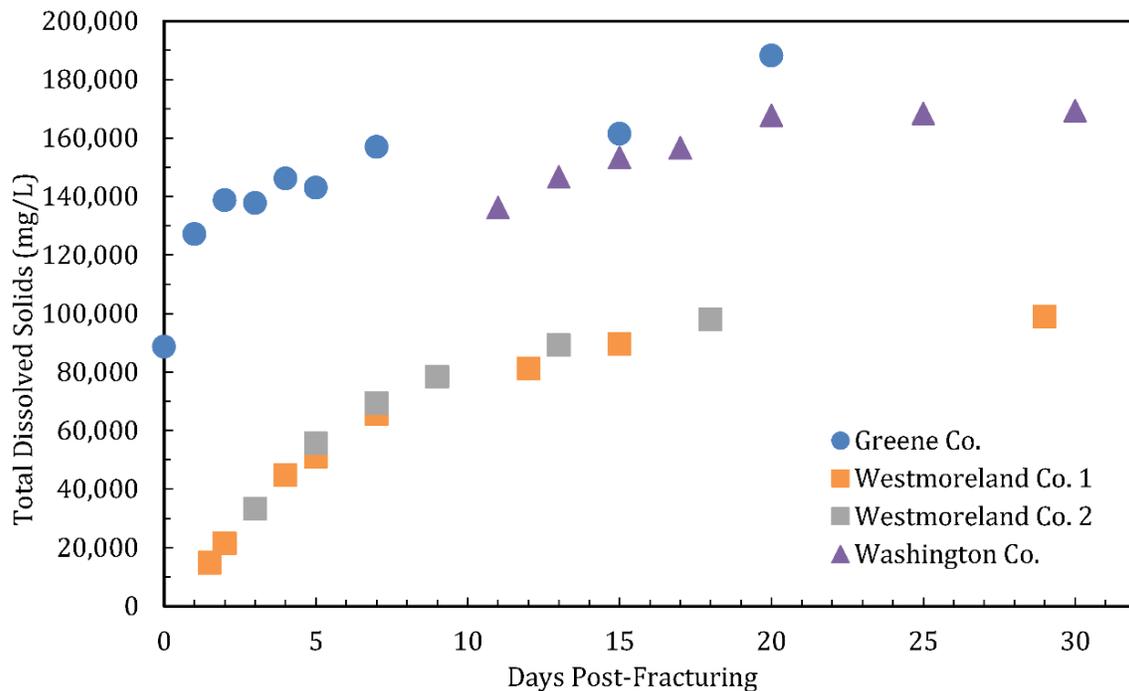

Figure 7-3. TDS concentrations measured through time for injected fluid (at 0 days), and produced water samples from four Marcellus Shale gas wells in three southwest Pennsylvania counties.
Data from Chapman et al. (2012).

7.3.3.2   Radionuclides

Shales and sandstones naturally contain various radionuclides (Sturchio et al., 2001).[1] Radium in pore waters or adsorbed onto clay particles and grain coatings can dissolve and return in produced water (Langmuir and Riese, 1985). Available data indicate that radium and TDS concentrations in produced water are positively correlated (Rowan et al., 2011; Fisher, 1998), likely because radium remains adsorbed to mineral surfaces when salinity is low, and then desorbs into solution with increased salinity (Sturchio et al., 2001). As an example, over the course of 20 days, radium concentration in flowback from a Marcellus Shale gas well increased by almost a factor of four (Chapman et al., 2012; Rowan et al., 2011) (Figure 7-4).
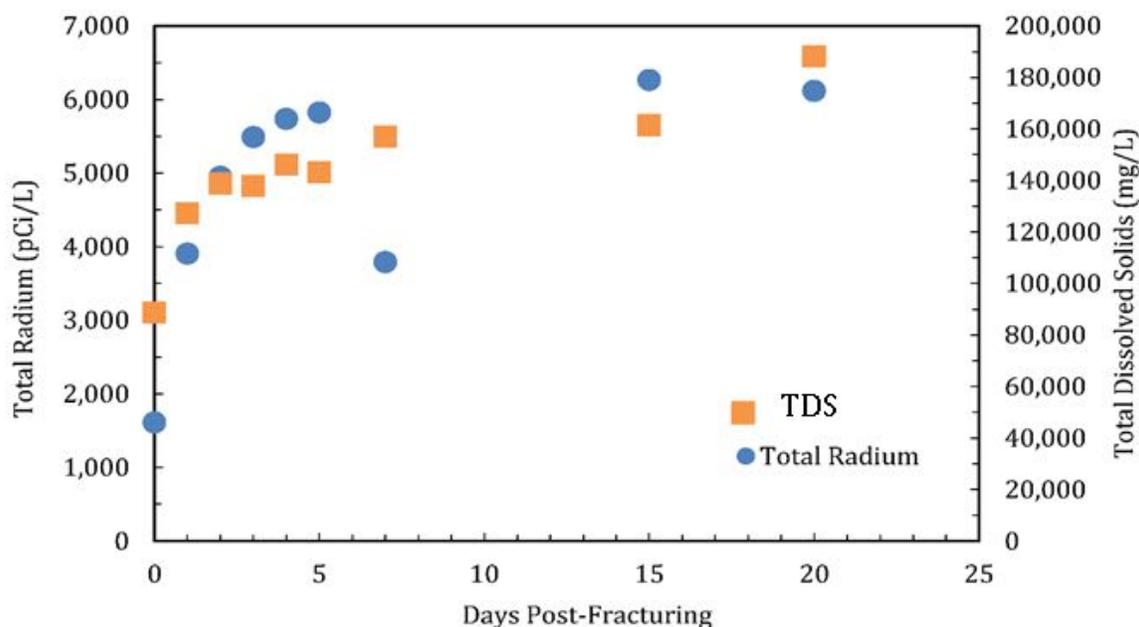

Figure 7-4. Total radium and TDS concentrations measured through time for injected (day 0), and produced water samples Greene County, PA, Marcellus Shale gas wells.
Data from Rowan et al. (2011) and Chapman et al. (2012).

7.3.3.3   Dissolved Organic Carbon

Dissolved organic carbon (DOC) concentrations decrease from initial levels in shales and coalbeds (Murali Mohan et al., 2013; Orem et al., 2007). This occurs while TDS and chloride concentrations are increasing (Barbot et al., 2013; Chapman et al., 2012). DOC sorption, dilution with injected or formation water, biochemical reactions, and microbial transformation may all cause decreased concentrations of DOC during flowback. Injected organics can include gel polymer formulations, namely guar gum; petroleum distillates; and ethyl and ether glycol formulations, which can serve as food sources for microbes. (Wuchter et al., 2013; Arthur et al., 2009b; Hayes, 2009). In coalbeds,

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[1] Hydraulic fracturing fluids typically do not contain radioactive material (Rowan et al., 2011). However, reusing produced water can introduce radioactive material into hydraulic fracturing fluid. See Section 7.3.4.6 and PA DEP (2015b).

water contacting the coal may become depleted in DOC to the degree that when outside water of lower DOC is produced, the resulting DOC concentrations in the produced water are reduced (Orem et al., 2014).
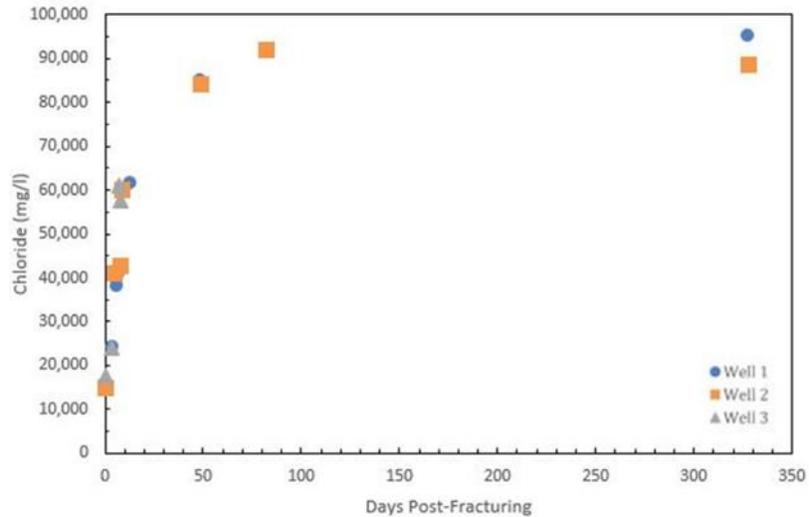
(a)
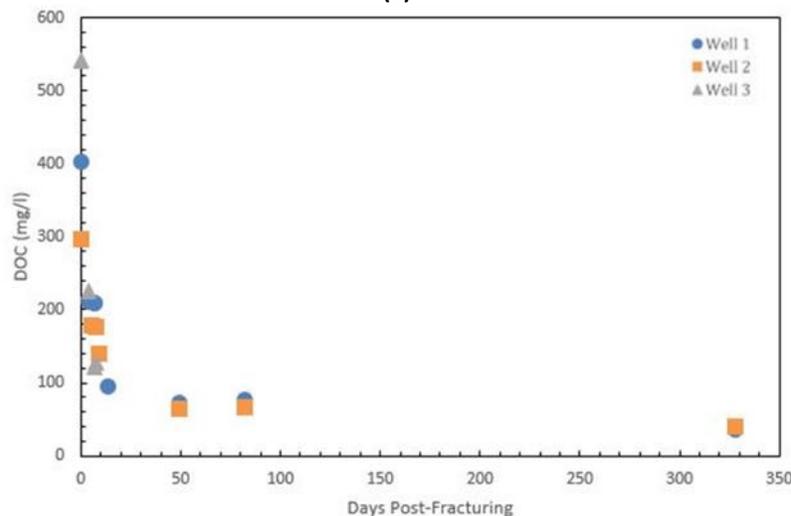
(b)

Figure 7-5. (a) Increasing chloride (Cl) and (b) decreasing DOC concentrations measured through time for samples from three Marcellus Shale gas wells on a single well pad in Greene County, PA.

Data from Cluff et al. (2014). Reprinted with permission from Cluff, M; Hartsock, A; Macrae, J; Carter, K; Mouser, PJ. (2014). Temporal changes in microbial ecology and geochemistry in produced water from hydraulically fractured Marcellus Shale Gas Wells. Environ Sci Technol 48: 6508-6517. Copyright 2014 American Chemical Society.

As an example, produced water DOC concentrations decreased from their initial levels twofold from the hydraulic fracturing fluid and initial samples (Figure 7-5b) followed by a decrease of 11-fold

over nearly 11 months. The DOC leveled off several months after hydraulic fracturing, presumably as a result of in situ attenuation processes (Cluff et al., 2014). As DOC was decreasing, chloride concentrations increased five- to six-fold. These chloride concentrations increased linearly during the first two weeks (Cluff et al., 2014) and then later approached higher levels (Figure 7-5a). The pattern in the DOC and chloride levels reflected the changing composition of the produced water—initially high in DOC from hydraulic fracturing additives and low in salinity, then higher in salinity and lower in DOC reflecting the chemistry of formation water. The changing composition of produced water suggests that the potential concern for produced water spills also changes: initially the produced water may contain more hydraulic fracturing chemicals, and later the concern may shift to the impact of high salinity water.

7.3.4 Produced Water Composition

The chemical composition of produced water continues to change after the initial flowback period. Produced water may contain a range of constituents, but in widely varying amounts. Generally, these can include:

- Salts, including those composed from chloride, bromide, sulfate, sodium, magnesium and calcium;

- Metals including barium, manganese, iron, and strontium;

- Radioactive materials including radium (radium-226 and radium-228);

- Oil and grease, and dissolved organics (including BTEX);[1]

- Hydraulic fracturing chemicals, including tracers and their transformation products; and

- Produced water treatment chemicals.[2]

We discuss these groups of chemicals and then conclude by discussing variability within formation types and within production zones.

7.3.4.1 Similarity of Produced Water from Conventional and Unconventional Reservoirs

Produced water generated from unconventional reservoirs is reported to be similar to produced water from conventional reservoirs in terms of TDS, pH, alkalinity, oil and grease, TOC, and other organics and inorganics (Wilson, 2014; Haluszczak et al., 2013; Alley et al., 2011; Hayes, 2009; Sirivedhin and Dallbauman, 2004). Although produced water salinity varies within and among shales and tight formations, produced water is typically characterized as saline (Lee and Neff, 2011; Blauch et al., 2009). Produced water from coalbeds may have low TDS if the coal source bed was formed in freshwater. Saline produced water is also enriched in major anions (e.g., chloride, bicarbonate, sulfate); cations (e.g., sodium, calcium, magnesium); metals (e.g., barium, strontium);

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[1] BTEX is an acronym representing benzene, toluene, ethylbenzene, and xylenes.

[2] Some chemicals are added to produced water for the purpose of oil/water separation, improved pipeline flow, or equipment maintenance, including prevention of corrosion and scaling in equipment (Cal/EPA, 2016). Generally the chemicals serve as clarifiers, emulsifiers, emulsion breakers, floating agents, and oxygen scavengers. Among proprietary formulations, a few specific chemicals have been disclosed including low concentrations of benzene, toluene, and inorganics (acetic acid, ammonium chloride, cupric sulfate, sodium hypochlorite).

naturally occurring radionuclides (e.g., radium-226, radium-228) ([Chapman et al., 2012](); [Rowan et al., 2011]()); and organics (e.g., hydrocarbons) ([Orem et al., 2007](); [Sirivedhin and Dallbauman, 2004]()).

7.3.4.2 Variability in Produced Water Composition Among Unconventional Reservoirs

[Alley et al. (2011)]() compared geochemical parameters of shale gas, tight gas, and CBM produced water. This comparison aggregated data on produced water from original analyses, peer-reviewed literature, and public and confidential government and industry sources and determined the statistical significance of the results.

As shown in Table 7-5, [Alley et al. (2011)]() found that of the constituents of interest common to all three types of produced water from unconventional reservoirs (calcium, chloride, potassium, magnesium, manganese, sodium, and zinc):

1. Shale gas produced water had significantly different concentrations from those of CBM;

2. Shale gas produced water constituent concentrations were significantly similar to those of tight gas, except for potassium and magnesium; and

3. Five tight gas produced water constituent concentrations (calcium, chloride, potassium, magnesium, and sodium) were significantly similar to those of CBM ([Alley et al., 2011]()).

The degree of variability between produced waters of these three resource types is consistent with the degree of mineralogical and geochemical similarity between shale and sandstone formations, and the lack of the same between shale and coalbed formations ([Marshak, 2004]()). Compared to the others, shale gas produced water tends to be more acidic, as well as enriched in strontium, barium, and bromide. CBM produced water is alkaline, and it contains relatively low concentrations of TDS (one to two orders of magnitude lower than in shale and sandstone). It also contains lower levels of sulfate, calcium, magnesium, DOC, sodium, bicarbonate, and oil and grease than typically observed in shale and sandstone produced waters ([Alley et al., 2011](); [Dahm et al., 2011](); [Benko and Drewes, 2008](); [Van Voast, 2003]()).[1]

Table 7-5. Compiled minimum and maximum concentrations for various geochemical constituents in produced water from shale gas, tight gas, and CBM produced water.
Source: [Alley et al. (2011)]().

Parameter	Unit	Shale gas[a]	Tight Gas Sands[b]	CBM[c]
Alkalinity	mg/L	160–188	1,424	54.9–9,450
Ammonium-N	mg/L	-	2.74	1.05–59
Bicarbonate	mg/L	ND–4,000	10–4,040	-
Conductivity	µS/cm	-	24,400	94.8–145,000
Nitrate	mg/L	ND–2,670	-	0.002–18.7

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[1] Several regions had low representation in the [Alley et al. (2011)]() data set, including the Appalachian Basin (western New York and western Pennsylvania), West Virginia, eastern Kentucky, eastern Tennessee, and northeastern Alabama.

Parameter	Unit	Shale gas[a]	Tight Gas Sands[b]	CBM[c]
Oil and grease	mg/L	-	42	-
pH	SU[d]	1.21–8.36	5–8.6	6.56–9.87
Phosphate	mg/L	ND–5.3	-	0.05–1.5
Sulfate	mg/L	ND–3,663	12–48	0.01–5,590
Radium-226	pCi/g	0.65–1.031	-	-
Aluminum	mg/L	ND–5,290	-	0.5–5,290
Arsenic	mg/L	-	0.17	0.0001–0.06
Boron	mg/L	0.12–24	-	0.002–2.4
Barium	mg/L	ND–4,370	-	0.01–190
Bromide	mg/L	ND–10,600	-	0.002–300
Calcium	mg/L	0.65–83,950	3–74,185	0.8–5,870
Cadmium	mg/L	-	0.37	0.0001–0.01
Chloride	mg/L	48.9–212,700	52–216,000	0.7–70,100
Chromium	mg/L	-	0.265	0.001–0.053
Copper	mg/L	ND–15	0.539	ND–0.06
Fluorine	mg/L	ND–33	-	0.05–15.22
Iron	mg/L	ND–2,838	0.015	0.002–220
Lithium	mg/L	ND–611	-	0.0002–6.88
Magnesium	mg/L	1.08–25,340	2–8,750	0.2–1,830
Manganese	mg/L	ND–96.5	0.525	0.002–5.4
Mercury	mg/L	-	-	0.0001–0.0004
Nickel	mg/L	-	0.123	0.0003–0.20
Potassium	mg/L	0.21–5,490	5–2,500	0.3–186
Sodium	mg/L	10.04–204,302	648–80,000	8.8–34,100
Strontium	mg/L	0.03–1,310	-	0.032–565
Uranium	mg/L	-	-	0.002–0.012
Zinc	mg/L	ND–20	0.076	0.00002–0.59

-, No value available; ND, non-detect. If no range, but a singular concentration is given, this is the maximum concentration.

[a] *n* = 541. Alley et al. (2011) compiled data from USGS (2006); McIntosh and Walter (2005); McIntosh et al. (2002) and confidential industry documents.

[b] *n* = 137. Alley et al. (2011) compiled data from USGS (2006) and produced water samples presented in Alley et al. (2011).

[c] Alley et al. (2011) compiled data from Montana GWIC (2009); Thordsen et al. (2007); ESN Rocky Mountain (2003); Rice et al. (2000); Rice (1999); Hunter and Moser (1990).

[d] SU = standard units.

7.3.4.3 General Water Quality Parameters

Data characterizing the content of produced water from unconventional reservoirs in 12 shale and tight formations and CBM basins were evaluated for this assessment. These reservoirs and basins include parts of 18 states, but the data do not allow for comparison of trends over time.

For most reservoirs, the amount of available general water quality parameter data is variable (see Appendix Table E-2 for an example). Average pH levels range from 5.87 to 8.19, with typically lower values for shales. Larger variations in average specific conductivity are seen among unconventional reservoirs and range from 213 microsiemens (μS)/cm in the Bakken Shale to 184,800 μS/cm in Devonian sandstones (Appendix Table E-2). Shale and tight formation produced waters are enriched in suspended solids, as reported concentrations for total suspended solids and turbidity exceed those of coalbeds by one to two orders of magnitude.

The average dissolved oxygen (DO) concentrations of CBM produced water range from 0.39-1.07 mg/L (Appendix Table E-3). By comparison, well-oxygenated surface water can contain up to 10 mg/L DO at 59 °F (15 °C) (U.S. EPA, 2012a). Thus, coalbed produced water is either hypoxic (less than 2 mg/L DO) or anoxic (less than 0.5 mg/L DO) and, if released to surface waters, could contribute to aquatic organism stress (USGS, 2010; NSTC, 2000).

7.3.4.4 Salinity and Inorganics

The TDS profile of produced water from unconventional reservoirs is dominated by sodium and chloride, with large contributions to the profile from mono- and divalent cations (Sun et al., 2013; Guerra et al., 2011). Shale and sandstone produced waters tend to be characterized as sodium-chloride-calcium water types, whereas CBM produced water tends to be characterized as sodium chloride or sodium bicarbonate water types (Dahm et al., 2011). Elevated levels of bromide, sulfate, and bicarbonate are also present (Sun et al., 2013). Elevated strontium and barium levels are characteristic of Marcellus Shale produced water (Barbot et al., 2013; Haluszczak et al., 2013; Chapman et al., 2012). Data representing shales and tight formations are presented in Appendix Table E-4.

Marcellus Shale produced water salinities range from less than 1,500 mg/L to over 300,000 mg/L, as shown by Rowan et al. (2011). By comparison, the average salinity concentration for seawater is 35,000 mg/L.

Of the CBM data presented in Appendix Table E-5, differences are evident between the Black Warrior and the three western formations (Powder River, Raton, and San Juan). The Black Warrior is higher in average chloride, specific conductivity, TDS, TOC, and total suspended solids, and lower in alkalinity and bicarbonate than the other three. These differences are due to the saline or brackish conditions during deposition in the Black Warrior, and its older geologic age that contrasts with the freshwater conditions for the younger western basins. The TDS concentration of CBM

produced water can range from 170 mg/L to nearly 43,000 mg/L (range composited from Dahm et al. (2011) and Benko and Drewes (2008); see also Van Voast (2003)).[1]

7.3.4.5 Metals

The metals content of produced water from unconventional reservoirs varies by well and site lithology. Levels of iron, magnesium, and boron were within ranges known for conventional produced water (Hayes, 2009). Produced water from unconventional reservoirs may also contain low levels of heavy metals (e.g., chromium, copper, nickel, zinc, cadmium, lead, arsenic, and mercury as found by Hayes). Data illustrating metal concentrations in produced water appear in Appendix Tables E-6 and E-7.

7.3.4.6 Naturally Occurring Radioactive Material (NORM) and Technologically Enhanced Naturally Occurring Radioactive Material (TENORM)

Geologic environments contain naturally occurring radioactive material (NORM). Radioactive materials commonly present in shale and sandstone sedimentary environments include uranium, thorium, radium, and their decay products. Elevated formation uranium levels have been used to identify potential areas of natural gas production for decades (Fertl and Chilingar, 1988). Shales that contain significant levels of uranium include the Barnett in Texas, the Woodford in Oklahoma, the New Albany in the Illinois Basin, the Chattanooga Shale in the southeastern United States, and a group of black shales in Kansas and Oklahoma (Swanson, 1955).[2] When exposed to the environment in produced water, NORM is called *technologically enhanced* naturally occurring radioactive material (TENORM).[3] Water soluble forms of TENORM are present in most produced water from unconventional reservoirs, but particularly so in Marcellus Shale produced water (Rowan et al., 2011; Fisher, 1998).

Due to insolubility under prevailing reducing conditions encountered within shale formations, only low levels of uranium and thorium are found in produced water, typically in the concentrated form of mineral phases or organic matter (Nelson et al., 2014; Sturchio et al., 2001). Conversely, radium, a decay product of uranium and thorium, is known to be relatively soluble within the redox range encountered in subsurface environments (Sturchio et al., 2001; Langmuir and Riese, 1985). As noted in Section 7.3.3.2, radium and TDS produced water concentrations are positively correlated (Rowan et al., 2011; Fisher, 1998); therefore, in formations containing radium, increasing TDS concentration indicates likely increasing radium concentration.

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[1] From a similar dataset, Dahm et al. (2011) report TDS concentrations from a composite CBM produced water database (n = 3,255) for western basins that often are less than 5,000 mg/L (85% of samples).

[2] Marine black shales are estimated to contain an average of 15–60 ppm uranium depending on depositional conditions (Fertl and Chilingar, 1988).

[3] The U.S. EPA Office of Air and Radiation's website (https://www.epa.gov/radiation/technologically-enhanced-naturally-occurring-radioactive-materials-tenorm) states that TENORM is produced when activities such as uranium mining or sewage sludge treatment concentrate or expose radioactive materials that occur naturally in ores, soils, water, or other natural materials. Formation water containing radioactive materials contains NORM, because it is not exposed; produced water contains TENORM, because it has been exposed to the environment.

Median values of total radium in the Marcellus Shale ranged from about 1,000 pCi/L to less than 6,000 pCi/L, which are values far exceeding the industrial discharge limit of 60 pCi/L (Rowan et al., 2011) (Figure 7-6). In the Marcellus Shale, TENORM levels in produced water from unconventional reservoirs exceeded levels from conventional reservoirs levels by factors of 4 to 26 (PA DEP, 2015b) (Appendix Table E-8). The individual median concentrations in produced water from unconventional reservoirs of 11,300 pCi/L gross alpha, 3,445 pCi/L gross beta, and total radium of 7,180 pCi/L (Appendix Table E-8). TENORM has been identified in hydraulic fracturing fluid, presumably due to the reuse of produced water at levels from 2 to 4.5 times lower than produced water from unconventional reservoirs (PA DEP, 2015b) (Appendix Table E-8).
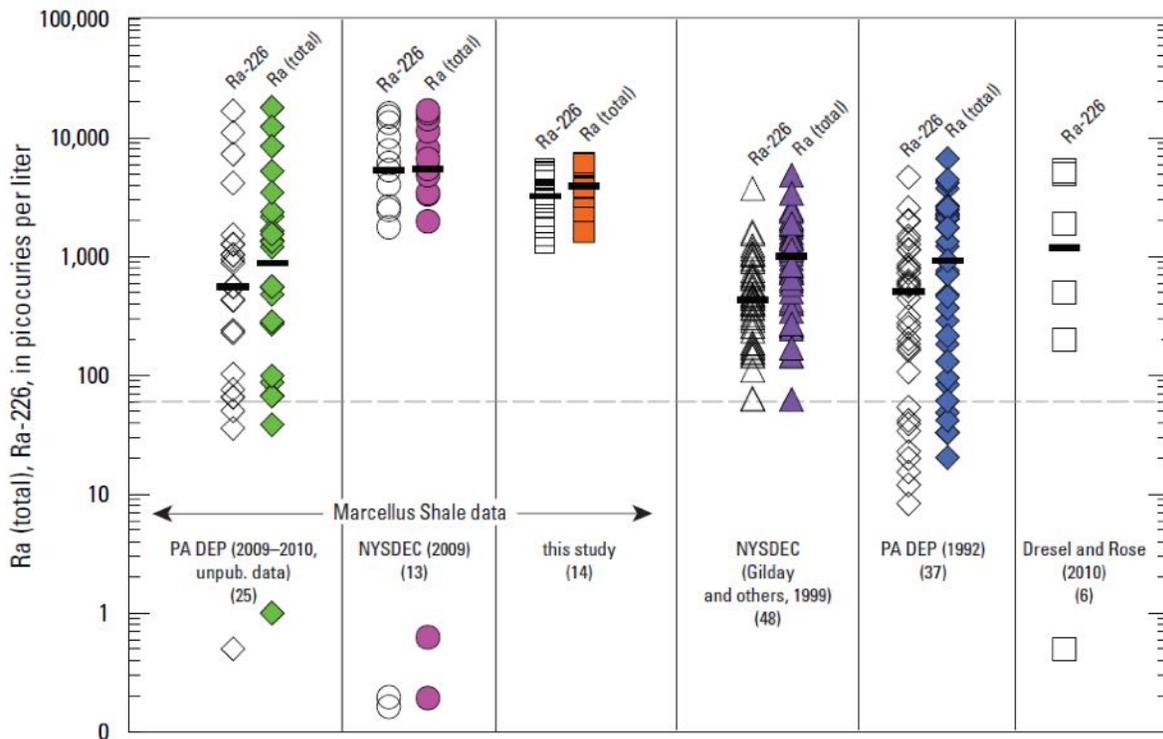

Figure 7-6. Data on radium 226 (open symbols) and total radium (filled symbols) for Marcellus Shale wells (leftmost three columns) and other formations (rightmost three columns).
Source: Rowan et al. (2011). The dashed line represents the industrial effluent discharge limit of 60 pCi/L set by the Nuclear Regulatory Commission. The black lines indicate the median concentrations, and the number of points in each dataset are shown in parentheses. Citations within the figure are provided in Rowan et al. (2011).

7.3.4.7 Organics

The organic content of produced water varies by well and lithology, but consists of naturally occurring and injected organic compounds (Lee and Neff, 2011). Of the organics detected by either routine or advanced analytical methods (Section 7.3.1), the majority are naturally occurring constituents of petroleum (Appendix Tables H-4 and H-5). These organics may be dissolved in water or, in the case of oil production, in the form of a separate or emulsified phase. Several classes of organic chemicals have been found in shale gas and CBM produced water, including aromatics,

polyaromatic hydrocarbons, heterocyclic compounds, aromatic amines, phenols, phthalates, aliphatic alcohols, fatty acids, and nonaromatic compounds (list from Orem et al. (2014), see also: Hayes (2009), Benko and Drewes (2008), Orem et al. (2007), and Sirivedhin and Dallbauman (2004)). Compounds found in CBM waters included pyrene, phenanthrenone, alkyl phthalates, C_{12} through C_{18} fatty acids, and others. Similarly, compounds found in shale gas produced water included pyrene and perylene, ethylene glycol, diethylene glycol monodocecyl ether, 2-(2-butoxyethoxy) ethanol, and others (Orem et al., 2014). Biomarkers—organic molecules characteristically produced by life forms, and unique to shale formations—have recently been suggested to fingerprint produced water (Hoelzer et al., 2016). More representative examples from five coal bed and two shale gas formations with reported concentrations are given in Appendix Tables E-9, E-11, and E-12, and the complete list of chemicals with CAS registry numbers identified by the EPA for this assessment appears in Appendix H. (See Appendix Table H-4 for chemicals with EPA-identified CAS numbers and Appendix Table H-5 for chemicals without.) Appendix Table E-13 lists concentrations of organic chemicals that were identified in three specific studies (Khan et al., 2016; Lester et al., 2015; Orem et al., 2007).

7.3.4.8 Hydraulic Fracturing Fluid Additives

Several chemicals used in hydraulic fracturing fluids have been identified in produced water. (Examples are shown in Table 7-6, Appendix Table E-10, and Appendix Tables H-4 and H-5.) Many of these chemicals were identified through advanced analytical procedures and equipment, and would not be expected to be found by routine analyses. Of note is that phthalates do not occur naturally. Their presence in produced water is due to either their use in hydraulic fracturing fluids; polyvinyl chloride (PVC) in well adhesives, valves, or fittings; or coatings on laboratory sample bottles (Orem et al., 2007).[1] Phthalates can also be used in drilling fluids, as breaker additives, or as plasticizers (Maguire-Boyle and Barron, 2014; Hayes and Severin, 2012a).[2] One of the produced water phthalates has been identified as a component of hydraulic fracturing fluid (di(2-ethylhexyl) phthalate) (Appendix Table H-2), while others have not, and those may originate from laboratory or field equipment.

Table 7-6. Examples of compounds identified in produced water that can be components of hydraulic fracturing fluid.

Appendix Tables H-4 and H-5 list chemicals identified in produced water and indicates those also identified as constituents of hydraulic fracturing fluid. Chemical or class designation in this table is taken directly from the text of the cited references except where noted, and may or may not reflect the chemical names from the Distributed Structure-Searchable Toxicity Database (DSSTox) show in Appendix Table H-4 or other chemicals listed in Appendix Table H-5.

Chemical or class	Use	Reference
2-Butanone	Solvent; microbial degradation product	Lester et al. (2015)

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[1] Examples include di(2-ethylhexyl) phthalate, diisodecyl phthalate, and diisononyl phthalate (Orem et al., 2007).

[2] Specifically fatty acid phthalate esters (Maguire-Boyle and Barron, 2014).

Chemical or class	Use	Reference
2-Butoxyethanol	Acid dispersant, solvent, non-emulsifier	Thacker et al. (2015)
Acetone	Solvent; microbial degradation product	Lester et al. (2015)
Cocamidopropyl dimethylamine (C-7)	Foaming and lubrication enhancer	Lester et al. (2015)
Di(2-ethylhexyl) phthalate[a]	Derivative of polyvinyl chloride used in adhesives, valves, fittings or coatings of sample bottles	Orem et al. (2007)
Diethylene glycol monododecyl ether	Antifreeze, scale inhibitor, friction reducer	Orem et al. (2014)
Dioctadecyl ester of phosphate phosphoric acid	Common lubricant	Maguire-Boyle and Barron (2014)
Ethylene glycol	Antifreeze, scale inhibitor, friction reducer	Orem et al. (2014)
Fatty acid phthalate esters	(Related to) use in drilling fluids and breakers	Maguire-Boyle and Barron (2014)
Fluorocarbons	Tracers	Maguire-Boyle and Barron (2014)
Hexahydro-1,3,5-trimethyl-1,3,5-triazine-2-thione	Biocide	Orem et al. (2014)
Linear alkyl ethoxylates (C-4 to C-8, C-11 to C-14)	Enhancer of surfactant properties	Lester et al. (2015); Thurman et al. (2014)
Polyethylene glycol carboxylates (PEG-C-EO2 to PEG-C-EO10)	Friction reducer, clay stabilizer, surfactants	Thurman et al. (2016)
Polyethylene glycols (PEG-EO4 to PEG-EO10)	Friction reducer, clay stabilizer, surfactants	Thurman et al. (2016)
Polypropylene glycols (PPG-PO2 to PPG PO10)	Friction reducer, clay stabilizer, surfactants	Thurman et al. (2016)
Toluene	Solvent, scale inhibitor	Thacker et al. (2015)
Triethylene glycol monododecyl ether	Antifreeze, scale inhibitor, friction reducer	Orem et al. (2014)
Xylenes	Solvent, scale inhibitor	Thacker et al. (2015)

[a] Di(2-ethylhexyl) phthalate was named di-2-ethyl hexyl phthalate in Maguire-Boyle and Barron (2014).

7.3.4.9   Reactions within Formations

The introduction of hydraulic fracturing fluids into the target formation induces a number of changes to formation solids and fluids that influence the chemical evolution and composition of produced water. These changes can result from physical processes (e.g., rock fracturing and fluid mixing); geochemical processes (e.g., introducing oxygenated fluids of composition unlike that of the formation); and down hole conditions (elevated temperature, salinity, and pressure) that mobilize trace or major constituents into solution.

The creation of fractures exposes new formation surfaces to interactions involving hydraulic fracturing fluids and existing formation fluids. Formations in unconventional reservoirs targeted for development are composed of detrital, cement, and organic fractions. For example, elements potentially available for mobilization when exposed via fracturing include calcium, magnesium, manganese, and strontium in cement fractions, and silver, chromium, copper, molybdenum, niobium, vanadium, and zinc in organic fractions.

From organic compounds identified in five flowback samples and one produced water sample from the Fayetteville Shale, three possible types of reactions were identified by Hoelzer et al. (2016): hydrolysis of delayed acids, oxidant-caused halogenation reactions, and transformation of disclosed additives. First, delayed acids are used to "break" gel structures and would be intentionally introduced for their ability to cause in-formation reactions. Second, strong oxidants or other compounds introduced as breakers, along with elevated temperature and salinity, can trigger reactions between halogens (chloride, bromide, and iodide) and methane, acetone and pyrane resulting in halomethane compounds. A similar suggestion was made by Maguire-Boyle and Barron (2014). Low pH was found to promote oxidation of additives (Tasker et al., 2016). Third, known additives may react to form byproducts. Hoelzer et al. (2016) postulate examples from several types of compounds, two of these are the formation of benzyl alcohol from the hydraulic fracturing additive benzyl chloride, and abiotic and biotic reactions of phenols. In a study that used synthetic fracturing fluid, Tasker et al. (2016) reported that surfactants were recalcitrant to degradation under high pressure and temperature, which may explain the presence of the surfactant glycols in produced water as reported by Thurman et al. (2016) (Table 7-6), and the oxidation of other additives (gelling and some friction reducers (Table 5-1)) may explain their absence.

7.3.5   Spatial Trends in Produced Water Composition

As was reported for the volume of produced water (Section 7.2.2), the composition of produced water varies spatially on a regional to local scale according to the geographic and stratigraphic locations of each well within a hydraulically fractured production zone (Bibby et al., 2013; Lee and Neff, 2011). Spatial variability of produced water content occurs: (1) between plays of different rock sources (e.g., coal vs. sandstone); (2) between plays of the same rock type (e.g., Barnett Shale vs. Bakken Shale); and (3) within formations of the same source rock (e.g., northeastern vs. southwestern Marcellus Shale) (Barbot et al., 2013; Alley et al., 2011; Breit, 2002).

Geographic variability in produced water content has been established at a regional scale for conventional produced water. As an example, Benko and Drewes (2008) demonstrate TDS

variability in conventional produced water among fourteen western geologic basins (e.g., Williston, San Juan, and Permian Basins). Median TDS in these basins range from as low as 4,900 mg/L in the Big Horn Basin to as high as 132,400 mg/L in the Williston Basin based on over 133,000 produced water samples from fourteen basins ([Benko and Drewes, 2008]).[1]

Average or median TDS of more than 100,000 mg/L has been reported for the Bakken (North Dakota, Montana) and Marcellus (Pennsylvania) formations; between 50,000 mg/L and 100,000 mg/L for the Barnett (Texas), and less than 50,000 mg/L for the Fayetteville (Arkansas) shale formations.[2] In tight formations, the average TDS was above 100,000 mg/L for the Devonian Sandstone (Pennsylvania) and Cotton Valley Group (Louisiana, Texas), between 50,000 mg/L and 100,000 mg/L for the Oswego (Oklahoma), and less than 50,000 mg/L for the Mesaverde Formation (Colorado, New Mexico, Utah, Wyoming). Maximum concentrations above 200,000 mg/L have been reported for the Marcellus, Bakken, Cotton Valley Group and Devonian Sandstone (Appendix Table E-2).

CBM produced waters had average TDS of less than 5,000 mg/L in the Powder River (Montana, Wyoming), Raton (Colorado, New Mexico), and San Juan (Arizona, Colorado, New Mexico, Utah) basins; while above 10,000 mg/L in the Black Warrior Basin (Alabama, Mississippi), which as noted above are due to the depositional history of these basins (Appendix Table E-3, Section 7.3.2).

Data further illustrating variability within both shale and tight gas reservoirs, as well as coalbed methane fields, at both the formation and local scales are presented and discussed in Appendix Section E.3.

7.4 Spill and Release Impacts on Drinking Water Resources

Surface spills of produced water from oil and gas production have occurred across the country and, in some cases, have caused impacts to drinking water resources. Released fluids can flow into nearby surface waters, if not contained on-site, or infiltrate into groundwater via soil. In this section, we first briefly describe the potential for spills from produced water handling equipment. Next, we address individually reported spill events. These have originated from pipeline leaks, well blowouts, well communication events, and leaking pits and impoundments. We then summarize several studies of aggregated spill data, which are based on state agency spill reports.

7.4.1 Produced Water Handling and Spill Potential

Throughout the production phase at oil and certain wet gas production facilities, produced water is stored in containers and pits that can contain free phase, dissolved phase, and emulsified crude oil. Since the crude oil is not efficiently separated out by the flow-through process vessels (such as

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[1] Data were drawn from the USGS National Produced Water Geochemical Database v2.0. Published updates made in October 2014 to the database (v2.1) are not reflected in this document.

[2] Because publications we are comparing may report either average or median values (but not uniformly both), we combine average and medians in this paragraph.

three-phase separators, heater treaters, or gun barrels), this crude oil can remain present in the produced water container or pit.

Produced water can be transferred to surface pits for long-term storage and evaporation. Surface pits are typically uncovered, earthen pits that may or may not be lined.[1] Unlined pits can lead to contamination of groundwater, especially shallow alluvial systems. Recovered fluids can overflow or leak from surface pits due to improper pit design and weather events.

Produced water that is to be treated or disposed of off-site is typically stored in storage tanks or pits until it can be loaded into transport trucks for removal (Gilmore et al., 2013). Tank storage systems are typically closed loop systems in which produced water is transported from the wellhead to aboveground storage tanks through interconnecting pipelines (GWPC and IOGCC, 2014). Failure of connections and lines during the transfer process or the failure of a storage tank can result in a surface release of fluids.

Depending on its characteristics, produced water can be recycled and reused on-site. It can be directly reused without treatment (after blending with freshwater), or it can be treated on-site prior to reuse (Boschee, 2014). As with other produced water management options, these systems also can spill during transfer of fluids.

7.4.2   Spills of Produced Water

7.4.2.1   Pipeline Leaks

Produced water is typically transported from the wellhead through a series of pipes or flowlines to on-site storage or treatment units (GWPC and IOGCC, 2014), or nearby injection wells. Faulty connections at either end of the transfer process or leaks or ruptures in the lines carrying the fluid can result in surface spills. A field report from PA DEP (2009b) described a leak from a 90-degree bend in an overland pipe carrying a mixture of produced water and freshwater between two pits. The impact included a "dull sheen" on the water and measured chloride concentration of 11,000 mg/L. The leak impacted a 0.4 mi (0.6 km) length of a stream, and fish and salamanders were killed. Beyond a confluence at 0.4 mi (0.6 km) with a creek, no additional dead fish were found. The release was estimated at 11,000 gal (42,000 L). In response to the incident, the pipeline was shut off, a dam was constructed for recovering the water, water was vacuumed from the stream, and the stream was flushed with fresh water (PA DEP, 2009b).

Another example of a pipeline release occurred in January 2015, when 70,000 bbls (2,940,000 gal or 11,130,000 L) of produced water containing petroleum hydrocarbons (North Dakota Department of Health, 2015) were released from a broken pipeline that crosses Blacktail Creek in Williams County, ND. The response included placing absorbent booms in the creek, excavating contaminated soil, removing oil-coated ice, and removing produced water from the creek. The electrical conductivity and chloride concentration in the water along the creek, the Little Muddy River, and Missouri River were found to be elevated above background levels, as were samples

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[1] The use of the terms "impoundments" and "pits" varies and is described in Chapter 8. For the purposes of this section, the term "pits" will be generally used to cover all below-grade storage (but not above ground closed or open tanks).

taken from groundwater recovery trenches. Remediation work on this site continues as of the date of this writing (August, 2016).

7.4.2.2   Well Blowouts

Spills of produced water have occurred as a result of well blowouts. Fingerprinting of water from two monitoring wells in Killdeer, ND, was used to determine that brine contamination in the two wells resulted from a well blowout during a hydraulic fracturing operation. See the discussion in Section 6.2.2.1 for more information.

Another example of a well blowout associated with a hydraulic fracturing operation occurred in Clearfield County, PA. The well blew out, resulting in an uncontrolled flow of approximately 35,000 gal (132,000 L) of brine and fracturing fluid; some of the liquids reportedly reached a nearby stream (Barnes, 2010). The blowout occurred during drilling of plugs that were used to isolate fracture stages from each other. An independent investigation found that the primary cause of the incident was that the sole blowout preventer on the well had not been properly tested. In addition, the company did not have certified well control experts on hand or a written pressure control procedure (Vittitow, 2010).

In North Dakota, a blowout preventer failed, causing a release of between 50 and 70 bbls per day (2,100 gal/day or 7,900 L/day and 2,940 gal/day or 11,100 L/day) of produced water and oil (Reuters, 2014). Frozen droplets of oil and water sprayed on a nearby frozen creek. Liquid flowing from the well was collected and trucked offsite. A 3-ft (0.9-m) berm was placed around the well for containment. Multiple well communication events have also led to produced water spills ranging from around 700 to 35,000 gal (2,600 L to 130,000 L) (Vaidyanathan, 2013a). Well communication is described in Section 6.3.2.3.

The Chesapeake Energy ATGAS 2H well, located in Leroy Township, Bradford County, PA, experienced a wellhead flange failure on April 19, 2011, during hydraulic fracturing operations. Approximately 10,000 gal (38,000 L) of produced water spilled into an unnamed tributary of Towanda Creek, a state-designated trout stock fishery and a tributary of the Susquehanna River (USGS, 2013b; SAIC and GES, 2011). Chesapeake conducted post-spill surface water and groundwater monitoring (SAIC and GES, 2011).

Chesapeake concluded that there were short-term impacts to surface waters of a farm pond within the vicinity of the well pad, the unnamed tributary, and Towanda Creek following the event (SAIC and GES, 2011). The lower 500 ft (200 m) of the unnamed tributary exhibited elevated chloride, TDS, and specific conductance, which returned to background levels in less than a week. Towanda Creek experienced these same elevations in concentration, but only at its confluence with the unnamed tributary; elevated chloride, TDS, and specific conductance returned to background levels the day after the blowout (SAIC and GES, 2011).

7.4.2.3   Leaks from Pits and Impoundments

Leaks of produced water from on-site pits have caused releases as large as 57,000 gal (220,000 L) and have caused surface water and groundwater impacts (Vaidyanathan, 2013b; Levis,

2011; 2010c; PADEP, 2010). VOCs have been measured in groundwater near the Duncan Oil Field in New Mexico downgradient of an unlined pit storing produced water. More example releases from pits are described in Section 8.4.5.

Two of EPA's retrospective case studies evaluated potential impacts from produced water pits. The EPA retrospective case studies were designed to determine whether multiple lines of evidence might be found that could specifically link constituent(s) found in drinking water to hydraulic fracturing activities using the tiered assessment framework presented in Appendix Section E.6. A multiple-lines-of-evidence approach was used to evaluate potential cause-and-effect relationships between hydraulic fracturing activities and contaminant presence in groundwater. Such an approach is needed, because the presence of a constituent in groundwater that is also found in hydraulic fracturing fluids or produced water does not necessarily implicate hydraulic fracturing activities as the cause. This is because some constituents of hydraulic fracturing fluids or produced water are ubiquitous in society (i.e., BTEX), and some constituents of produced water can be present in groundwater as background constituents (i.e., methane, iron, and manganese).

Elements of the assessment framework include gathering background information, including pre-drilling sample results; developing a conceptual model of the site; and assessing multiple analytes to develop lines of evidence. Development of these requires adherence to sampling and quality assurance protocols to generate defensible data. Among many other quality assurance requirements, proper well purging and analyses of field and laboratory blanks are needed (Appendix Table E-17 and Figure E-15).

In the EPA's *Retrospective Case Study in Southwestern Pennsylvania: Study of the Potential Impacts of Hydraulic Fracturing on Drinking Water Resources* (U.S. EPA, 2015j), elevated chloride concentrations and their timing relative to historical data suggested a recent groundwater impact on a private water well occurred near a pit. The water quality trends suggested that the chloride anomaly was related to the pit, but site-specific data were not available to provide a definitive assessment of the cause(s) and the longevity of the impact. Evaluation of other water quality parameters did not provide clear evidence of produced water impacts.

In the EPA's *Retrospective Case Study in Wise County, Texas: Study of the Potential Impacts of Hydraulic Fracturing on Drinking Water Resources* (U.S. EPA, 2015l), impacts to two water wells were attributed to brine, but the data collected for the study were not sufficient to distinguish among multiple possible brine sources, including reserve pits, migration from underlying formations along wellbores, migration from underlying formation along natural fractures and a nearby brine injection well.

To aid in assessing impacts, a number of geochemical indicators and isotopic tracers for identifying oil and gas produced water have been identified. These include (Lauer et al., 2016; Warner et al., 2014a, b):

- Common ion ratios, including bromide/chloride and lithium/chloride;
- Isotope ratios, especially Strontium isotope ratios ($^{87}Sr/^{86}Sr$); and

- Enrichment of certain isotopes: $\delta^{18}O$, δ^2H, δ^7Li, $\delta^{13}C\text{-DIC}$, $\delta^{11}B$.[1]

For the case study, twelve geochemical indicators, including the bromine/chlorine (Br/Cl) and strontium isotope ratios, were considered for the well-water samples.[2] The results were used to assess whether the likelihood that the observed values originated with produced water (the aforementioned sources of brine), sea water, road salt, landfill leachate, sewage/septic tank leachate, and animal waste. In each sample evaluated, it was found that the water could have originated with one or more of the six sources. Thus these lines of evidence did not allow identification of neither a specific source nor a hydraulic fracturing source (Appendix Table E-18). A third well experienced similar impacts, and a landfill leachate source could not be ruled out in that case.

The case studies illustrate how multiple lines of evidence were needed to assess suspected impacts and that no single constituent or parameter could be used alone to assess potential impacts.

7.4.2.4 Other Sources

In the EPA's *Retrospective Case Study in Northeastern Pennsylvania: Study of the Potential Impacts of Hydraulic Fracturing on Drinking Water Resources* (U.S. EPA, 2014f), a pond was found to be impacted due to elevated chloride and TDS, along with strontium ratios ($^{87}Sr/^{86}Sr$) characteristic of Marcellus Shale produced water. Here, the suspected source of the impact was a well pad which had a hydrochloric acid spill, a possible produced water spill and been used for temporary storage of drill cuttings. The same mulidence fracturing impacts from constituents characteristic of produced water (TDS, chloride, sodium, barium, strontium and radium) found in three domestic wells located in an area with naturally occurring saline groundwater. Conversely, at a spring with organic chemical contamination but no associated chloride or TDS impacts, hydraulic fracturing activities were also ruled out.

An estimated 6,300 to 57,373 gal (24,000 to 217,280 L) of Marcellus Shale produced water was discharged through an open valve that drained a tank at XTO Energy Inc.'s Marquardt pad and flowed into a tributary of the Susquehanna River in November 2010 (U.S. EPA, 2016e; PA DEP, 2011c). Overland and subsurface flow of released fluids impacted surface water, a subsurface spring, and soil. Five hundred tons of contaminated soil were excavated, and an estimated 8,000 gal (30,000 L) of produced water was recovered (Science Applications International Corporation, 2010). Elevated levels of TDS, chloride, bromide, barium and strontium that indicated a release of produced water were present in the surface stream and a spring for roughly 65 days (U.S. EPA, 2016e). At that time the chloride concentration in the spring dropped below the state surface water standard of 250 mg/L. The impact extended a distance of approximately 1,400 ft (440 m) to the spring from the release point. Samples were taken in the tributary roughly 500 ft downstream from the spring, where chloride concentrations remained below the 250 mg/L standard throughout the sampling period, but were above the upstream concentrations (PA DEP, 2011c; Schmidley and Smith, 2011). Similarly, the total barium, total and dissolved iron, manganese and alkalinity concentrations remained below the Pennsylvania surface water quality standards at the downstream monitoring location throughout the monitoring period (Schmidley and Smith, 2011).

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[1] DIC is dissolved inorganic carbon.
[2] The full list was: Br vs. B, Cl vs. Mg, Cl vs. Br, Cl vs. HCO_3, Cl vs. Ca, Cl vs. K, Cl vs. Na, Cl vs. SO_4, Cl/Br, Cl/I, K/Rb, $^{87}Sr/^{86}Sr$.

In Pennsylvania, discharges of brine were made into a storm drain that itself discharges to a tributary of the Mahoning River in Ohio. Analyses of the brine and drill cuttings that were discharged indicated the presence of contaminants, including benzene and toluene (U.S. Department of Justice, 2014). In California, an oil production company periodically discharged hydraulic fracturing wastewaters to an unlined sump for 12 days. It was concluded by the prosecution that the discharge posed a threat to groundwater quality (Bacher, 2013). These unauthorized discharges represent both documented and potential impacts on drinking water resources. However, data do not exist to evaluate whether such episodes are uncommon or whether they happen on a more frequent basis and remain largely undetected. Other cases of unpermitted discharges have been reported by various sources (Caniglia, 2014; Paterra, 2011).[1]

7.4.2.5   Data Compilation Studies

Three datasets were examined for produced water spill data. These included two published studies: a review of spills in Oklahoma that occurred prior to the onset of widespread high-volume hydraulic fracturing (Fisher and Sublette, 2005), and an EPA study of spills occurring between February 2006 and April 2012 on the well pads of hydraulically fractured wells (U.S. EPA, 2015m). The EPA spills study, *Review of state and industry spill data: characterization of hydraulic fracturing-related spills*, is described in Text Box 5-10. Because of data availability, EPA's study was dominated by data from Pennsylvania (21% of releases) and Colorado (48% of releases). Several difficulties are encountered in compiling and evaluating data on produced water spills and releases. Because states have differing minimum reporting levels, more spills are potentially reported in states with lower reporting limits.[2]

To include data from another state and to give results current to 2015, data from North Dakota were reviewed for this assessment.[3] Details on the procedures and results for non-produced water spills are given in Appendix Section E.5. The North Dakota Department of Health (NDDOH) collects data on environmental incidents and separately compiles oil field incidents; information is made available to the public at http://www.ndhealth.gov/EHS/Spills/. Of these incidents, most describe a release of oil, salt water, or other liquid. Of the remainder, a few describe releases of gas only.

For the period from November 2012 to November 2013, NDDOH reported 552 releases of produced water that were retained within the boundaries of the production or exploration facility and 104 that were not (North Dakota Department of Health, 2011). Thus, 16% of the releases were not contained within facility boundaries and had greater potential for impacting drinking water resources.

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[1] Section 8.4 discusses permitted discharges of wastewater.

[2] For example, two agencies in the state of California manage different databases that both store information on spills associated with oil and gas production (CCST, 2015a). CCST (2015a) reported that the databases contain inconsistencies as to the number of spills and the details regarding those spills (e.g., quantity, chemical composition of the wastewater) resulting in uncertainty on the impacts spills have on the environment.

[3] Wirfs-Brock (2015) presented an analysis of North Dakota spill data through 2013.

7.4.2.6   Frequency of Spills and Releases

The EPA analyzed these data and found that, in recent years (2010-2015), there were between five and seven produced water spills per hundred active production wells (Figure 7-7). Spills declined between 2014 and 2015 (from 846 to 609), although the number of production wells increased. A study of 17 states indicated that there was an overall reduction of 8% in spills from 2014 to 2015, and an increase of 9% in Texas (King and Soraghan, 2016). More details on the data analysis are given in Appendix Section E.5, which includes results on North Dakota oil and spills of other types, including hydraulic fracturing fluids (as noted in Chapter 5).
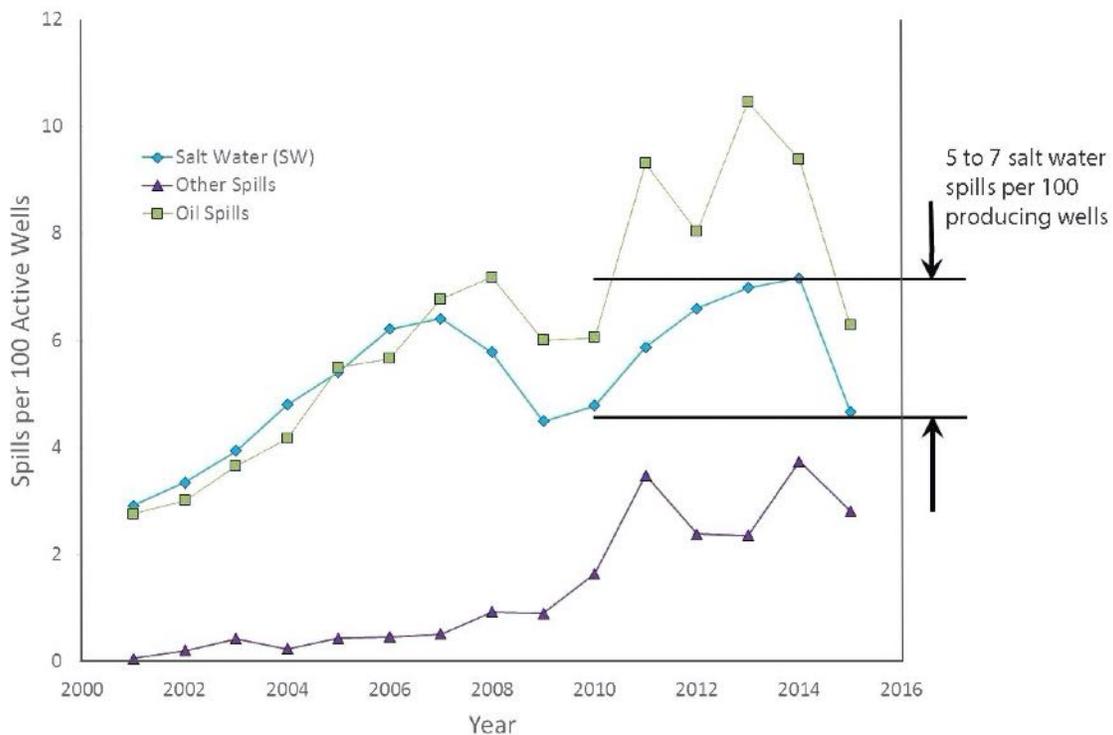
Figure 7-7. Produced water spill rates (spills per active wells) for North Dakota from 2001 to 2015 (Appendix Section E.5).

7.4.2.7   Produced Water Releases—Causes and Sources

The causes and sources identified for releases vary among the three datasets reviewed. North Dakota releases were dominated by leaks from various pieces of equipment, followed by "others," and various overflows (Figure 7-8). While the release rate declined from 2014 to 2015, the causes remained ranked relatively in the same order; notably fewer releases were attributed to "other" and more to equipment failure in 2015. The EPA's spills study found on- or near-well pad releases to be dominated by human error, unknown, and equipment failure (U.S. EPA, 2015m). The earlier

Oklahoma study was dominated by overflows, unpermitted discharges, and storms (Figure 7-9).[1] Storms can cause releases, as was noted after a major flood in northeastern Colorado that caused damage to produced water storage tanks releasing an estimated 43,000 gal (160,000 L) of produced water (COGCC, 2013).

The sources of releases are documented for the Oklahoma and EPA studies (Figure 7-10). The EPA cites storage, unknown, and hoses or lines as the major sources for its 225 well-pad releases. The earlier Oklahoma study cites unclassified, lines, and tanks as major sources of its 8,874 releases.
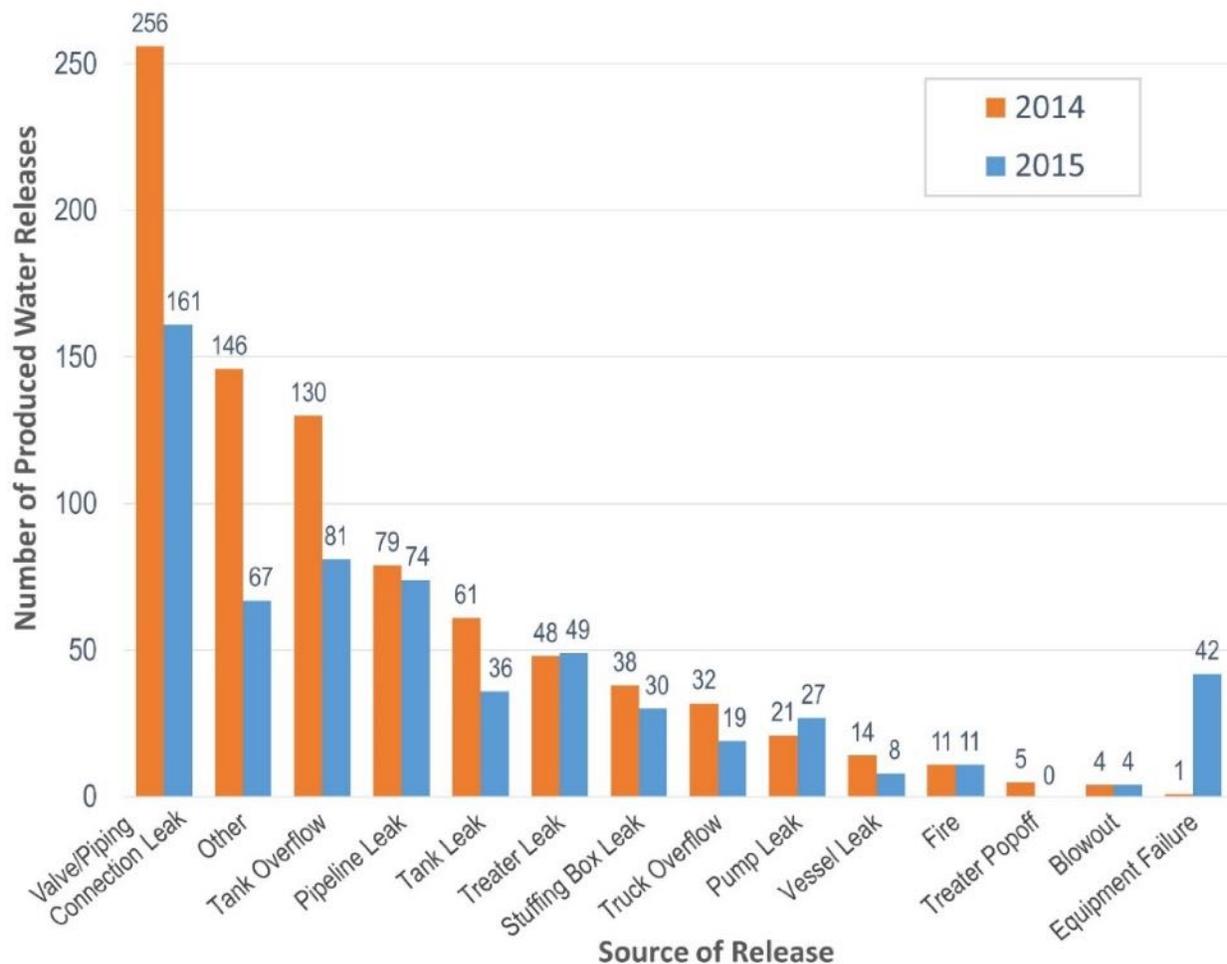
Figure 7-8. Number of produced water releases in North Dakota by cause for 2014 and 2015 (Appendix Section E.5).

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[1] Some of the causes in the three studies may be more similar than they appear, because the categorization used in the different studies overlap. For example, the EPA categorized overflows as "human error;" blowouts, vandalism and weather as "other;" and corrosion as "equipment failure," while other studies listed these separately.
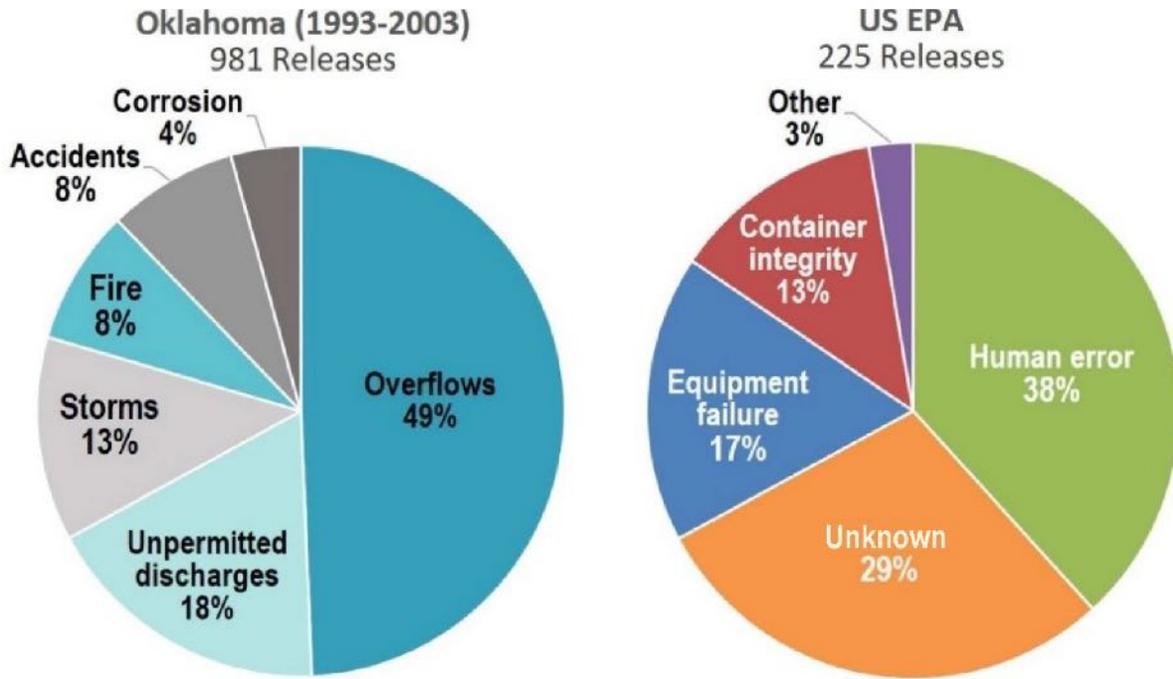
Figure 7-9. Distribution of spill causes in Oklahoma, pre-high volume hydraulic fracturing years of 1993-2003 (left) and in the EPA study of spills on production pads (right).
Data sources: left, Fisher and Sublette (2005); right, U.S. EPA (2015m).
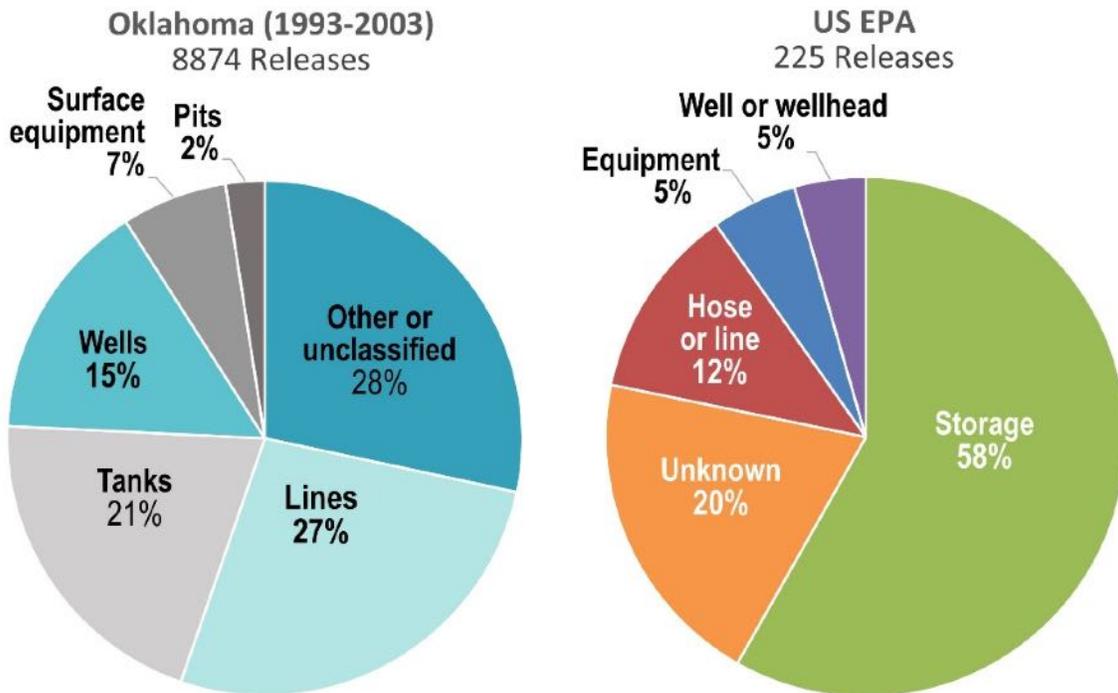
Figure 7-10. Distribution of spill sources in Oklahoma, pre-high volume hydraulic fracturing years of 1993-2003 (left) and in the EPA study of spills on production pads (right).
Data sources: left, Fisher and Sublette (2005); right, U.S. EPA (2015m).

7.4.2.8   The Volumes of Spilled Produced Water

The 2015 North Dakota spills were ranked from by the median volume, which is the level at which 50% of the spills are below this volume and 50% above (Figure 7-11).[1] Of the North Dakota spills in 2015, the highest median spill volume was caused by a blowout (2,400 gal, 91,000 L, left-most red box). The smallest median volume spill is approximately 10 times lower in volume (84 gal, 320 L). Spills larger than the median are of interest, because of their potential for impacting drinking water resources. The largest volume spill occurred from a pipeline break (2,900,000 gal, 11,000,000 L). The EPA spills study found the highest median volume spill was from equipment failure (1,700 gal, 6400 L), while the highest volume spill was due to container integrity (1,300,000 gal, 4,900,000 L) (Figure 7-12).
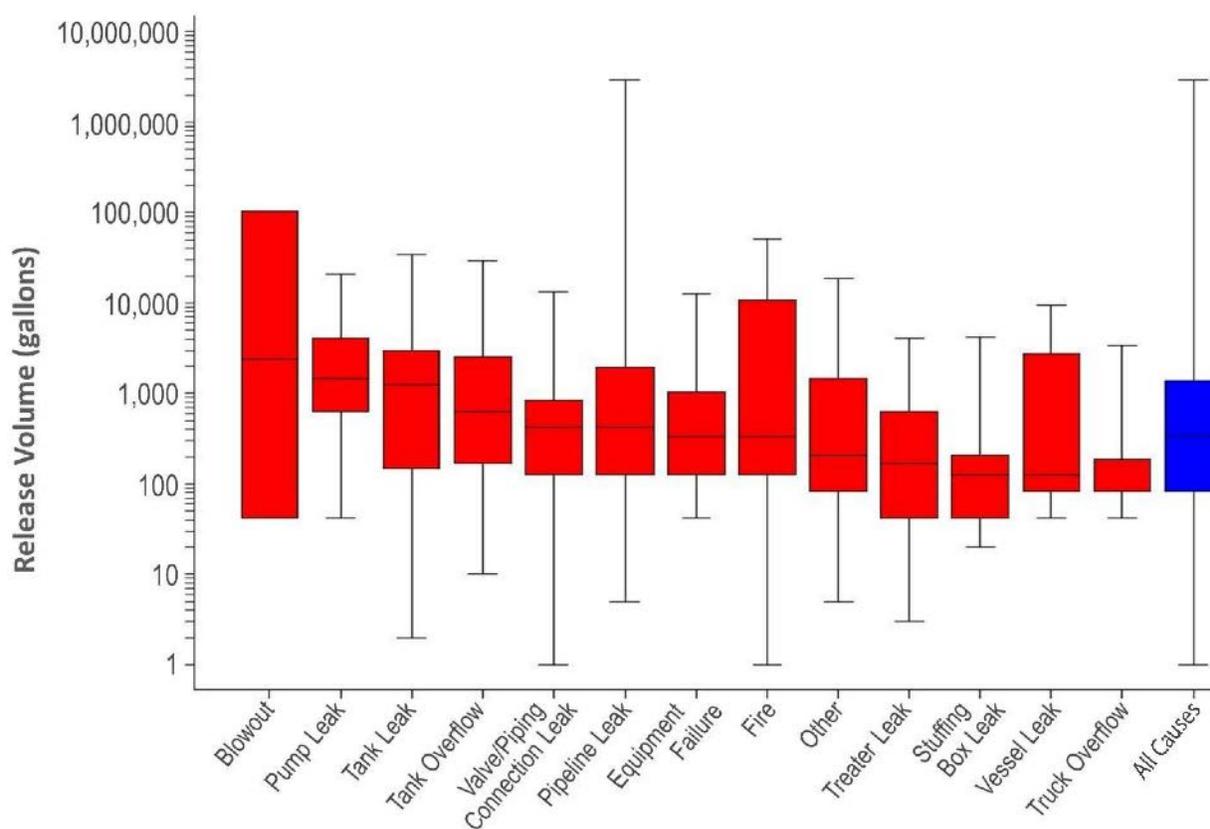
Figure 7-11. Volumes of 2015 North Dakota salt water releases by cause (leftmost 13 boxes in red), and all causes (last box in blue).

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[1] These figures are called "box" plots or "box and whisker" plots. The rectangle in the middle represents the range of data from the 25th to 75th percentile. The line across the box represents the 50th percentile, also known as the median. Fifty percent of the data are below the median. The lines extending above and below the boxes represent the range of data from minimum to maximum. These concepts are illustrated in Appendix Figure E-6.
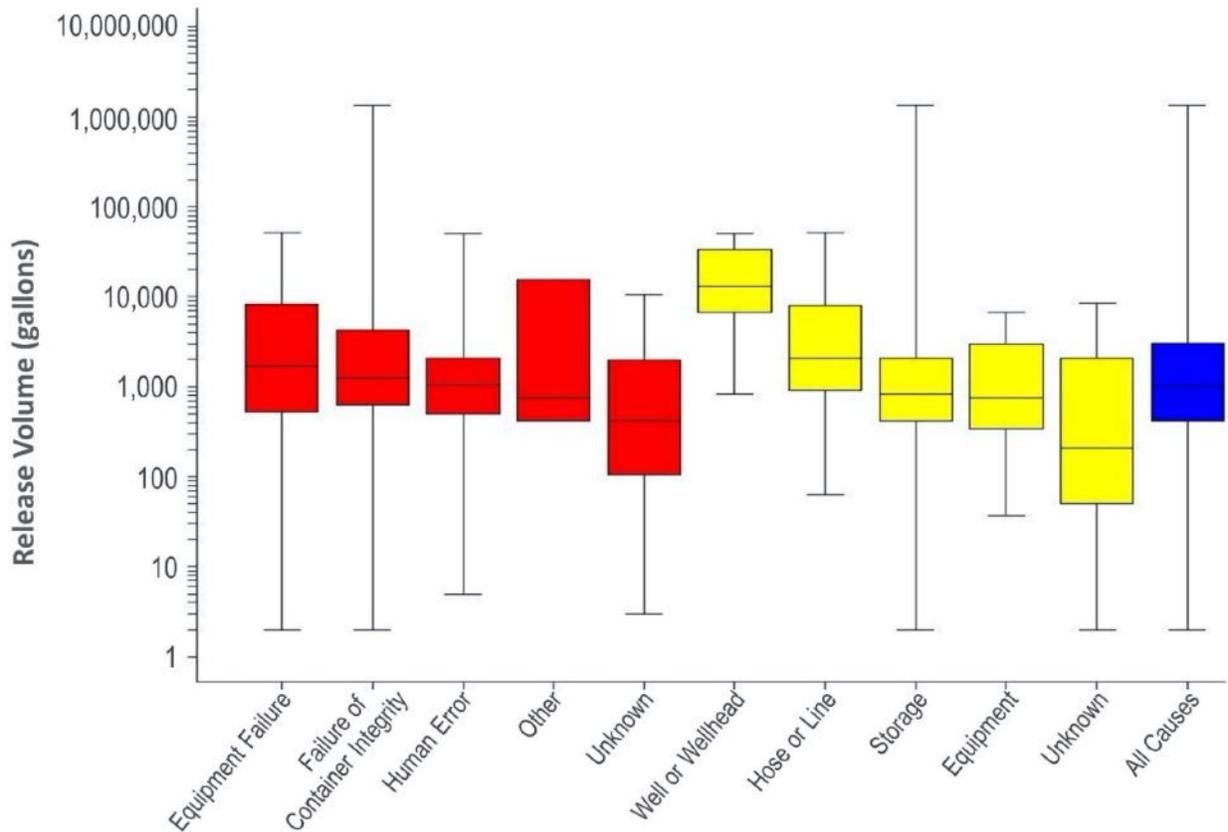
Figure 7-12. Volumes of produced water spills reported by the EPA for 2006 to 2012 by cause (the five left most boxes in red), source (the second five boxes in yellow), and all spills (blue).
Calculated from Appendix B of U.S. EPA (2015m).

From the analyses, half of the spills are less than 1,000 gal (3,800 L) (EPA) and 340 gal (1,300 L) (North Dakota) (Figure 7-12, Figure 7-13, and medians in Table 7-7). The medians for the Oklahoma study were higher (overall 1,700 gal or 6,400 L; see Table 7-7 for yearly values) (Fisher and Sublette, 2005). These occurred in a different state and over an earlier time period, so a direct connection with the recent North Dakota and EPA results has not been made.

The skewed nature of the distributions are noted by the mean values being considerably higher than these medians (see Figure 7-13). In each case, this is caused by a small number of large spills. For 2015 in North Dakota, for example, there were 12 releases of 21,000 gal (79,000 L) or more; 5 of 42,000 gal (160,000 L) or more; and one of greater than 420,000 gal (1,600,000 L) (Appendix Table E-15). The largest spills from these data sets ranged from 1,000,000 gal (3,800,000 L) to 2,900,000 gal (11,000,000 L).

The EPA results give insight into recovery and reuse. Of the volume of spilled produced water, 16% was recovered for on-site use or disposal, 76% was reported as unrecovered, and the rest was unknown. The fewest spills occurred from wells and wellheads, but these spills had the greatest median volumes. Failure of container integrity was responsible for 74% of the volume spilled (U.S. EPA, 2015m).
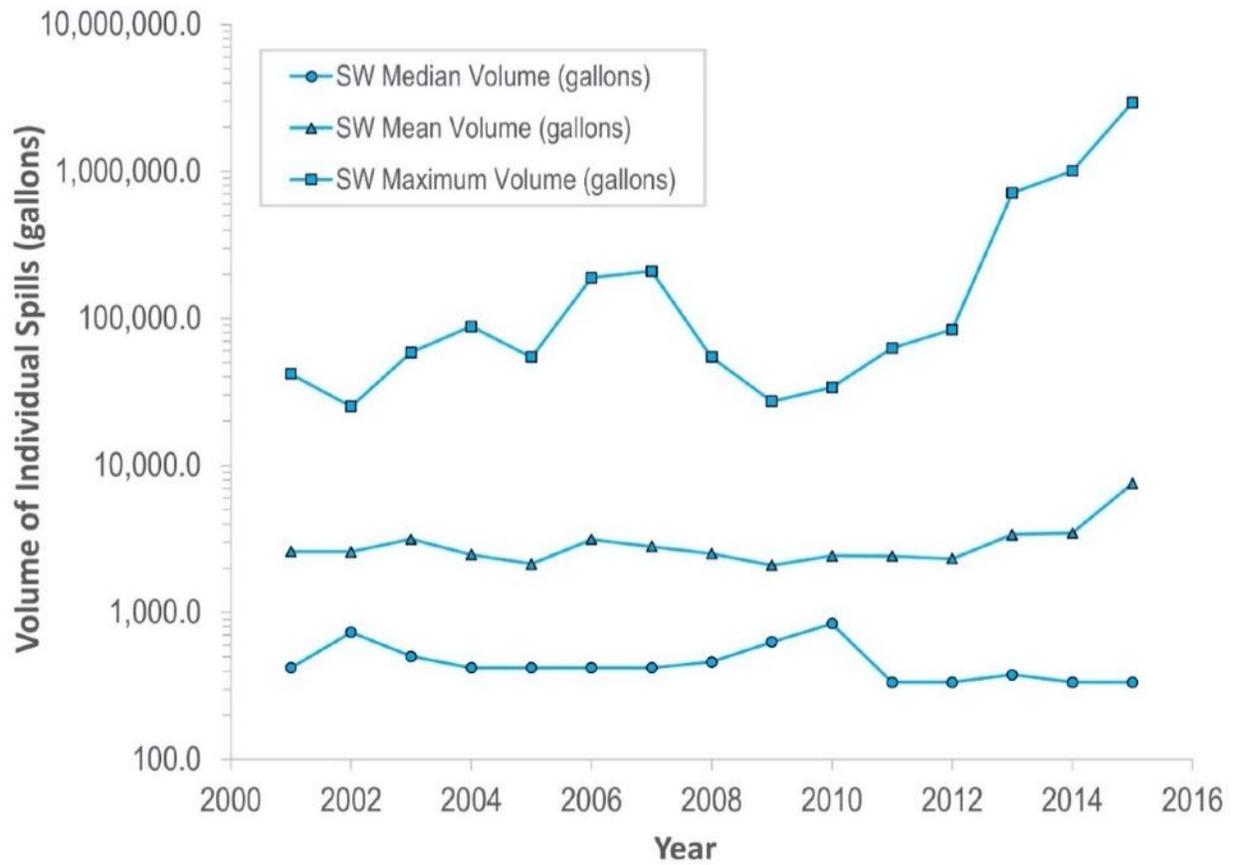
Figure 7-13. Median, mean, and maximum produced water spill volumes for North Dakota from 2001 to 2015.

Table 7-7. Summary of produced water release volumes.

Sources: U.S. EPA (2015m), Fisher and Sublette (2005), and Appendix Section E.5.

Study	Year(s)	Number		Minimum	25th percentile	Median	Mean	75th percentile	Maximum
		Total	Quantified	(gal)	(gal)	(gal)	(gal)	(gal)	(gal)
Oklahoma	1993-2002	7,916	2,365	0.0	630	1,700	7,000	4,200	3,400,000
	1993	373	161	0.4	420	1,500	3,900	4,200	46,000
	1994	844	333	0.4	420	1,600	5,400	4,200	84,000
	1995	913	333	0.0	420	1,500	3,700	4,200	63,000
	1996	880	333	4.2	630	2,100	6,500	4,200	420,000
	1997	806	270	0.4	630	1,900	6,000	4,200	120,000
	1998	825	236	2.1	798	4,900	2,100	4,200	105,000
	1999	886	218	10.5	840	2,100	6,600	4,200	120,000
	2000	853	155	4.2	840	2,100	5,600	5,040	210,000
	2001	826	144	21.0	840	2,100	31,000	6,510	3,400,000
	2002	710	182	0.8	630	1,700	5,500	3,276	130,000
U.S. EPA	2006-2012		225	2.1	420	1,008	10,920	2,982	1,344,000
North Dakota	2001		97	21.0	168	420	2,646	2,520	42,000
	2002		110	4.2	210	756	2,604	2,100	25,200
	2003		128	2.1	126	504	3,150	2,562	58,800
	2004		159	10.5	126	420	2,478	2,100	88,200
	2005		184	5.0	126	420	2,142	1,680	54,600
	2006		226	5.0	126	420	3,150	1,680	189,000
	2007		248	0.4	210	420	2,814	2,100	210,000

Study	Year(s)	Number		Minimum	25th percentile	Median	Mean	75th percentile	Maximum
		Total	Quantified	(gal)	(gal)	(gal)	(gal)	(gal)	(gal)
North Dakota, cont.	2008		248	8.4	84	504	2,520	2,058	54,600
	2009		208	2.1	126	630	2,100	2,100	27,300
	2010		255	0.1	126	840	2,478	2,310	34,020
	2011		381	2.1	126	336	2,436	1,680	58,800
	2012		543	7.1	84	336	2,310	1,260	84,000
	2013		700	2.1	126	378	3,402	1,428	714,000
	2014		846	0.8	84	336	3,528	1,470	1,008,000
	2015		609	0.8	84	336	7,560	1,386	2,940,000

7.4.2.9 Environmental Receptors and Transport

Data from the EPA (U.S. EPA, 2015m) were used to show that some spills were known to impact environmental receptors: soil (141 spills, 340,000 gal, or 1.3 million L); surface water (17 spills, 170,000 gal, or 640,000 L); surface water and soil (13 spills); and groundwater (1 spill, 130 gal, or 490 L).[1] Although 1 spill was identified as reaching groundwater, the possible groundwater impact of 107 of the spills was unknown.

In summary, 18 produced water spills reached surface water or groundwater, accounting for 8% of the 225 cases and accounting for approximately 170,000 gal (640,000 L) of produced water. Spills with known volumes that reached a surface water body ranged from less than 170 gal (640 L) to almost 74,000 gal (280,000 L), with median of 5,900 gal (22,000 L). In 30 cases, it is unknown whether a spill of produced water reached any environmental receptor.

An assessment conducted by the California Council on Science and Technology (CCST, 2015a) states that between January 2009 and December 2014, 575 produced water spills were reported to the California Office of Emergency Services of which nearly 18 percent impacted waterways (CCST, 2015a). These spills occurred in areas where production from both unconventional and conventional reservoirs occurs. Additional studies of spill impacts are presented in Appendix Section E.5.3.

Studies of Environmental Transport of Released Produced Water

The processes that affected the fate and transport of spilled produced water (Figure 7-14) are the same as those processes that impact the fate and transport of spilled chemicals (Section 5.8). Produced water spills differ from the chemical spills as they are always primarily spills of water containing multiple chemicals. Additionally, produced water of high salinity is denser than water and may alter transport and transformation properties of the chemicals and soils.[2] If a spill occurs prior to treatment in an oil and water separator, the produced water can be spilled along with oil. In the environment, oil is transported as a separate phase liquid as it is immiscible with water. The oil phase may become trapped (similarly to how oil is trapped in oil reservoirs) and serve as a slowly dissolving source of hydrocarbons to the environment.

For example, Whittemore (2007) described a site with relatively little infiltration due to moderate to low permeability of silty clay soil and low permeability of underlying shale units. Thus, most, but not all, of the historically surface-disposed produced water at the site flowed into surface drainages. Observed historic levels of chloride in receiving waters resulted from the relative balance of produced water releases and precipitation runoff, with higher concentrations corresponding to low stream flows. Persistent surface water chloride contamination was attributed to slow flushing and discharge of contaminated groundwater.

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[1] Quoted volumes.

[2] Appendix Section E.7 describes the estimation of chemical properties for organic chemical constituents of produced water for baseline conditions of low TDS. Elevated salinity, as is common for produced water, would alter these values.
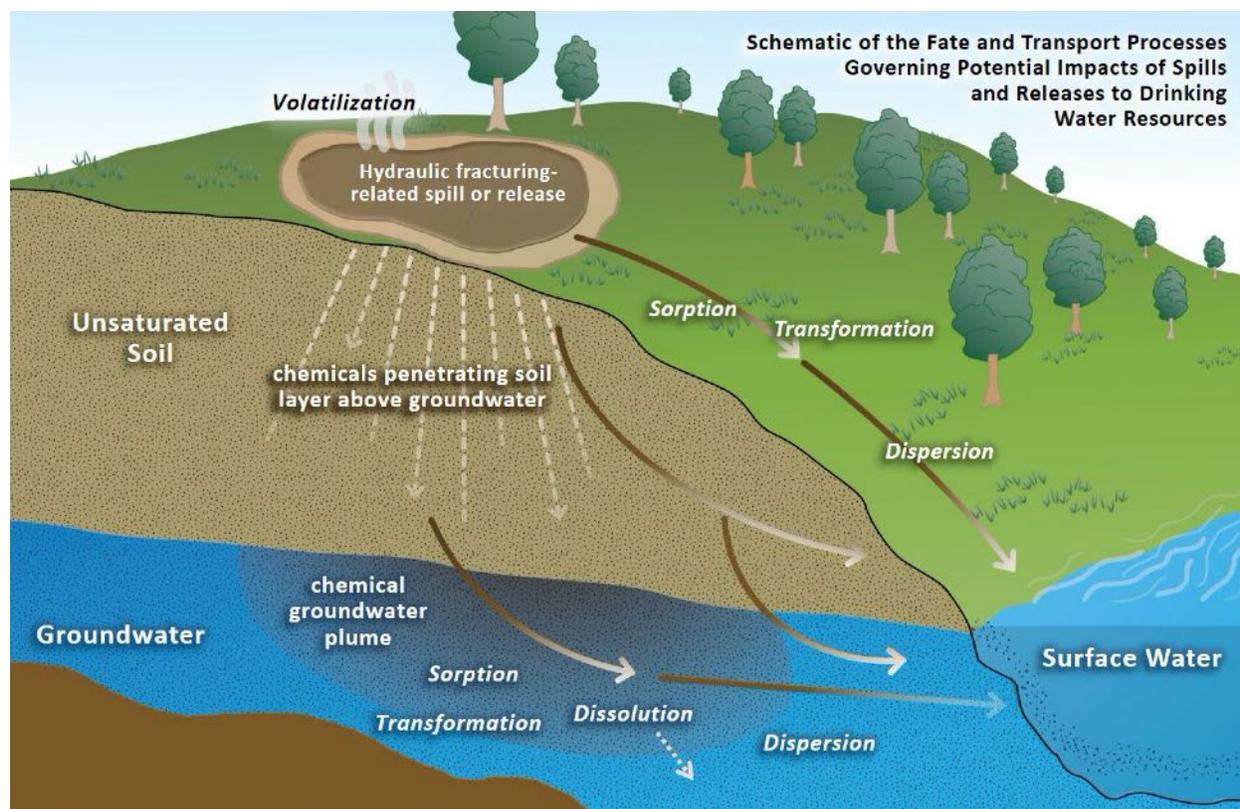
Figure 7-14. Schematic view of transport processes occurring during releases of produced water.

Because it is denser than freshwater, saline produced water can migrate downward through aquifers. Whittemore (2007) reported finding oilfield brine with a chloride concentration of 32,900 mg/L at the base of the High Plains aquifer. Where aquifers discharge to streams, saline stream water has been reported, although at reduced concentrations (Whittemore, 2007), likely due to diffusion within the aquifer and mixing with stream water. The stream flow rate, in part, determines mixing of substances in surface waters. High flows are related to lower chemical concentrations, and vice versa, as demonstrated for bromide in the Allegheny River (States et al., 2013).

7.5 Roadway Transport of Produced Water

Produced water is transported to treatment and disposal sites via pipeline, roadways, or railroad tankers. Accidents during transportation of hydraulic fracturing produced water are a possible mechanism leading to potential impacts to drinking water as truck-related releases have been reported. Nationwide data are not available, however, on the number of such accidents that result in impacts.

Crash rate estimates for Texas showed that commercial motor vehicle (CMV) crashes were correlated with oil and gas development activities over a recent period of increased oil and gas development (Quiroga and Tsapakis, 2015). As an example of the results, the number of new wells

in the Permian Basin increased (by 61%) and so did rural CMV crashes (by 52%). For the Barnett Shale region, the number of new wells decreased (by 49%), and so did rural CMV crashes (by 34%). The correlations were strongest for the rural areas with oil and gas development (Permian and Eagle Ford).

Based on scenarios presented in Appendix Section E.8, the EPA estimated for this assessment the number of releases from truck crashes as having a chance of occurrence ranging between 1:110 and 1:13,000 over the lifetime of a producing well. The wide range of these estimates reflects both variable (distance and volume transported) and uncertain (crash rate) quantities. At 5,300 gal (20 m^3) per truckload, the volume from an individual spill would be low relative to the typical volume of water produced from a well. Several limitations are inherent in this analysis, including differing rural road and highway accident rates, differing transport distances, and differing amounts of produced water transported. Further, the estimates present an upper bound on impacts, because not all releases would reach or impact drinking water resources.

As for other types of impacts to drinking water resources, local effects can be significant despite the generally small numbers. For example, a brine-truck spill in Ohio resulted in concern for impacts to a drinking-water-source reservoir ([Tucker, 2016](#)).

7.6 Synthesis

Produced water is a by-product of oil and gas production and is that water that comes out of the well after hydraulic fracturing is completed and injection pressure is reduced. Produced water may contain hydraulic fracturing fluid, water from the surrounding formation, and naturally present hydrocarbons. Initially the chemistry of produced water reflects that of the hydraulic fracturing fluid. With time, the chemistry of the produced water becomes more similar to the water in the formation. Produced water is directly re-injected or stored at the surface for eventual reuse or disposal. Impacts to drinking water resources from produced water have been shown where spilled produced water entered surface water bodies or aquifers.

7.6.1 Summary of Findings

The volume and composition of produced water vary geographically, both within and among different production zones and with time and other site-specific factors. In most cases, there are high initial flow rates of produced water that last for a few weeks, followed by lower flow rates throughout the duration of gas production. The amount of fracturing fluid returned to the surface varies, and typically is less than 30%. In some formations (e.g., the Barnett Shale), the ultimate volume of produced water can exceed the volume of hydraulic fracturing fluid because of an inflow of water.

Knowledge of the composition of produced water comes from analysis of samples. Analysis of an individual sample is made much easier if the hydraulic fracturing and any equipment maintenance chemicals have been disclosed. Much of the chemical loading of produced water comes from naturally occurring material, both organic and inorganic, in the formation along with transformation products. As such, knowledge of produced water composition is uniquely

dependent on sampling and analysis, which requires appropriate analytical methods. These are methods that can deal especially with high levels of TDS. Recently developed laboratory methods have greatly expanded the knowledge of organic chemicals in shale-gas and CBM produced waters, but these methods rely on advanced equipment and techniques. Routine methods of laboratory analysis do not detect many of the organic constituents of produced water.

The composition of produced water changes with time as the hydraulic fracturing fluid contacts the formation and mixes with the formation water. Typically it becomes more saline and more radioactive, if those constituents are present in the formation, while containing less DOC. The changing composition of produced water suggests that the potential concern for produced water spills also changes: initially the produced water may contain more hydraulic fracturing chemicals, later the concern may shift to the impact of high salinity water. Although varying within and between formations, shale and tight gas produced water typically contains high levels of TDS (salinity) and associated ionic constituents (bromide, calcium, chloride, iron, potassium, manganese, and sodium). Produced water can also contain toxic materials, including barium, cadmium, chromium, lead, mercury, nitrate, selenium, and BTEX. CBM produced water can have lower levels of salinity if its coal source was deposited under fresh water conditions, or if freshwater inflows to coal beds dilutes the formation water ([Dahm et al., 2011](#)). Many organic compounds have been identified in produced water. Most of these are naturally occurring constituents of petroleum. With the advent of advanced analytical techniques, more hydraulic fracturing fluid chemicals have been identified in produced water. These include some known tracer compounds, but others are known to exist whose identities have not yet been determined. Work has been done to identify environmentally benign tracers for assessing impacts, but these tracers have not been fully developed. Despite the presence in produced water of known hydraulic fracturing chemicals, the majority of organic and inorganic constituents of produced water come from the formation and cannot be minimized through actions of the operator. Throughout the formation-contact time, reactions occur between the constituents of the fracturing fluid and the formation.

Produced water spills have occurred across the country. From evaluation of data from across the United States and a focused study of North Dakota, the median produced water spill ranges from 336 to 1,000 gal (1,300 to 3,800 L). Although half of the spills are smaller than the median spill size, small numbers of much higher volume spills occur. In 2015, there were 12 spills in North Dakota greater than 21,000 gal (80,000 L), and one of 2,900,000 gal (11,000,000 L). From 2010 to 2015, there were approximately 5 to 7 produced water spills per hundred operating production wells. The major causes identified for these spills are container and equipment failures, human error, well communication, blowouts, pipeline leaks, and unpermitted discharges. Section 7.4.2 described impacts that were both of short and long term duration.

Highway transportation of produced water has resulted in crashes, but the impacts from these are unknown. Analysis of Texas crashes shows that as the oil and gas development activities increase, so do crashes, especially in rural areas. The EPA estimated the chance of a crash releasing produced water to range from 1:110 to 1:13,000.

7.6.2 Factors Affecting the Frequency or Severity of Impacts

The potential of spills of produced water to affect drinking water resources depends upon the release volume, duration, and composition, as well as watershed and water body characteristics. Larger spills of greater duration are more likely to reach a nearby drinking water resource than are smaller spills. Small releases, however, can impact resources where there are direct conduits from a source to receptor, such as fractures in rock. The composition of the spilled fluid also impacts the severity of a spill, as certain constituents are more likely to affect the quality of a drinking water resource.

Potential impacts to water resources from hydraulic fracturing related spills are expected to be affected by watershed and water body characteristics. For example, overland flow is affected by surface topography and surface cover. Infiltration of spilled produced water reduces the amount of water threatening surface water bodies. However, infiltration through soil can lead to groundwater impacts. Releases from pits can directly impact drinking water resources.

7.6.3 Uncertainties

The volume and some compositional aspects of produced water are known from published sources. The amount of hydraulic fracturing fluid returned to the surface is not well defined, because of the imprecise distinction between flowback and produced water. With regard to composition, TENORM and organics have the most limited data. Most of the available data on TENORM has come from the Marcellus Shale, where concentrations are typically high in comparison to the limited data available from other formations. Many organic constituents of produced water have been identified, and many of them are naturally occurring petroleum hydrocarbons. As methods improve and more data are collected, an increasing number of hydraulic fracturing fluid chemicals are being identified in produced water. Little is known concerning subsurface transformations and is reflected in only a few transformation products have been positively identified. Halogenation of organics has been noted, though.

Nationwide data on spills of produced water are limited in two primary ways: the completeness of reported data cannot be determined, and individual states' reporting requirements differ (U.S. EPA, 2015m). Therefore, the total number of spills occurring in the United States, their release volumes, and associated concentrations can only be estimated because of these underlying data limitations.

Spills vary in volume, duration, and composition, and most spill response focusses on immediate clean up, so several aspects of spills are not precisely characterized. The volume released is often a rough estimate, in part, because the spilled liquid spreads across the scene and is inherently difficult to measure. Simple measurements are often used to characterize the spill, rather than determining chemical concentrations (e.g., measuring electrical conductivity). As a consequence the suite of chemicals, and their concentrations, potentially impacting drinking water resources are usually unknown. Thus, the severity of impacts to drinking water resources is not usually well quantified.

Spills can originate from blowouts, well communication, aboveground or underground pipeline breaks, leaking pits, failed containers, human error (including unpermitted discharges, failure to

detect spills, and failure to report spills) or unknown causes. The difference between these causes affects the location and size of the spill or release. For example, a container that fails may release a small amount of produced water, and be located on the well pad. A pipeline break may occur at a distance away from the well pad and release a larger amount of water from a bigger source (i.e., a pit). In addition, the factors governing transport of spilled fluid to a potential receptor vary by site: the presence and quality of secondary or emergency containment and spill response; the rate of overland flow and infiltration; the distance to a surface water body or drinking water well; and transport and fate processes. Impacts to drinking water resources from spills of produced water depend on environmental transport parameters, which can, in principle, be determined but are unlikely to be known or adequately specified in advance of a spill.

Because some constituents of produced water are constituents of natural waters (e.g., bromide in coastal surface waters) or can be released into the environment by other pollution events (e.g., benzene from gasoline releases, bromide from coal mine drainage), baseline sampling prior to impacts is one way to increase the certainty of an impact determination. Further sampling and investigation can be used to develop the linkage between a release and a documented drinking water impact. Appropriate sampling and analysis protocols, using quality assurance procedures, are essential for developing data that can withstand scrutiny. The EPA's northeastern Pennsylvania case study illustrates that the analytes that can be used to distinguish among types of water vary depending on the specifics of the situation. No single constituent or parameter could be used alone to assess impacts, and multiple lines of evidence were needed to assess the suspected impacts.

7.6.4   Conclusions

Produced water has the potential to affect the quality of drinking water resources if it enters into a surface water or groundwater body used as a drinking water resource. This can occur through spills at well pads or during transport of produced water. Specific impacts depend upon the spill itself, the environmental conditions surrounding the spill, water body and watershed characteristics, and the composition of the spilled fluid. The impacts from the majority of spills and releases is generally localized in extent as only the largest spills and releases impact large areas.

WildEarth Guardians Exhibit 2

Benko, K.L. & J.E. Drewes, Produced Water in the Western United States: Geographical Distribution, Occurrence, and Composition, 25 Envtl. Engineering Science No. 2, 239 (2008).

Produced Water in the Western United States: Geographical Distribution, Occurrence, and Composition

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ABSTRACT

Coproduced water is a byproduct of oil and natural gas production. Because it is in contact with hydrocarbon products and geologic formations in underground basins, it usually contains elevated concentrations of inorganic and organic constituents. This paper aims to illustrate the concentration ranges for specific contaminants and the estimated quantity of coproduced water in the Western United States. The total dissolved solids (TDS) concentration in coproduced water can vary between 1,000 mg/L and over 400,000 mg/L; however, some basins tend to have much lower median values of TDS. Sodium chloride was found to be most dominant salt found in coproduced water across all basins studied. Oil and grease, ethyl benzene, benzene, phenols, and toluene are the most common organic contaminants found in coproduced water. The total oil content in coproduced water can range from 40 mg/L to 2,000 mg/L. Understanding the composition and quantity of coproduced water is essential for assessing the viability of beneficial reuse and selecting appropriate treatment processes for the water.

Key words: coproduced water; water quality; oil; natural gas; geographical distribution

INTRODUCTION

COPRODUCED WATER is defined as water that is extracted from subsurface geologic formations containing oil and gas (Society of Petroleum Engineers, N.D.). It is estimated that the oil and gas industry generates 10 times more water than oil and gas (Desalination and Water Purification Technology Roadmap, 2003). Current practice for disposal of coproduced water includes reinjection into underground formations, surface discharge into receiving waters, or land application. Reinjection is an expensive option for oil and gas producers and can only be done when the underground structure can accommodate the water. Surface discharge can cause contamination of drinking water or irrigation water supplies either underground or on the surface. When applied to land, the excess salt commonly found in coproduced water can make soil less permeable to air and water and reduce the availability of nutrients in the soil (Veil *et al.*, 2004).

The estimated amount of coproduced water generated in the United States is between 6.1×10^6 m³/day and 7.8×10^6 m³/day (1,600 mg.day and 2,100 mg.day) (Boysen *et al.*, 2002; Veil *et al.*, 2004). This amount of water is greater than the combined daily water consumption for New York City and Los Angeles ("More Masses Huddling, 2006; Los

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Angeles Department of Water and Power, N.D.). In many areas of the United States, fresh water supplies have been fully allocated; therefore, additional sources of water must be identified to meet increasing water demands (Desalination and Water . . . , 2003). In the arid regions of the Western United States, treated coproduced water may relieve stresses on conventional water supplies and provide a stable source of water during times of drought (Veil *et al.*, 2004). Especially the Western U.S. is currently experiencing a significant growth of coproduced water production due to the increasing interest in exploring unconventional natural gas resources (coal bed methane, oil shale, and tight gas sands) to diversify the energy portfolio of the United States (Stevens *et al.*, 1998). Coal bed methane (CBM) accounts for 7% of the total natural gas production and 8% of the gas reserves in the United States. Development from the Rocky Mountain states of Colorado, New Mexico, Utah, and Wyoming accounts for nearly 8% of the total coalbed methane production in the United States (Bryner, 2006).

Understanding the chemical characteristics of coproduced water is important for determining appropriate treatment technologies and optimal beneficial uses of the water. Reactions between dissolved constituents in the water and interactions between the water and surrounding rocks or petroleum can affect the composition of coproduced water (Veil *et al.*, 2004). The inorganic chemical characteristics of coproduced water vary considerably depending on the geographic location and the geologic formation from which the petroleum and water were produced. The organic content of coproduced water depends heavily on the type of hydrocarbon produced and exists in two forms: suspended, dispersed oil droplets, and dissolved organic material (Stephensen, 1992).

The purpose of this study is to describe the current state of knowledge regarding the chemical characteristics of coproduced water from both conventional and nonconventional oil and gas, including the inorganic and organic content, along with the estimated volume of water available based on peer reviewed literature. Additionally, the scope of interest for this paper is the Western United States, including Montana, North Dakota, South Dakota, Wyoming, Utah, Colorado, Nebraska, Kansas, Arizona, New Mexico, Oklahoma, Texas, and California. The major oil and gas producing basins in the Western U.S. are Williston, Powder River, Big Horn, Wind River, Green River, Denver, Uinta-Piceance, Paradox, San Juan, Raton, Anadarko, Permian, San Joaquin, and Los Angeles (Energy Information Administration, 2004). A basin is a geographically confined depression in the earth's surface, consisting of layers of stratified rock, in which sediments accumulated and hydrocarbons may have formed (Van Dyke, 1997). This paper provides insight into the quantity and quality of coproduced water originating from these 14 basins.

CONVENTIONAL OIL AND GAS COPRODUCED WATER CHARACTERISTICS

Methodology

The U.S. Geological Survey (USGS) has published an extensive database containing the major ion analysis and total dissolved solids for water from 58,706 oil and gas wells (primarily from conventional oil and gas operations) from the mainland U.S., Alaska, and offshore (Breit and Otton, 2002). The database allows the user to download data by state or region. For this work, data were used from Montana, North Dakota, Wyoming, South Dakota, Utah, Colorado, Nebraska, Kansas, Arizona, New Mexico, Oklahoma, Texas, and California. There were 33,189 wells considered in this analysis (56.5% of the entries in the database where used). The geologic basin is provided for each well in the database. The data was reorganized by geologic basin, rather than by state. For some basins, the total dissolved solids (TDS) varied by geographical location and for these basins, the data was further organized by state within the basin. The minimum, median, first quartile, third quartile, and maximum values were calculated for each basin. Using the major ion analysis provided by the USGS database, milliequivalent concentrations were calculated for each ion. The anion and cation with the largest milliequivalent concentration was considered the dominant salt in the water.

A limitation of the USGS database is that it does not explicitly state which wells produce oil and which produce natural gas, the lifecycle of the wells, the flow rate of water from the well at the time of sampling, or the extraction technique used. Thus, the database is best used to draw general conclusions about the water generated by the petroleum industry as a whole.

Inorganic constituents

Coproduced water is generally characterized as brackish groundwater with elevated concentrations of total dissolved solids. The inorganic constituents present in coproduced water are primarily derived from the rock formations with which the water is in contact; therefore, the water quality regarding inorganic constituents is organized and presented by geologic basin. Water from conventional oil and gas can exhibit a wide range of TDS concentrations; 1,000 mg/L to over 400,000 mg/L. The TDS concentration range observed in coproduced water represented in the USGS database is presented in a box and whisker format with the minimum, first quartile, third quartile, and maximum value of TDS within each basin (Fig. 1). The data is presented on a log-scale to accommodate the large range of TDS values observed. For basins in which the TDS varied significantly, TDS statistics were calculated for each state occupied by the basin.

The Williston Basin exhibits the most geographical vari-
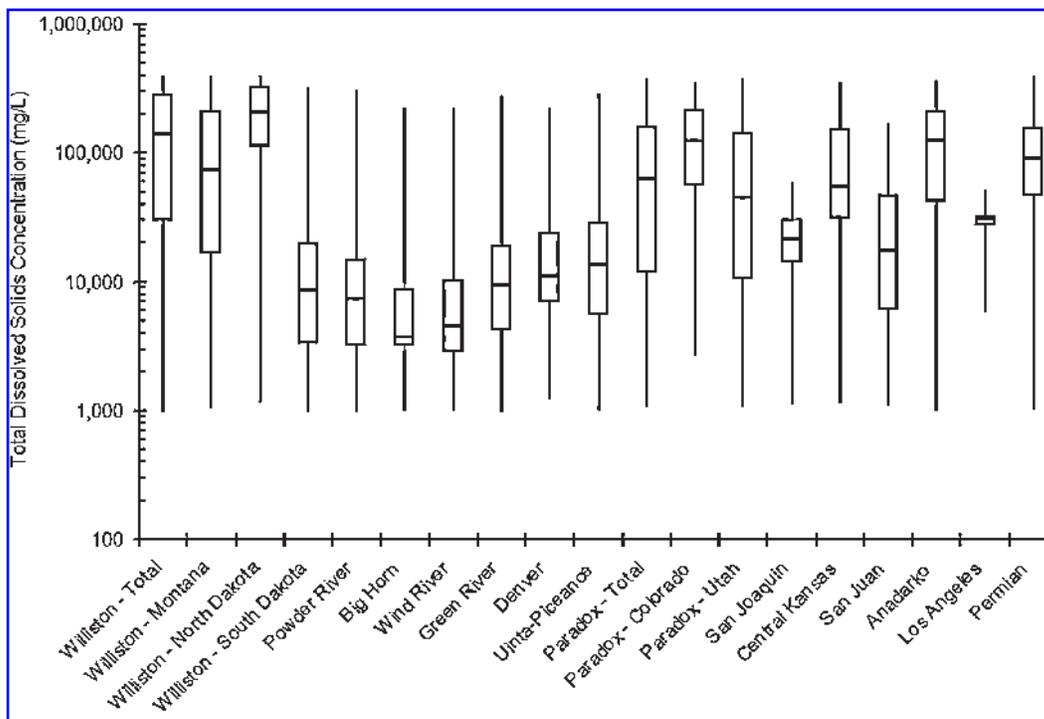
Figure 1. Distribution of TDS in produced water by basin. (Note: the outline of the box represents the 1st and 3rd quartiles, the bar in the box represents the median value, and the wisker length represents the minimum and maximum TDS values).

ation by state of any of the basins studied. The TDS of water samples within the Williston Basin are much higher for the portion of the basin that lies in North Dakota. Ranges of the most common inorganic constituents were obtained for all basins (Table 1). The TDS concentration ranged from 1,000 mg/L to 400,000 mg/L, with a median value of 32,300 mg/L for all basins. Sodium and chloride were the ions generally found in the highest concentrations.

Data was not available for arsenic, boron, and silica; however, these constituents are important to consider when using and treating the water because boron and arsenic are not removed by the majority of treatment processes and silica can cause scaling problems in membrane processes.

The USGS Produced Waters Database was used to compute the dominant salts present for each water sample analyzed. Sodium chloride was found to be the dominant salt in over 76% of the coproduced water samples. The next most common salts found in coproduced water are sodium bicarbonate and sodium sulfate (Fig. 2). Magnesium sulfate and magnesium chloride were found in a high concentration in the Big Horn Basin, Permian Basin, and Wind River Basin.

Organic contaminants

In contrast to the occurrence of inorganic constituents, which are determined by the geology of a basin, the quantity and characteristics of organic contaminants in copro-

duced water is impacted by a number of factors including type of hydrocarbon product the water is in contact with, volume of water production, artificial lift technique, and the age of production. To date, no studies have been conducted to quantify the impact of these factors on the organic content of coproduced water. The organic data presented here was derived from sources that reported on the organic content regardless of location and type of product. Table 2 lists the concentration ranges of organic material commonly found in coproduced water from oil and gas operations. Benzene, ethyl benzene, toluene, and phenol typically occur in the highest concentration in coproduced water (Table 2).

The data presented in Table 2 does not distinguish between water from oil operations and water from gas operations; however, water from gas production tends to have higher concentrations of low molecular-weight aromatic hydrocarbons, such as benzene, toluene, ethyl benzene, and xylene, than water from oil production (Jacobs *et al*., 1992). Detectable concentrations of volatile organics are found in 75 to 80% of all gas coproduced water samples (Fillo *et al*., 1992). Semi-volatile organics are rarely found in gas coproduced water and are much more prevalent in oil coproduced water.

Coproduced water occurrence

The amount of water generated during oil and gas extraction is not known exactly. Some states keep records of

Table 1. Ranges of common inorganic constituents in coproduced water.

Constituent	Units	Low	High	Median	Number of data points considered	Reference
TDS	mg/L	1000	400,000	32,300	33,189	Breit and Otton, 2002
Sodium	mg/L	ND	150,000	9,400	33,189	Breit and Otton, 2002
Chloride	mg/L	ND	250,000	29,000	33,189	Breit and Otton, 2002
Barium	mg/L	ND	850	Unknown	Unknown	Breit and Otton, 2002
Strontium	mg/L	ND	6,250	Unknown	Unknown	Breit and Otton, 2002
Sulfate	mg/L	ND	15,000	500	33,189	Breit and Otton, 2002
Bicarbonate	mg/L	ND	15,000	400	33,189	Breit and Otton, 2002
Calcium	mg/L	ND	74,000	1,500	33,189	Breit and Otton, 2002

Note: "unknown" in table signifies information not provided by the source.

coproduced water volumes, but for other states, estimates of water production are derived from oil/gas to water ratios. A number of different sources have provided estimates of coproduced water quantities (Boysen *et al.*, 2002; Veil *et al.*, 2004; Bryner, 2006); however, there is a large variation in the water quantities reported. Where multiple values were obtained for water volume, the state reported figure was used preferentially. The oil/gas to water ratio was used only when a state figure was not available. The total amount of water generated in within the basins pre-
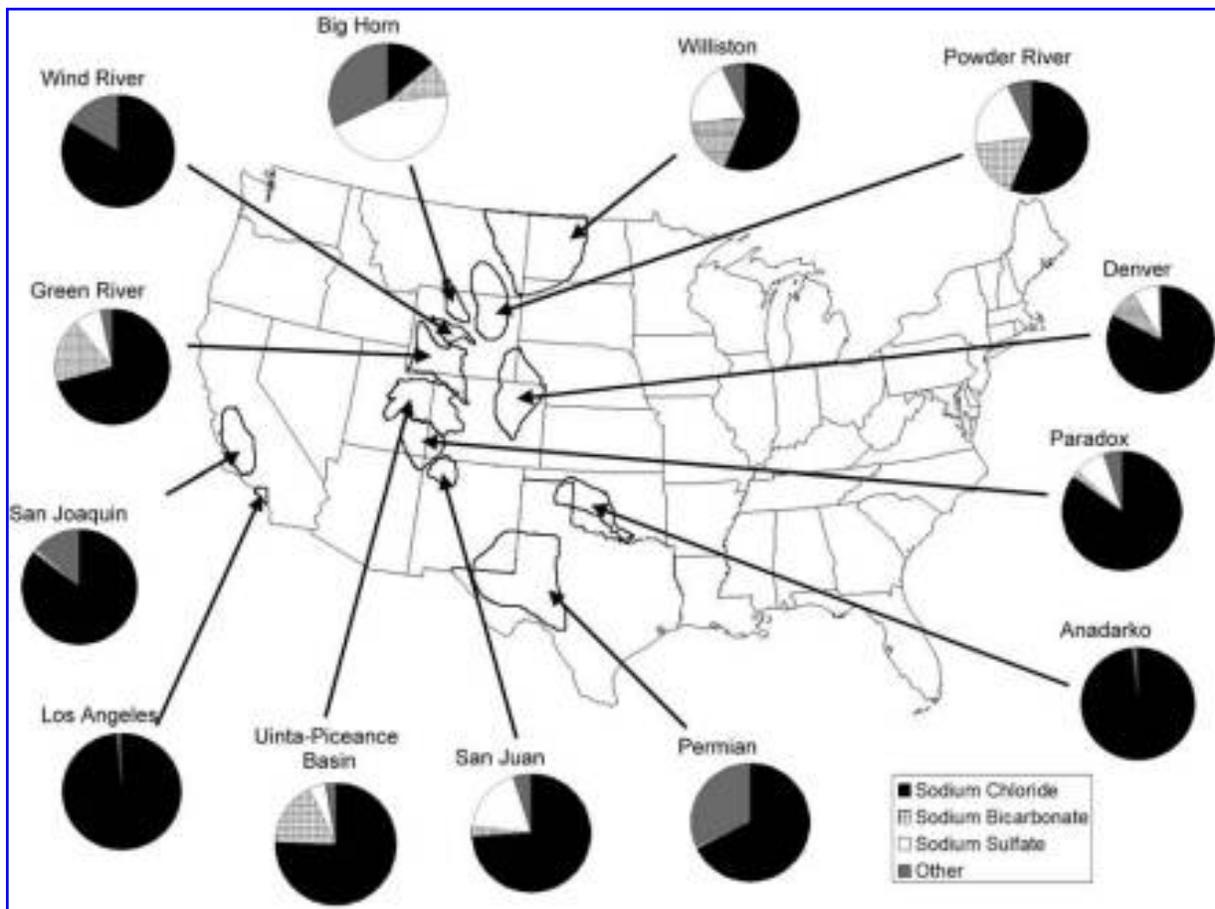

Figure 2. Dominant salts in produced water by geologic basin.

Table 2. Concentration ranges of organic material in coproduced water from conventional oil and gas.

Constituent	Low	High	Median	Technique (method)	Reference
TOC (mg/L)	ND	1,700	Unknown	UV Oxidation/IR (EPA 415.1)	Tibbetts et al. 1992
TSS (mg/L)	1.2	1,000	Unknown	Gravimetric (EPA 160.2)	Tibbetts et al. 1992
Total volatile organics (mg/L)	0.39	35	Unknown	GC/MS (EPA 1624 Rev B and EPA 24 & CLP)	Tibbetts et al. 1992
Total polar compounds (mg/L)	9.7	600	Unknown	Florisil column/IR	Tibbetts et al. 1992
Volatile fatty acids (mg/L)	2	4,900	Unknown	Direct GC/FID of water	Tibbetts et al. 1992
Total recoverable oil and grease (mg/L)	6.90	210.0	39.8	Unknown	Science Applications, 1994
2-Butanone (mg/L)	ND	0.37	Unknown	Unknown	Wesolowski et al., 1986
Benzene (mg/L)	ND	27	10	EPA Method 1624 and 624	Fillo et al., 1992
Benzoic acid (mg/L)	ND	13.5	3.80	Unknown	Science Applications, 1994
Bis (2-chlorethyl) ether (mg/L)	ND	0.03	Unknown	Unknown	Wesolowski et al., 1989
Ethyl benzene (mg/L)	ND	19	1.8	EPA Method 1624 and 624	Wesolowski et al., 1989
Hexanoic acid (mg/L)	ND	3.43	0.815	Unknown	Science Applications, 1994
Methylene Chloride (mg/L)	1.41	1.71	0.179	Unknown	Science Applications, 1994
m-xylene (mg/L)	0.015	0.611	0.137	Unknown	Science Applications, 1994
Naphthalene (mg/L)	ND	0.556	0.119	Unknown	Science Applications, 1994
N-decane (mg/L)	ND	0.797	0.116	Unknown	Science Applications, 1994
N-dodecane (mg/L)	ND	2.89	0.245	Unknown	Science Applications, 1994
N-hexadecane (mg/L)	ND	1.11	0.298	Unknown	Science Applications, 1994
N-octadecane (mg/L)	ND	0.246	0.106	Unknown	Science Applications, 1994
N-tetradecane (mg/L)	ND	0.404	0.138	Unknown	Science Applications, 1994
p-cresol (mg/L)	ND	0.541	0.123	Unknown	Science Applications, 1994
Phenol (mg/L)	0.009	23	NA	Silylation GC/MS	Tibbetts et al., 1992
Toluene (mg/L)	ND	37	9.7	EPA Method 1624 and 624	Fillo et al., 1992

ND, below detection limit; unknown, information was not provided by reference.

sented is estimated to vary from 106,000 m³/day (28 mgd) (Veil *et al.*, 2004) to over 1,197,000 m³/day (316 mgd) (Van Dyke, 1997). Water production data, median TDS value, and the potential for treatment was determined for each of the major producing basins in the Western United States (Table 3).

The potential for treatment within each basin was determined based on the median TDS concentration and the quantity of water within the basin, and is used as a preliminary assessment of where desalination treatment efforts should be focused on. Basins containing large quantities of water with relatively low TDS are considered to have more potential for treatment than basins producing small quantities with elevated TDS concentrations. Additional considerations impacting the potential for reuse, which were not considered in this study, are agricultural activity, stream flows, population centers, and logistical infrastructure (i.e., chemical supplies for water treatment processes) in proximity to the water production.

Table 3. Coproduced water generation by geologic basin.

Geologic basin	Water production m³/day	mg · day[a]	Median TDS (mg/L)[b]	Potential for treatment
Williston	18,000	4.9	132,400	Low
Powder River	370,000	97	7,300	Very high
Big Horn	360,000	94	4,900	Very high
Wind River	54,000	14	5,300	Very high
Green River	41,000	11	9,400	High
Denver	14,000	3.8	10,200	High
Uinta-Piceance	42,000	11	13,200	High
Paradox	21,000	5.6	67,000	Low
San Juan	14,000	3.6	22,700	Medium
Anadarko	34,000	8.9	132,200	Very low
Permian[c]	250,000	65	89,200	Low
San Joaquin	NA	NA	22,700	Medium
Los Angeles	NA	NA	30,330	Medium

[a]Boysan et al, 2002; [b]Breit and Otton, 2002; [c]for natural gas only and for the New Mexico portion of the Permian Basin.

Table 4. Total dissolved solids concentration for CBM producing basins.

Basin	Units	Low	High	Mean	Number of data points considered	Reference
Powder River	mg/L	370	1,940	840	47	[a]
Uinta	mg/L	6,000	43,000	15,000	Unknown	[b,c]
Piceance	mg/L	7,252	15,500	Unknown	Unknown	[d]
San Juan	mg/L	10,434	23,464	Unknown	Unknown	[d]
Raton	mg/L	1,100	4,600	1,500	Unknown	[c,e]

Unknown, reference did not provide information; [a]Rice, 2000; [b]Handbook, 2003; [c]Hightower, ND; [d]Myers, 2005; [e]Raton Basin, 2003.

CBM COPRODUCED WATER CHARACTERISTICS

Methodology

Public domain and peer reviewed papers were used to gather data on the inorganic and organic constituents found in coal bed methane coproduced water.

Inorganic constituents

There are significant differences in the concentrations of major ions in coproduced water from CBM compared to conventional oil and gas. CBM generally produces water that has significantly lower TDS concentrations, ranging from 300 mg/L to 15,000 mg/L (Van Voast, 2003).

Water associated with CBM has a common chemical character: minimal sulfate, calcium, and magnesium, and larger quantities of sodium and bicarbonate (Van Voast, 2003). Based on the solubility of calcium and magnesium in the presence of bicarbonate, higher bicarbonate concentrations cause calcium and magnesium to precipitate, thus explaining their low concentrations in CBM coproduced water where bicarbonate is the dominant anion (Van Voast, 2003). There are five geologic basins that produce the majority of the CBM in the Western U.S.: Powder River, Uinta,

Piceance, Raton, and San Juan. The TDS range for CBM water generated in these basin is presented in Table 4. The concentration ranges of the common ions found in CBM water from the Powder River Basin are provided in Table 5.

Organic contaminants

The organic contaminants in water from CBM are derived from coal. CBM coproduced water generally has no oil and grease, and has relatively low dissolved organic carbon concentrations, usually varying from 2 mg/L to 10 mg/L (Kharaka and Rice, 2003). Some of the dissolved organic constituents known to be present in CBM water include goitrogens, such as 2-methyl resorcinol, 5-methylresorcinol, and hydroxypyridines. Polycyclic aromatic hydrocarbons, such as aminophenols and aromatic amines, are also known to leach into water from coals (Fisher and Santamaria, 2002). To the best knowledge of the authors, no studies have attempted yet to characterize dissolved organic constituents from CBM water.

Quantity of coproduced water

The quantity and quality of coproduced water in each basin was used to determine which basins are the most likely candidates for treatment of coproduced water toward bene-

Table 5. Ranges of common inorganic constituents in coproduced water from CBM in the Powder River Basin (Rice, 2000).

Constituent	Units	Low	High	Mean	Number of data points considered
Sodium	mg/L	130	800	300	47
Chloride	mg/L	6.3	64	13	47
Barium	mg/L	0.14	1.6	0.62	47
Strontium	mg/L	0.10	1.9	0.70	47
Sulfate	mg/L	ND	12	2.4	47
Bicarbonate	mg/L	290	2,320	950	47
Calcium	mg/L	5.9	57	32	47

Table 6. Coproduced water generation by geologic basin.

Geologic basin	Water production m³/day	mg · day[a]	Median TDS (mg/L)	Potential for treatment
Powder River	170,000	46	840	Very high
Uinta	19,000	5.1	15,000	Medium
San Juan	12,000	3.2	>10,000	High
Raton	13,000	3.6	1,500	High

[a]Rice and Nuccio, 2000.

ficial use. Basins exhibiting small TDS values and high water volumes were considered to have the most potential for reuse. The following values were compiled for water production from CBM producing basins (Rice and Nuccio, 2000) (Table 6).

QUALITY ASSURANCE

It is noteworthy that information regarding the makeup of coproduced water from both conventional and CBM exploration are associated with a fair degree of uncertainty. Although individual producers usually have a good understanding of quantity and quality of coproduced water from their operations, frequently this information is not readily available. Where possible, water quality parameters and water quantity estimates provided in this study were obtained from multiple sources. Additionally, these values were checked and found to be consistent with select complete water quality analyses from various coproduced water samples collected and analyzed by the authors.

SIGNIFICANCE OF WATER QUALITY AND QUANTITY TO TREATMENT

The analysis conducted in this study provides a starting point for determining what types of treatment strategies are appropriate for different types of coproduced water. Treatment technologies need to be tailored to the types and concentrations of constituents present in the water, the type of intended end-use, and the conditions under which the treatment will occur. Findings of this study illustrate that the TDS concentration of coproduced water might frequently be unsuitable for the desired end use of the water, and desalination technologies must be employed. Typical desalination technologies that have been used or proposed to treat coproduced water include reverse osmosis and nanofiltration, electrodialysis, capacitive deionization, ion exchange, chemical precipitation, and thermal or distillation processes, and hybrid combinations of these technologies. Some of these technologies may not be capable in achieving the desired inorganic constituent removal efficiency or might exhibit limitations due to the presence of organic contaminants. Because many basins exhibit very similar water compositions, appropriate treatment process combinations are needed that meet the unique goals of coproduced water treatment, such as a high degree of robustness, high water recovery, little need for maintenance and treatment chemicals, minimal generation of treatment residuals, and ease of operation.

Attention should also be given to certain constituents present in the water that can be recovered and potentially sold as a product. In some cases, these products, such as iodide, can generate revenues that could cover the cost of the water treatment (Xu and Drewes, 2006). Currently, information is lacking regarding the concentrations of recoverable products within the basins targeted in this study; these constituents will need to be analyzed for on an individual basis.

CONCLUSIONS

Understanding the chemical composition and quantity of water available provides an idea of which areas of the Western U.S. have water most favorable for treatment, leading to beneficial use. Nearly all of the water qualities presented would require at least minimal organics removal and desalination to render it for beneficial use. Because the majority of coproduced waters exhibits a rather homogeneous composition of major ions, such as sodium, chloride, sulfate, and bicarbonate, desalination technologies that are already well established in the water industry like reverse osmosis, nanofiltration, or electrodialysis or combinations of these processes could assure a treated water quality that meets nonpotable and potable standards. However, some of the basins presented here have water with such high TDS concentrations that treatment will most likely not be cost effective. For these basins, treatment for beneficial use is not practical, and other options need to be investigated for disposal. Future research should be directed toward the development of robust, low-maintenance, easy to operate, package treatment technologies that can be employed at the wellhead or well clusters of oil and gas production sites.

ACKNOWLEDGMENTS

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E.G. Elliott, Unconventional Oil and Gas Development and Risk of Childhood Leukemia: Assessing the Evidence, Science of the Total Environment 138 (2017).

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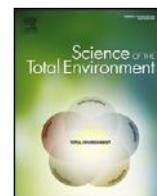
Unconventional oil and gas development and risk of childhood leukemia: Assessing the evidence

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HIGHLIGHTS

- Concerns exist about carcinogenic effects of unconventional oil & gas development.
- We evaluated the carcinogenicity of 1177 water pollutants and 143 air pollutants.
- These chemicals included 55 known, probable, or possible human carcinogens.
- Specifically, 20 compounds had evidence of leukemia/lymphoma risk.
- Research on exposures to unconventional oil & gas development and cancer is needed.

GRAPHICAL ABSTRACT
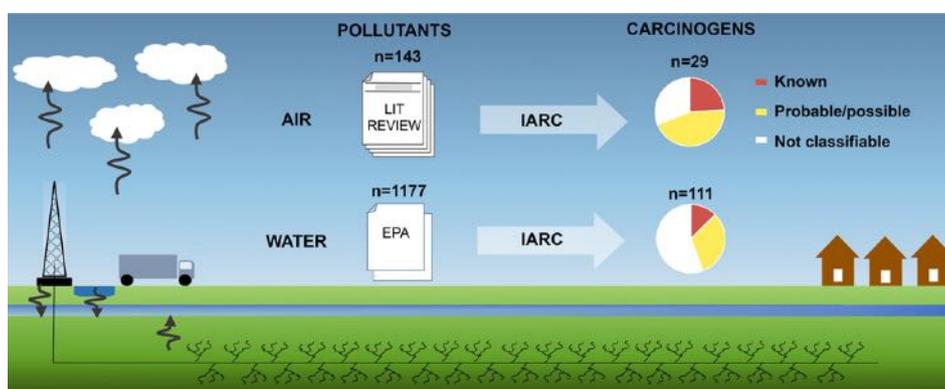
ABSTRACT

The widespread distribution of unconventional oil and gas (UO&G) wells and other facilities in the United States potentially exposes millions of people to air and water pollutants, including known or suspected carcinogens. Childhood leukemia is a particular concern because of the disease severity, vulnerable population, and short disease latency. A comprehensive review of carcinogens and leukemogens associated with UO&G development is not available and could inform future exposure monitoring studies and human health assessments. The objective of this analysis was to assess the evidence of carcinogenicity of water contaminants and air pollutants related to UO&G development. We obtained a list of 1177 chemicals in hydraulic fracturing fluids and wastewater from the U.S. Environmental Protection Agency and constructed a list of 143 UO&G-related air pollutants through a review of scientific papers published through 2015 using PubMed and ProQuest databases. We assessed carcinogenicity and evidence of increased risk for leukemia/lymphoma of these chemicals using International Agency for Research on Cancer (IARC) monographs. The majority of compounds (>80%) were not evaluated by IARC and therefore could not be reviewed. Of the 111 potential water contaminants and 29 potential air pollutants evaluated by IARC (119 unique compounds), 49 water and 20 air pollutants were known, probable, or possible human carcinogens (55 unique compounds). A total of 17 water and 11 air pollutants (20 unique compounds) had evidence of increased risk for leukemia/lymphoma, including benzene, 1,3-butadiene, cadmium, diesel exhaust, and several polycyclic aromatic hydrocarbons. Though information on the carcinogenicity of compounds associated with UO&G development was limited, our assessment identified 20 known or suspected carcinogens that could be measured in future studies to advance exposure and risk assessments of cancer-causing agents. Our findings

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support the need for investigation into the relationship between UO&G development and risk of cancer in general and childhood leukemia in particular.

1. Introduction

Unconventional oil and gas (UO&G) development is a complex, multi-phase process of extracting oil and natural gas from low-permeable rock formations that were inaccessible prior to recent technological advances in hydraulic fracturing and directional drilling. It has expanded rapidly in the past decade and now occurs in as many as 30 states within the United States, with millions of people living within 1 mile of a hydraulically fractured well (US EPA, 2015). Concerns have been raised about the potential exposures to water and air pollutants and related health impacts (Adgate et al., 2014). Chemicals involved in or produced by UO&G development may include reproductive/developmental toxicants (Elliott et al., 2016; Kahrilas et al., 2015; Wattenberg et al., 2015), endocrine disruptors (Kassotis et al., 2014), or known or suspected carcinogenic agents (McKenzie et al., 2012). The limited epidemiologic studies of UO&G development have observed an increase in adverse perinatal outcomes (Casey et al., 2016; McKenzie et al., 2014; Stacy et al., 2015), asthma exacerbations (Rasmussen et al., 2016), dermal irritation (Rabinowitz et al., 2015), hospitalization rates (Jemielita et al., 2015), and nasal, headache, and fatigue symptoms (Tustin et al., 2016).

Childhood leukemia in particular is a public health concern related to UO&G development, and it may be an early indicator of exposure to environmental carcinogens due to the relatively short disease latency and vulnerability of the exposed population (Rothwell et al., 1991; Shy et al., 1994). The age-adjusted incidence rate of leukemia in the United States for children under the age of 15 was 5.3 per 100,000 persons in 2011, the highest among all types of childhood cancer, and the peak age of incidence is 2–5 years (CDC, 2015). The U.S. incidence rates for acute lymphocytic leukemia, the most common subtype of childhood leukemia, increased annually by 1.4% from 2000 to 2010 (Gittleman et al., 2015). Environmental exposures, such as ionizing radiation, benzene, traffic exhaust, tobacco smoke, and pesticides, have been linked to childhood acute lymphoblastic leukemia, though evidence is generally limited or inconsistent (Bailey et al., 2015a; Bailey et al., 2015b; Tong et al., 2012; Ward et al., 2014; Wiemels, 2012; Zachek et al., 2015). A comprehensive review of the carcinogens and leukemogens associated with UO&G development is not available and could inform future environmental and biological monitoring and human health studies. In this analysis, we aimed to systematically assess the evidence for a possible carcinogenic/leukemogenic role of (1) water contaminants and (2) air pollutants associated with UO&G development.

1.1. Unconventional oil and gas development: description of the process

In oil and gas extraction, a well pad must first be constructed. This involves the use of construction vehicles, heavy equipment, and diesel generators in continuous operation to create roads, clear and set up a well site, and transport materials to the site (Moore et al., 2014). After well pad construction is complete, drilling rigs drill vertically past the deepest freshwater aquifer down to the level of the source formation, such as shale rock, turn and drill horizontally for distances up to 3000 m (Laurenzi and Jersey, 2013). After drilling, the well is hydraulically fractured. In this step, large volumes of fracturing fluids consisting of water, chemicals, and proppants (sand or ceramic beads) are forced into wells under high pressure, creating fissures or fractures in the rock along the horizontal section of the wellbore to release oil or gas. Typically, about 15–100 million l of fluid are used for each well, of which approximately 1–2% are chemical additives, representing a substantial volume of chemicals used per well (estimated as upwards of 114,000 l) (US DOE, 2013; US EPA, 2012). Chemical additives in fracturing fluids include biocides, surfactants, and anti-corrosive agents (US EPA, 2015). After fracturing, wastewater flows up the wells. Within 1–4 weeks about 30% of injected fracturing fluids rapidly return to the surface through the well as "flowback" water; subsequently, "produced" water returns up the well more slowly. The produced water includes the injected fluids along with mobilized, naturally-occurring compounds (e.g., heavy metals, bromides, radionuclides) (Ferrar et al., 2013; Vidic et al., 2013). Flowback and produced wastewater are stored in large open pits or storage tanks until they can be treated, reused, or disposed of offsite, such as in injection wells. Oil, gas, and produced water flow up the well for years or decades during the production phase of the well (Barbot et al., 2013; Nicot et al., 2014). During production, diesel-power trucks may be used to maintain the wells or transport oil or gas off the well pad. This stage also includes the processing and distribution of the produced oil and gas at other facilities (NYS DEC, 2011).

1.2. Possible pathways of environmental exposure to carcinogenic agents

Possible pathways of water contamination during fracturing and production include faulty or deteriorating well casings, equipment failure, surface spills of fracturing fluids or wastewater on-site or from tanker trucks transporting these liquids, migration of chemicals from fractures to shallow aquifers, leakage from wastewater pits, and unauthorized discharge and release of inadequately treated wastewater into the environment (Adgate et al., 2014; Brantley et al., 2014; Ferrar et al., 2013; Gross et al., 2013; Jackson et al., 2013b; Osborn et al., 2011; Rozell and Reaven, 2012; Shonkoff et al., 2014; US EPA, 2015; Vengosh et al., 2014; Vengosh et al., 2013; Warner et al., 2012). Surface activities may pose the greater potential threat in the near-term (Drollette et al., 2015), with sub-surface activities potentially presenting a hazard over a longer period of time. Several water quality studies have measured total dissolved solids, isotopes, and other chemicals to characterize a geochemical fingerprint of UO&G development (Jackson et al., 2013a; Vengosh et al., 2013; Warner et al., 2013; Warner et al., 2012); these studies are not necessarily focused on compounds with evidence of toxicity to humans. Studies measuring concentrations of health-relevant chemicals in drinking water sources are emerging (Harkness et al., 2015; Hildenbrand et al., 2015; Llewellyn et al., 2015), but data are limited.

UO&G development activities that could generate air pollution include operation of diesel-powered equipment, use of vehicles to transport materials and waste to and from the site, addition of sand (silica) to the fracturing fluid mixture, volatilization of compounds from wastewater, and processing and distribution of the oil and gas (Moore et al., 2014). Air pollutants, such as diesel exhaust, fine and coarse air particulates, crystalline silica, and polycyclic aromatic hydrocarbons (PAHs), are a few examples commonly cited as being generated as part of the various phases of UO&G development (Burnham et al., 2012; McCawley, 2015; Moore et al., 2014). To our knowledge, no comprehensive list of air pollutants potentially related to UO&G development is available in the published literature or government reports.

1.3. Epidemiologic studies of unconventional oil and gas development

Knowledge of the health risks of UO&G development is sparse, though epidemiologic studies on this topic are emerging. Studies

using proximity-based metrics observed associations between UO&G development and congenital heart defects in children (McKenzie et al., 2014), self-reported dermal irritation (Rabinowitz et al., 2015), decreased birth weight and increased incidence of small for gestational age (Stacy et al., 2015), increased preterm birth (Casey et al., 2016), increased in mild, moderate, and severe asthma exacerbations (Rasmussen et al., 2016), and increasesd chronic rhinosinusitis, migraine headache, and fatigue symptoms (Tustin et al., 2016). The number of wells per ZIP code was associated with increased hospitalization rates, particularly in the areas of dermatology, neurology, oncology, and urology (Jemielita et al., 2015).

The only epidemiologic analysis of the association between UO&G development and risk of cancer published in the scientific literature reported similar county-level standardized incidence ratios for childhood leukemia before and after drilling of any oil and gas wells in any Pennsylvania counties during 1990–2009 (Fryzek et al., 2013). Also in this analysis, standardized incidence ratios were similar before and after drilling started in counties with unconventional wells, specifically. However, several important shortcomings of this study have been noted. For example, this ecologic study did not account for a latency period between exposure and cancer incidence. In addition, though the study objective was to examine risk associated with hydraulic fracturing, 98% of the wells included in the study were "non-horizontal" wells that likely did not involve the practice of hydraulic fracturing (Goldstein and Malone, 2013). Case-control studies of proximity to other petroleum-based sources provide some evidence of an association with childhood leukemia risk. Two case-control studies in France reported increased odds of childhood leukemia among those living in proximity to the petroleum-based sources of petrol stations and automotive repair garages (Brosselin et al., 2009; Steffen et al., 2004). Another case-control study reported elevated odds of childhood leukemia with proximity to petrol stations, but the relationship was not statistically significant, possibly due to small sample size (Harrison et al., 1999). Another study observed an association with proximity to petrochemical plants and increased odds of leukemia in young adults (20–29 years), but not children ages 0–15 (Yu et al., 2006). Additionally, a human health risk assessment found an increased risk of cancer for residents living ≤0.5 versus >0.5 mile from a well, attributable primarily to benzene, a known human carcinogen associated with leukemia risk (McKenzie et al., 2012). Taken together, these findings support the plausibility of an increased risk of childhood leukemia related to oil and gas development. The current analysis investigates whether there is additional evidence for the plausibility of a carcinogenic risk from air or water contaminants and provides information to improve the specificity of exposure assessments and human health research of the potential adverse effects of UO&G development.

2. Methods

2.1. Identification of potential water contaminants

We compiled a list of all chemicals used in hydraulic fracturing fluids, detected in hydraulic fracturing wastewater, or both from the U.S. Environmental Protection Agency (US EPA) Appendices A of the progress report "Study of the Potential Impacts of Hydraulic Fracturing on Drinking Water Resources" and draft report "Assessment of the Potential Impacts of Hydraulic Fracturing for Oil and Gas on Drinking Water Resources" (US EPA, 2012; US EPA, 2015). We eliminated duplicate entries and combined the entries for xylene isomers. This yielded a total of 1177 distinct compounds or groups of compounds (1043 in fracturing fluids only, 98 in wastewater only, 36 in both). The U.S. EPA developed these chemical lists from federal and state databases of well permits and construction records, industry disclosures and monitoring reports, trade journals, the scientific literature, and governmental and non-governmental reports. The fracturing fluid list contains a greater number of substances because it reflects reported usage and includes

disclosed substances used across varying companies, locations, and geological formations. The list of wastewater constituents is shorter because it is based on the limited wastewater measurement data available from industry, government reports, or the published literature.

2.2. Classification of carcinogenicity of potential water contaminants

We searched the International Agency for Research on Cancer (IARC) monographs for evidence of carcinogenicity of the potential water contaminants. IARC is an internationally recognized authority on carcinogenicity of chemicals and other agents (Pearce et al., 2015). The monographs are written by working groups of international experts convened by IARC, and they provide detailed evaluations of the quality and strength of evidence of carcinogenicity of agents. The agents are selected for evaluation based on exposure prevalence and suggestive evidence of likelihood to pose a cancer hazard to humans (Tomatis, 1976). Other organizations evaluate environmental agents for carcinogenicity, such as the U.S. EPA through their Integrated Risk Information System (IRIS) or the National Institutes of Health through their National Toxicology Program (NTP). Their lists of agents evaluated for their carcinogenicity contain much overlap with IARC and are less comprehensive; IARC, IRIS, and NTP have evaluated 1050, 264, and 243 compounds, respectively (IARC, 2016; IRIS, 2016; NTP, 2014).

Chemicals were designated as "no information available" if they were not evaluated in an IARC monograph. For chemicals that were evaluated, we indicated their IARC carcinogenicity classification: carcinogenic to humans (Group 1), probably carcinogenic to humans (Group 2A), possibly carcinogenic to humans (Group 2B), not classifiable as to their carcinogenicity to humans (Group 3), and probably not carcinogenic to humans (Group 4). We calculated frequencies and percentages of the potential water contaminants in each carcinogenicity classification. For chemicals in Groups 1, 2A, or 2B, we assessed whether these chemicals had evidence linked to leukemia and/or lymphoma specifically, based on the available information on human and animal study data provided in the monograph summary or synthesis.

2.3. Identification of potential air pollutants

We constructed a list of potential air pollutants associated with UO&G development by conducting a comprehensive review of the scientific literature. First, we systematically searched the biomedical and health-oriented PubMed database for papers published through December 31, 2015 using the terms "fracking air", "hydraulic fracturing air", "unconventional gas air", "shale gas air," "unconventional oil air," and "shale oil air," which yielded 136 unique publications. Next, we searched the ProQuest Environmental Science Collection database for papers published in environmental science-oriented journals through December 31, 2015 using the terms "fracking", "hydraulic fracturing", "unconventional gas", "shale gas", "unconventional oil", and "shale oil" with the term "air pollution." This search yielded 42 publications (31 additional, unique publications and 11 previously identified through PubMed). We included three types of studies in this analysis: 1) studies that collected primary air pollutant measurements or presented air pollutant measurements from secondary data sources, such as a state or county dataset ("measurement" studies), 2) studies that modeled air pollutant concentrations using inputs from primary or secondary measurements, emission rates from equipment or UO&G activities, and/or meteorological data ("modeling" studies), and 3) studies with qualitative assessments of potential or expected air pollutants based on review of the scientific literature, government or non-governmental reports, and/or expert judgement about the types of pollutants likely to be generated from UO&G activities ("descriptive" studies). We excluded papers not directly related to environmental air pollution associated with UO&G development (n = 86), papers describing generic chemical classes (e.g., volatile organic compounds (VOCs)) but not specific

chemical names (e.g., benzene) (n = 25), publications that were not peer-reviewed original research or review papers or were corrected and updated after 2015 (n = 4), and papers written in foreign languages (n = 3). From the 49 publications meeting our criteria, we abstracted chemical names of air pollutants from tables, text, and figures, if explicitly reported as present or predicted to be present at UO&G sites. For example, we abstracted names of target analytes from tables and figures presenting measured or estimated concentrations of pollutants near UO&G sites. This approach is consistent with the U.S. EPA water list construction, which included any compounds reportedly used in hydraulic fracturing fluids or detected in wastewater. We combined individual chemicals into one category if these agents were evaluated as a group by IARC (e.g. xylenes, particulate matter).

2.4. Classification of carcinogenicity of potential air contaminants

We searched the IARC monographs for evidence of carcinogenicity using chemical names of the potential air pollutants. Following the same procedure as for potential water contaminants (Section 2.2), chemicals were designated as "no information available" if they were not present in the IARC monographs; or else were reported as Groups 1, 2A, 2B, 3, or 4. For the compounds in Groups 1, 2A, and 2B, we determined whether the monograph summary or synthesis indicated that there was sufficient evidence of increased risk of leukemia and/or lymphoma specifically, based on human or animal data.

3. Results

3.1. Carcinogenicity of potential water contaminants

Of the 1177 potential water contaminants assessed, 1066 compounds (91%) had not been evaluated for carcinogenicity by IARC. The 111 potential water contaminants evaluated included 14 (13%) known human carcinogens (Group 1), 6 (5%) probable human carcinogens (Group 2A), and 29 (26%) possible human carcinogens (Group 2B), and 62 (56%) compounds were not classifiable with respect to their carcinogenicity (Group 3) (Fig. 1). None were designated as probably not carcinogenic to humans, though only one compound has ever been assigned this classification. The distribution of compounds among the carcinogenicity classifications was similar between the fracturing fluid

compounds and wastewater compounds (Fig. 1). Of the 49 potential water contaminants classified as known, probable, or possible human carcinogens (Groups 1, 2A, 2B), 17 had evidence of an increased risk of leukemia and/or lymphoma (Table 1). This included 7 known human carcinogens (1,3-butadiene, benzene, cadmium, ethanol, ethylene oxide, formaldehyde, and quartz), 3 probable carcinogens (dibenz[*a,h*]anthracene, dichloromethane, tetrachloroethylene), and 7 possible carcinogens (1,2-propylene oxide, benzo[*b*]fluoranthene, benzo[*k*]fluoranthene, heptachlor, hydrazine, indeno[1,2,3-*cd*]pyrene, styrene). This list reflects petroleum-related volatile organic compounds (e.g., benzene), metals (e.g., cadmium), solvents (e.g., dichloromethane, tetrachloroethylene), and PAHs (benzo[*b*]fluoranthene, dibenz[*a,h*]anthracene, benzo[*k*]fluoranthene).

3.2. Identification of potential air pollutants

Our literature review yielded 143 distinct potential air pollutants or groups of pollutants related to UO&G development from 49 studies (Supplemental Table S1, Table 1). Of the 143 compounds, 97 had also been identified in water and 46 were unique to air. A total of 27 studies included measurements, 19 used modeling, and 15 were descriptive in nature; some studies incorporated a combination of these approaches (Table 2). There were 31 studies of gas development, 1 of oil development, and 17 of both. Studies reporting primary measurements or modeled estimates of air pollutants were conducted mainly in Colorado, Pennsylvania, Texas, and Wyoming. Frequently reported air pollutants (reported in ≥5 studies) included benzene, ethylbenzene, hydrogen sulfide, methane, nitrogen oxides, ozone, particulate matter, toluene, and styrene (Supplemental Table S1). Sampling locations included perimeters of UO&G well sites, mobile monitoring stations, and fixed community sites. Sampling durations varied, such as one-time grab samples of 2 to 3 min (Macey et al., 2014) and weekly 24-hour integrated samples collected over a period of two years (McKenzie et al., 2012).

3.3. Carcinogenicity of potential air pollutants

Of the 143 potential air pollutants, 114 compounds (80%) had not been evaluated for carcinogenicity by IARC. Of the 29 potential air pollutants evaluated, 7 (24%) were considered carcinogenic to humans (Group 1), 2 (7%) were considered probably carcinogenic to humans
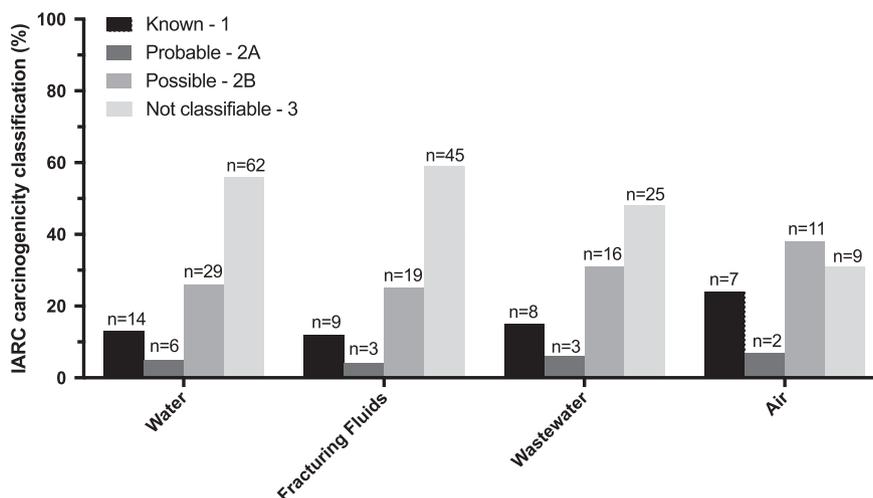
Fig. 1. International Agency for Research on Cancer carcinogenicity classification of chemicals in water (n = 111), hydraulic fracturing fluids (n = 76), hydraulic fracturing wastewater (n = 52), and in air (n = 29) related to unconventional oil and gas development.[1,2] [1]All potential water contaminants were obtained from the U.S. Environmental Protection Agency draft report "Assessment of the Potential Impacts of Hydraulic Fracturing for Oil and Gas on Drinking Water Resources" (2015). [2]All potential air pollutants were abstracted from the scientific literature through systematic review of studies (n = 50) including measurement, modeling, or description of potential air pollutants related to unconventional oil and gas development.

Table 1
Potential water contaminants related to unconventional oil and gas development with evidence of carcinogenicity (n = 49).[a]

CASRNs	Chemical name	Associated with leukemia/lymphoma[b]	Water source	IARC monograph publication year	IARC monograph volume #
Group 1: Carcinogenic to humans					
106-99-0	1,3-Butadiene	Leukemia, lymphoma	FF	2012	Sup 7, 54, 71, 97, 100F
7440-38-2	Arsenic	–	FF, WW	2012	23, sup 7, 100C
71-43-2	Benzene	Leukemia, lymphoma	FF, WW	2012	29, sup 7, 100F
50-32-8	Benzo(a)pyrene	–	WW	2012	Sup 7, 92, 100F
7440–41-7	Beryllium	–	WW	2012	Sup 7, 58, 100C
7440–43-9	Cadmium	Leukemia, lymphoma	WW	2012	58, 100C
18,540–29-9	Chromium (VI)	–	FF, WW	2012	Sup 7, 49, 100C
64–17-5	Ethanol	Leukemia, lymphoma	FF	2012	96, 100E
75–21-8	Ethylene oxide	Leukemia, lymphoma	FF	2012	97, 100F
50–00-0	Formaldehyde	Leukemia, lymphoma	FF	2012	Sup 7, 62, 88, 100F
14,808–60-7	Quartz	Lymphoma	FF	2012	Sup 7, 68, 100C
13,982–63-3	Radium 226	–	WW	2012	78, 100D
15,262–20-1	Radium 228	–	WW	2012	78, 100D
7664–93-9	Sulfuric acid	–	FF	2012	54, 100F
Group 2A: Probably carcinogenic to humans					
79–06-1	Acrylamide	–	FF	1994	60
100–44-7	Benzyl chloride	–	FF	1999	29, sup 7, 71
53–70-3	Dibenz(a,h)anthracene	Lymphoma	WW	2010	Sup 7, 92
75–09-2	Dichloromethane	Lymphoma	WW	in prep	Sup 7, 71, 110
106–89-8	Epichlorohydrin	–	FF	1999	11, sup 7, 71
127–18-4	Tetrachloroethylene	Leukemia, lymphoma	WW	2014	Sup 7, 63, 106
Group 2B: Possibly carcinogenic to humans					
75–56-9	1,2-Propylene oxide	Leukemia, lymphoma	FF	1994	60
542–75-6	1,3-Dichloropropene	–	FF	1999	41, sup 7, 71
123–91-1	1,4-Dioxane	–	FF, WW	1999	11, sup 7, 71
108–10-1	4-Methyl-2-pentanone	–	FF	2013	101
75–07-0	Acetaldehyde	–	FF	1999	36, sup 7, 71
107–13-1	Acrylonitrile	–	WW	1999	71
1309–64-4	Antimony trioxide	–	FF	1989	47
205–99-2	Benzo(b)fluoranthene	Lymphoma	WW	2010	92
207–08-9	Benzo(k)fluoranthene	Lymphoma	WW	2010	92
75–27-4	Bromodichloromethane	–	WW	1999	52, 71
1333–86-4	Carbon black	–	FF	2010	65, 93
67–66-3	Chloroform	–	WW	1999	Sup 7, 73
68,603–42-9	Coconut oil acid/diethanolamine condensate (2:1)	–	FF	2013	101
7440–48-4	Cobalt	–	WW	1991	52
98–82-8	Cumene	–	FF, WW	2013	101
117–81-7	Di(2-ethylhexyl) phthalate	–	FF, WW	2013	77, 101
3252–43-5	Dibromoacetonitrile	–	FF	2013	52, 71, 101
111–42-2	Diethanolamine	–	FF	2013	77, 101
100–41-4	Ethylbenzene	–	FF, WW	2000	77
76–44-8	Heptachlor	Lymphoma	WW	2001	Sup 7, 53, 79
302–01-2	Hydrazine	Leukemia	FF	1999	4, sup 7, 71
193–39-5	Indeno(1,2,3-cd)pyrene	Lymphoma	WW	2010	Sup 7, 92
7439–92-1	Lead	–	FF, WW	1987, 2006	23, sup 7, 87
91–20-3	Naphthalene	–	FF, WW	2002	82
7440–02-0	Nickel	–	WW	1990	Sup 7, 49
139–13-9	Nitrilotriacetic acid	–	FF	1999	48, 73
94–59-7	Safrole	–	WW	1987	10, sup 7
100–42-5	Styrene	Leukemia	FF	2002	60, 82
13,463–67-7	Titanium dioxide	–	FF	2010	47, 93

CASRNs, Chemical Abstract Service Registry Numbers; FF, fracturing fluid; IARC, International Agency for Research on Cancer; WW, wastewater.

[a] All chemicals were obtained from the U.S. Environmental Protection Agency Appendices A of the progress report "Study of the Potential Impacts of Hydraulic Fracturing on Drinking Water Resources" (2012) and draft report "Assessment of the Potential Impacts of Hydraulic Fracturing for Oil and Gas on Drinking Water Resources" (2015).

[b] We abstracted leukemia/lymphoma association information from the IARC monographs report of an association with an increased risk of leukemia and/or lymphoma. If the association with leukemia and/or lymphoma was not reported in the monographs due to no/insufficient evidence of an association with an increased risk of leukemia and/or lymphoma, or if there was a null association, we determined the chemical not to be associated with leukemia and/or lymphoma ("-").

(Group 2A), and 11 (38%) were considered possibly carcinogenic to humans (Group 2B) (Fig. 1). A total of 9 (31%) compounds were not classifiable with respect to their carcinogenicity (Group 3) (Fig. 1). None were designated as probably not carcinogenic to humans (Group 4).

Of the 20 known, probable, or possible carcinogens (Groups 1, 2A, 2B), 11 had evidence of an increased risk of leukemia and/or lymphoma (Table 3). This included 5 known human carcinogens (1,3-butadiene, benzene, ethanol, formaldehyde, diesel engine exhaust), 2 probable human carcinogens (dibenz[a,h]anthracene, tetrachloroethylene), and 4 possible human carcinogens (carbon tetrachloroethylene, chrysene,

indeno[1,2,3-cd]pyrene, styrene). This list includes constituents of oil and gas resources (e.g., benzene) and diesel exhaust (e.g., formaldehyde, PAHs, 1,3-butadiene).

4. Discussion

We evaluated the evidence that potential exposures from UO&G development are risk factors for cancer in general and leukemia in particular. Our analysis of 1177 chemicals in hydraulic fracturing fluids or wastewater and 143 potential air pollutants identified 55 possible,

Table 2
Studies evaluating air pollutants related to unconventional oil and national gas development (n = 49).

Author	Study Type[a] Measurements (n = 27)	Modeling (n = 19)	Descriptive (n = 15)	Unconventional fuel type	Author	Study Type[a] Measurements (n = 27)	Modeling (n = 19)	Descriptive (n = 15)	Unconventional fuel type
Adgate et al. (2014)	.	.	x	Gas	McCawley (2015)	x	.	x	Gas
Ahmadi and John (2015)	x	.	.	Gas	McKenzie et al. (2012)	x	.	.	Gas
Allen et al. (2013)	.	.	x	Gas	Melikoglu (2014)	.	.	x	Gas
Allen (2014)	x	.	.	Gas	Moore et al. (2014)	.	.	x	Gas
Brown et al. (2014)	x	x	x	Gas	Nathan et al. (2015)	x	x	.	Gas
Brown et al. (2015)	.	x	.	Gas	Nduagu and Gates (2015)	.	x	.	Oil
Bunch et al. (2014)	x	.	.	Gas	Newell and Raimi (2014)	.	.	x	Gas
Burnham et al. (2012)	.	x	.	Gas/oil	Olaguer (2012)	.	x	.	Gas/oil
Carlton et al. (2014)	.	.	x	Gas	O'Sullivan and Paltsev (2012)	.	x	.	Gas
Casey et al. (2015)	x	.	.	Gas/oil	Pacsi et al. (2015)	.	x	.	Gas
Caulton et al. (2014)	x	.	.	Gas	Pekney et al. (2014)	x	.	.	Gas/oil
Chang et al. (2014)	.	x	.	Gas	Rella et al. (2015)	x	.	.	Gas/oil
Eapi et al. (2014)	x	.	.	Gas	Rich and Crosby (2013)	x	.	.	Gas
Edwards et al. (2014)	x	x	.	Gas/oil	Roy et al. (2014)	.	x	.	Gas
Evans et al. (2015)	.	.	x	Gas/oil	Rutter et al. (2015)	x	.	.	Gas/oil
Field et al. (2014)	.	.	x	Gas/oil	Shonkoff et al. (2014)	.	.	x	Gas
Goetz et al. (2015)	x	x	.	Gas	Swarthout et al. (2015)	x	.	.	Gas
Jackson et al. (2014)	x	x	x	Gas/oil	Ternes (2012)	.	.	x	Gas/oil
Karion et al. (2015)	x	x	.	Gas/oil	Townsend-Small et al. (2015)	x	.	.	Gas
Kemball-Cook et al. (2010)	.	x	.	Gas	Vinciguerra et al. (2015)	x	.	.	Gas
Lampe and Stolz (2015)	.	.	x	Gas	Walters et al. (2015)	x	.	x	Gas/oil
Lan et al. (2015)	x	x	.	Gas/oil	Yacovitch et al. (2015)	x	x	.	Gas/oil
Lavoie et al. (2015)	x	.	.	Gas	Zavala-Araiza et al. (2015)	.	x	.	Gas
Lyon et al. (2015)	.	x	.	Gas/oil	Zielinska et al. (2014)	x	.	.	Gas
Macey et al. (2014)	x	.	.	Gas/oil					

[a] "x" refers to study type as defined in section 2.3. Some studies corresponded to more than one study type.

probable, and known carcinogens related to UO&G development activities. However, the vast majority of chemicals (91% of potential water contaminants, 80% of potential air pollutants) were not evaluated for their carcinogenicity by IARC. Of the 55 known, probable, or possible human carcinogens, 20 had some evidence for increased risk of leukemia and/or lymphoma: 1,2-propylene oxide, 1,3-butadiene, benzene, benzo(b)fluoranthene, benzo(k)fluoranthene, cadmium, carbon tetrachloroethylene, chrysene, dibenz(a,h)anthracene, dichloromethane, engine exhaust (diesel), ethanol, ethylene oxide, formaldehyde, heptachlor, hydrazine, indeno(1,2,3-cd)pyrene, quartz, styrene, and tetrachloroethylene. These findings support the hypothesis that exposure to UO&G development could increase the risk of leukemia.

Our findings demonstrate the presence of known and suspected carcinogens surrounding UO&G facilities, but drawing conclusions about cancer or leukemia risk is challenging, due to the varied and limited water and air measurement data. With respect to water, for example, Fontenot et al. (2013) measured metals in private drinking water wells in a community proximate to UO&G activity and observed concentrations of the known carcinogen arsenic in exceedance of U.S. EPA Maximum Contaminant Levels, although possible sources included mobilization of natural constituents and hydrogeochemical changes in addition to UO&G activities. Drollette et al. (2015) detected trace levels of organic compounds, such as the known leukomogen benzene and possible carcinogen ethylbenzene, in private drinking water wells in areas with UO&G development in Pennsylvania, with highest observed concentrations within 1 km of active UO&G operations. Although the observed concentrations were below U.S. EPA Maximum Contaminant Levels, cancer risk is generally assumed not to have a threshold below which there is a safe level of exposure.

With respect to air, our literature review identified six studies measuring hazardous air pollutants associated with childhood leukemia (e.g., benzene, polycyclic aromatic hydrocarbons) near UO&G facilities (Bunch et al., 2014; Macey et al., 2014; McKenzie et al., 2012; Pekney et al., 2014; Rich and Crosby, 2013; Rutter et al., 2015). Differences in location, sampling duration, target agents, and sampling methodology in the air pollution literature hindered our ability to synthesize the air data and place it into context of human health risk. However, some individual studies used the air monitoring data to estimate cancer or health risk. Macey et al. (2014) identified concentrations of benzene, 1,3-butadiene, and formaldehyde in exceedance of EPA IRIS cancer risk levels; however, these were based on grab samples that represented high-exposure scenarios (e.g. ≤20 m of UO&G separator, compressor station, discharge canal, and well pad). McKenzie et al. (2012) estimated risk to communities based on Colorado measurement data collected over nearly three years from a fixed monitoring station in a rural community. They observed an excess risk of cancer for residents living <0.5 mile from the nearest well, mainly attributable to benzene and 1,3-butadiene. Bunch et al. (2014) used VOC measurements collected over ten years by the Texas Commission on Environmental Quality from seven fixed-site monitors in the Dallas/Fort Worth area to conduct deterministic and probabilistic risk assessments and found that all but one of the cancer risk estimates were within the acceptable cancer risk range. Pekney et al. (2014) collected mobile measurements of ambient concentrations of pollutants in Pennsylvania and found no exceedances of National Ambient Air Quality Standards for criteria pollutants. These studies indicate that water and air pollution related to UO&G activities may pose a public health and potential cancer risk. More environmental measurements of health-relevant chemicals

Table 3
Potential air pollutants related to unconventional oil and natural gas development with evidence of carcinogenicity (n = 20).[a]

CASRNs	Chemical name	Associated with leukemia/lymphoma[b]	Reference	IARC monograph publication year	IARC monograph volume #
Group 1: Carcinogenic to humans					
106-99-0	1,3-Butadiene	Leukemia, lymphoma	Brown et al. (2015), Macey et al. (2014), McKenzie et al. (2012), Olaguer (2012)	2012	Sup 7, 54, 71, 97, 100F
71-43-2	Benzene	Leukemia, lymphoma	Brown et al. (2015), Bunch et al. (2014), Field et al. (2014), Jackson et al. (2014), Lampe and Stolz (2015), Macey et al. (2014), McCawley (2015), McKenzie et al. (2012), Moore et al. (2014), Pekney et al. (2014), Rich and Crosby (2013), Rutter et al. (2015), Shonkoff et al. (2014), Ternes (2012)	2012	29, sup 7, 100F
	Engine exhaust (diesel)	Leukemia, lymphoma	Adgate et al. (2014), Lampe and Stolz (2015), McCawley (2015), Shonkoff et al. (2014)	2013	46, 105
64-17-5	Ethanol	Leukemia, lymphoma	McCawley (2015)	2012	96, 100E
50-00-0	Formaldehyde	Leukemia, lymphoma	Brown et al. (2015), Field et al. (2014), Jackson et al. (2014), Macey et al. (2014), McCawley (2015), Olaguer (2012), Shonkoff et al. (2014), Ternes (2012)	2012	Sup 7, 62, 88, 100F
	Particulate matter	–	Adgate et al. (2014), Brown et al. (2015), Brown et al. (2014), Evans et al. (2015), Field et al. (2014), Goetz et al. (2015), Jackson et al. (2014), Macey et al. (2014), Moore et al. (2014), Pacsi et al. (2015), Pekney et al. (2014), Roy et al. (2014), Song et al. (2015), Ternes (2012), Vinciguerra et al. (2015), Walters et al. (2015)	2015	109
	Radon	–	Casey et al. (2015), Evans et al. (2015), Shonkoff et al. (2014)	2012	43, 78, 100D
Group 2A: Probably carcinogenic to humans					
53-70-3	Dibenz(a,h)anthracene	Lymphoma	McCawley (2015)	2010	Sup 7, 92
127-18-4	Tetrachloroethylene	Leukemia, lymphoma	Brown et al. (2015)	2014	Sup 7, 63, 106
Group 2B: Possibly carcinogenic to humans					
75-07-0	Acetaldehyde	–	Brown et al. (2015), McCawley (2015), Ternes (2012)	1999	36, sup 7, 71
107-13-1	Acrylonitrile	–	Shonkoff et al. (2014)	1999	71
	Carbon tetrachloride	Lymphoma	Brown et al. (2015)	1999	20, sup 7, 71
	Chrysene	Lymphoma	McCawley (2015)	2010	92
98-82-8	Cumene	–	McCawley (2015), McKenzie et al. (2012)	2013	101
100-41-4	Ethylbenzene	–	Brown et al. (2015), Bunch et al. (2014), Field et al. (2014), Jackson et al. (2014), Lampe and Stolz (2015), Macey et al. (2014), McCawley (2015), McKenzie et al. (2012), Moore et al. (2014), Pekney et al. (2014), Rich and Crosby (2013), Shonkoff et al. (2014), Ternes (2012)	2000	77
193-39-5	Indeno(1,2,3-cd)pyrene	Lymphoma	McCawley (2015)	2010	Sup 7, 92
	Isoprene	–	McCawley (2015), McKenzie et al. (2012), Olaguer (2012), Rutter et al. (2015)	1999	60, 71
7439-92-1	Lead	–	Brown et al. (2015), Ternes (2012)	1987, 2006	23, sup 7, 87
91-20-3	Naphthalene	–	Brown et al. (2015), McCawley (2015)	2002	82
100-42-5	Styrene	Leukemia	McCawley (2015), McKenzie et al. (2012), Pekney et al. (2014), Rutter et al. (2015)	2002	60, 82

CASRNs, Chemical Abstract Service Registry Numbers; IARC, International Agency for Research on Cancer.

^a All compounds were abstracted from the scientific literature through systematic review of studies (n = 49) including measurement, modeling, or descriptive summary of air pollutants potentially associated with unconventional oil and gas development.

^b If an association with leukemia and/or lymphoma was not reported in the IARC monographs due to no/insufficient evidence, or if there was a null association, we determined the chemical not to be associated with leukemia and/or lymphoma ("-").

associated with UO&G development, particularly at residences in close proximity to these facilities, are needed to better characterize human exposures and determine whether confirmed or suspected carcinogens and toxicants are present and at what levels. In particular, studies with longer sampling durations or integrated over longer periods of time would be more relevant to chronic outcomes like cancer.

To our knowledge, our analysis represents the most expansive review of carcinogenicity of hydraulic fracturing-related chemicals in the published literature. Previous studies have examined the carcinogenicity of more selective lists of chemicals. For example, Kahrilas et al. (2015) reviewed the toxicological properties of biocide constituents of fracturing fluids and their degradation and reaction products and found that few had been evaluated by IARC. Compounds identified by Kahrilas et al. included formaldehyde (a known carcinogen associated with an increased risk of leukemia and lymphoma, identified in our analysis), dibromoacetonitrile (a possible carcinogen, identified in our analysis), nitrosamines (includes probable carcinogens, not identified in our analysis), and trihalomethanes (includes possible and probable carcinogens, four identified in our analysis: bromodichloromethane, chloroform, chlorodibromomethane, and bromoform). Stringfellow et al. (2014) assessed 81 common hydraulic fracturing fluid additives

and identified five confirmed or suspected carcinogens using the U.S. NTP carcinogenicity evaluations (Stringfellow et al., 2014). Our analysis also identified four of these five chemicals: ethanol (known carcinogen associated with an increased risk of leukemia and lymphoma), acetaldehyde (possible carcinogen), diethanolamine (possible carcinogen), and naphthalene (possible carcinogen). The fifth compound, thiourea, was included in our analysis, but was considered not classifiable with respect to human carcinogenicity by IARC. Colborn et al. (2011) abstracted a list of chemical additives of hydraulic fracturing fluids using information on Material Safety Data Sheets provided by government and natural gas industry sources (Colborn et al., 2011). They found that 25% of the 353 chemicals evaluated could cause cancer and mutations. However, the inclusion criteria for this carcinogenicity evaluation were not provided to make a direct comparison with our findings.

An experimental study on the carcinogenicity of hydraulic fracturing wastewater observed that immortalized human bronchial epithelial cells exposed to flowback water collected from unconventional natural gas drilling of the Marcellus Shale underwent malignant transformation and exhibited altered morphology compared to parental cells (Yao et al., 2015). The flowback water sample contained relatively high concentrations of barium and strontium. However, these metals were not

evaluated for carcinogenicity to humans by IARC and therefore were not included in our evaluation. Strontium was not evaluated by the NTP or U.S. EPA IRIS programs; barium was not evaluated by NTP, and it was deemed not classifiable with respect to carcinogenicity by the U.S. EPA.

Looking broadly at UO&G development and cancer risk, other risk factors should also be considered. For example, UO&G development could pose a risk for childhood leukemia through a phenomenon known as population mixing (Belson et al., 2007; Kinlen, 2012). This refers to the migration of new populations into previously contained rural areas, introducing new infectious agents. This could give rise to increasing underlying infections, for which childhood leukemia is a possible complication (Kinlen, 1988; Kinlen, 2012). An alternative hypothesis is that a delayed exposure to infectious agents among individuals who experienced an absence of exposure in very early life could increase the risk of an inappropriate immune response and lead to leukemia (Greaves, 2006; Greaves, 1997). UO&G development is a rapidly expanding industry that creates an influx of specialized, external workers into less populated areas to fill industry jobs (Brasier et al., 2011; Filteau, 2015b; Jacquet, 2014). Additionally, previous examples of resource extraction or energy development have reported population increases up to 80% and worker influx-related impacts on public health and local communities (Ennis and Finlayson, 2015; Filteau, 2015a; Keough, 2015). More research would be needed to demonstrate risk to newly introduced infectious agents. Another possible risk factor for childhood leukemia is parental occupational exposures to agents such as benzene or PAHs from work in the oil and gas industry during the pregnancy period, a critical window of vulnerability for childhood leukemia (Fusion et al., 2001). In addition, parents employed by oil and gas companies could introduce contaminants into the home environment through clothing, shoes, and skin (Newman et al., 2015; Sahmel et al., 2014). Also, the introduction of bromide constituents from hydraulic fracturing wastewater into drinking water sources could increase the subsequent, downstream formation of carcinogenic disinfection byproducts and increase the risk of cancer, such as bladder cancer (Regli et al., 2015). Further, agents released from other components of oil and gas infrastructure, such as petroleum storage tanks (Zusman et al., 2012), petrochemical plants (Yu et al., 2006), and petrol stations (Brosselin et al., 2009; Harrison et al., 1999; Steffen et al., 2004) could pose a leukemia risk.

This analysis has several limitations. The list of potential water contaminants from fracturing fluids is limited to non-proprietary chemicals that were reported to the U.S. EPA by oil and gas companies and included in the U.S. EPA reports on hydraulic fracturing (US EPA, 2012; US EPA, 2015). Our identification of potential air pollutants was based on information available in the PubMed and ProQuest Environmental Science databases and may not include all potential air pollutants associated with UO&G development. The published literature may be more likely to report air pollutants for which health data are available, which could explain why a greater percentage of chemicals in air were evaluated by IARC compared to chemicals that were potential water pollutants. Additionally, IARC only evaluates chemicals with suspected carcinogenicity. Therefore, the proportion of known, probable, and possible carcinogens among those compounds evaluated may not be representative of the proportion of carcinogens among those not evaluated. Although the IARC monographs are the most comprehensive, systematic carcinogenicity evaluations, a comprehensive literature review of all 1177 water contaminants and 143 air pollutants could identify additional compounds that pose an increased risk of cancer.

Conducting a well-designed sampling campaign for UO&G development is challenging, given the wide variety of potential target pollutants and the limited information available to identify which pollutants have the highest probability of exposure or health impact. Our list of 143 air pollutants associated with UO&G development (Supplemental Table S1) may serve as a useful resource for researchers designing future studies. Furthermore, our list of known, probable, and possible carcinogens linked to UO&G development can be used as a target analyte list for

environmental or biological measurements in future exposure and health studies. Measurements of these compounds in air or water in residences proximate to this activity would provide insights into whether exposures are occurring and at what levels. Additionally, air pollution measurements corresponding to the different phases of UO&G development would provide critical information about the relative contribution of exposures from various aspects of the development activities and priorities for exposure mitigation. Furthermore, geographical and seasonal variations could influence release, concentration, and dispersion of potential air pollutants. Therefore, additional water and air measurement studies are urgently needed to investigate the potential for spatial and temporal variations in exposures.

This analysis could also inform design of exposure metrics for epidemiologic studies. Epidemiologic studies have generally used individual-level, geographic information systems-based inverse-distance weighted metrics to estimate exposure to UO&G development, which characterize UO&G development as a collective process. More specific metrics or measurements could offer improvements to the exposure assessment and potential insights into etiologic agents. Future studies could incorporate environmental and/or biological monitoring of health-relevant chemicals, such as the 55 known, probable, and possible carcinogens in water or air, and examine the relationship between chemical concentrations and proximity and density-based metrics, to determine the extent to which proximity is associated with exposure. Though more measurement data is needed to better understand whether exposures are occurring and at what concentrations, release of any carcinogens from UO&G development should be minimized.

5. Conclusions

There is a need to better understand the potential risks of UO&G development with carefully designed exposure and epidemiologic studies. We identified 55 known, probable, or possible carcinogens (20 compounds associated with leukemia and/or lymphoma specifically) that are potential water contaminants and/or air pollutants related to UO&G development. Our study provides some support for the hypothesis that exposure to UO&G development could increase the risk of leukemia. Because children are a vulnerable population, research efforts should first be directed toward investigating whether exposure to UO&G development is associated with an increased risk in childhood leukemia. Environmental and biological measurements of the compounds identified in this analysis in communities proximate to UO&G development would be critical for future research on the potential public health impact.

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.scitotenv.2016.10.072.

Acknowledgements

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C.D. Kassotis et al., Endocrine-Disrupting Chemicals and Oil and Natural Gas Operations: Potential Environmental Contamination and Recommendations to Assess Complex Environmental Mixtures, 124 Environmental Health Perspectives 3, at 256 (Mar. 2016), available at: https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4786988/pdf/ehp.1409535.pdf.

Endocrine-Disrupting Chemicals and Oil and Natural Gas Operations: Potential Environmental Contamination and Recommendations to Assess Complex Environmental Mixtures

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BACKGROUND: Hydraulic fracturing technologies, developed over the last 65 years, have only recently been combined with horizontal drilling to unlock oil and gas reserves previously deemed inaccessible. Although these technologies have dramatically increased domestic oil and natural gas production, they have also raised concerns for the potential contamination of local water supplies with the approximately 1,000 chemicals that are used throughout the process, including many known or suspected endocrine-disrupting chemicals.

OBJECTIVES: We discuss the need for an endocrine component to health assessments for drilling-dense regions in the context of hormonal and antihormonal activities for chemicals used.

METHODS: We discuss the literature on *a*) surface and groundwater contamination by oil and gas extraction operations, and *b*) potential human exposure, particularly in the context of the total hormonal and antihormonal activities present in surface and groundwater from natural and anthropogenic sources; we also discuss initial analytical results and critical knowledge gaps.

DISCUSSION: In light of the potential for environmental release of oil and gas chemicals that can disrupt hormone receptor systems, we recommend methods for assessing complex hormonally active environmental mixtures.

CONCLUSIONS: We describe a need for an endocrine-centric component for overall health assessments and provide information supporting the idea that using such a component will help explain reported adverse health trends as well as help develop recommendations for environmental impact assessments and monitoring programs.

CITATION: Kassotis CD, Tillitt DE, Lin CH, McElroy JA, Nagel SC. 2016. Endocrine-disrupting chemicals and oil and natural gas operations: potential environmental contamination and recommendations to assess complex environmental mixtures. Environ Health Perspect 124:256–264; http://dx.doi.org/10.1289/ehp.1409535

Introduction

A novel source of human and animal exposure to endocrine-disrupting chemicals (EDCs) is through their use in oil and gas drilling operations. EDCs are exogenous compounds that can disrupt both development and normal hormone action either directly, by interacting with hormone receptors as agonists/antagonists, or indirectly by, for example, altering endogenous hormone concentrations, delivery to receptors, modulation of endogenous hormone responses, enzyme activities, or other mechanisms (Bergman et al. 2013; Diamanti-Kandarakis et al. 2009; Zoeller et al. 2014). Importantly, oil and gas operation chemicals have been shown to act through both direct and indirect mechanisms (Andric et al. 2006; Kassotis et al. 2014; Knag et al. 2013; Thomas and Budiantara 1995). EDCs can exhibit effects at extremely low, environmentally relevant concentrations, particularly during sensitive windows when exposure can alter normal development and result in adverse health outcomes during adulthood (Vandenberg 2014; Vandenberg et al. 2012; vom Saal et al. 2007; Welshons et al. 2003). Although chemicals used in and produced by oil and gas operations include EDCs, carcinogens, radioactive compounds, and other toxicants, herein, we will focus on the unique issues posed by their endocrine-disrupting activities.

In hydraulic fracturing, millions of gallons of water, tens of thousands of gallons of chemicals, and millions of kilograms of suspended solids are injected into the ground under high pressure. Hydraulic fracturing serves to fracture the shale or coal bed layer and release trapped natural gas or oil, allowing for increased well production. Although hydraulic fracturing technologies have been developed over the last 65 years, they have only recently been combined with horizontal drilling to unlock vast new oil and gas reserves around the world that were previously deemed either inaccessible or unprofitable (Waxman et al. 2011; Wiseman 2008). Chemicals are added throughout the entire production process (including drilling, fracturing, and through closure) for a number of reasons (Table 1) (Deutch et al. 2011; Riedl et al. 2013; Waxman et al. 2011). In total, approximately 1,000 chemicals are known to be used throughout the process [U.S. Environmental Protection Agency (EPA) 2015; Waxman et al. 2011].

Following the initial injection into the well to generate fractures, a portion of the injected volume returns to the surface immediately; this fluid is known as "flow-back." The remaining fluids either permeate the shale or coal bed formation and/or return to the surface over the life of the producing well; this fluid is known as "produced water." Both types of wastewater can contain fracturing fluids, naturally occurring salts, radioactive materials, heavy metals, and other chemicals from the shale formation such as polycyclic aromatic hydrocarbons, alkenes, alkanes, and other volatile and semi-volatile organic compounds (Deutch et al. 2011; Fontenot et al. 2013; Harkness et al. 2015; Harvey et al. 1984; Maule et al. 2013; Warner et al. 2012). Wastewater is disposed of via injection wells, open evaporation pits, landfills, or treatment plants; through on-site burial; by being spread over road or fields; and/or by being treated and reused in future hydraulic fracturing operations (Deutch et al. 2011; Gilmore et al. 2014; Lee et al. 2011; Wiseman 2008). Treatment of wastewater for reuse or disposal varies by geological region owing to differing chemical compositions and may include biological treatment, filtration or aeration steps, and/or reverse-osmosis separation (Lester et al. 2015).

Potential Routes of Exposure to Oil and Natural Gas Operation Chemicals

Water. Oil and natural gas operations can lead to the contamination of surface and groundwater, both of which are sources of drinking water (reviewed by Brantley et al. 2014; Burton et al. 2014; Vengosh et al. 2014). There are a variety of routes of contamination: spills of chemicals during transport to and from the fracturing site, the drilling and fracturing processes, improper treatment and disposal of wastewater, failure of well casings, and structural failure in abandoned wells (Ingraffea et al. 2014; Kell 2011; Mauter et al. 2014; Rozell and Reaven 2012).

In 2013, spills were reported at 1% of Colorado wells (550/51,000 active wells), and it has been estimated that 50% of surface spills contaminate groundwater on the basis of data from Weld County, Colorado (Gross et al. 2013). An analysis of permitted Pennsylvania wells suggests a similar total spill rate of 2% (103/5,580 active wells; Souther et al. 2014). Although all 24 states with active shale reservoirs report spills, reporting limits and required information vary widely, and only 5 states require maintenance of public records for spills and violations (Soraghan 2014; Souther et al. 2014). Given the limited mandatory reporting, it is likely that the magnitude of the impact of oil and gas operations on water quality is underestimated (Soraghan 2014; Souther et al. 2014). For example, an analysis in Pennsylvania found that industry had reported 59% of documented spills (Souther et al. 2014).

Wastewater is commonly sent to wastewater treatment plants in many regions (Gilmore et al. 2014) that are not able to remove many of the anthropogenic or naturally occurring compounds present in wastewater from shale operations (Braga et al. 2005; Campbell et al. 2006; Westerhoff et al. 2005). Following this treatment, these compounds can be discharged into surface water (Ferrar et al. 2013b; Harkness et al. 2015; Warner et al. 2013, 2014). Transportation of chemicals for drilling and fracturing to well pads and transportation of wastewater away from well pads poses risks for contamination (Burton et al. 2014). Spills and leaks occur during transportation through wastewater pipelines, transfer to trucks at well pads, and vehicular transport to disposal facilities (Gilmore et al. 2014).

Groundwater contamination associated with oil and gas operations has also been reported (Fontenot et al. 2013; Jackson et al. 2013; Osborn et al. 2011; Vengosh et al. 2014). This contamination can occur via migration of chemicals from the surface or underground. An investigation of wastewater

pits and impoundments in the Marcellus Shale region reported a lack of maintenance of containment and transport systems, with spills affecting groundwater largely as a result of equipment failures and corrosion of pipes and tanks (Ziemkiewicz et al. 2014). Surface spills of fracturing fluids can also contaminate groundwater, and elevated concentrations of benzene, toluene, ethylbenzene, and xylenes (BTEX) have been reported in groundwater near surface spills (Gross et al. 2013; Ziemkiewicz et al. 2014). A recent U.S. EPA report conclusively linked hydraulic fracturing to drinking-water contamination at wells within five of six retrospective study regions; no baseline testing was available for the sixth region (U.S. EPA 2015). Underground migration potential is also a concern. Concentrations of heavy metals have been shown to increase in drinking water with proximity to natural gas wells (Fontenot et al. 2013), and thermogenic (shale-origin) gas concentrations in drinking water sampled from close proximity to natural gas wells have

been reported to be higher than in water sampled from more distant sources (Jackson et al. 2013; Li and Carlson 2014; Osborn et al. 2011). Recent work suggests that the main reason for these findings may be faulty well casings (Darrah et al. 2014).

Air. Oil and natural gas production processes also contribute contaminants to the air, creating another potential route of exposure for humans and animals (Colborn et al. 2014; Helmig et al. 2014; Macey et al. 2014; Moore et al. 2014). Potential sources of inhalation exposure for these chemicals include evaporation from surface spills and evaporation pits, flaring at the surface, and release of chemicals during surface transfers and during processing (Colborn et al. 2014; Trimble 2012). High-level releases of chemicals are episodic (Brown et al. 2014, 2015). Elevated levels of volatile organic compounds (VOCs) such as BTEX, alkenes, alkanes, aromatic compounds, and aldehydes have been reported during drilling, production, and completion from nearby wells (Colborn

Table 1. Functional categories of hydraulic fracturing chemicals [adapted from Colborn et al. (2011)].

Chemical categories	Technical hydraulic fracturing use	Example compounds
Acids	To achieve greater injection ability or penetration and later to dissolve minerals and clays to reduce clogging, allowing gas to flow to the surface.	Hydrochloric acid
Biocides	To prevent bacteria that can erode pipes and fittings and to break down gellants that serve to ensure that fluid viscosity and proppant transport are maintained.	1-methyl-4-isothiazolin-3-one, bronopol, glutaraldehyde
Breakers	To allow the breakdown of gellants used to carry the proppant; these are added near the end of the hydraulic fracturing sequence to enhance flowback.	Ammonium persulfate, magnesium peroxide
Clay stabilizers	To create a fluid barrier to prevent mobilization of clays, which can plug fractures.	Tetramethyl ammonium chloride, sodium chloride
Corrosion inhibitors	To reduce the potential for rusting in pipes and casings.	Ethoxylated octylphenol and nonylphenol, isopropanol
Crosslinkers	To thicken fluids, often with metallic salts, in order to increase viscosity and proppant transport.	Ethylene glycol, sodium tetraborate decahydrate, petroleum distillate
Defoamers	To reduce foaming after it is no longer needed in order to lower surface tension and allow trapped gas to escape.	2-ethylhexanol, oleic acid, oxalic acid
Foamers	To increase carrying capacity while transporting proppants and decreasing the overall volume of fluid needed.	2-butoxyethanol, diethylene glycol
Friction reducers	To make water slick and minimize the friction created under high pressure and to increase the rate and efficiency of moving the hydraulic fracturing fluid.	Acrylamide, ethylene glycol, petroleum distillate, methanol
Gellants	To increase viscosity and suspend sand during proppant transport.	Propylene glycol, guar gum, ethylene glycol
pH control	To maintain the pH at various stages with buffers to ensure the maximum effectiveness of various additives.	Sodium hydroxide, acetic acid
Proppants	To hold fissures open, allowing gas to flow out of the cracked formation; usually composed of sand and occasionally glass or ceramic beads.	Styrene, crystalline silica, ceramic, graphite
Scale inhibitors	To prevent buildup of mineral scale that can block fluid and gas passage through the pipes.	Acrylamide, sodium polycarboxylate
Surfactants	To decrease liquid surface tension and improve fluid passage through pipes in either direction.	Naphthalene, 1,2,4-trimethylbenzene, ethanol, methanol, 2-butoxyethanol

Categories and uses for commonly applied chemicals that are commonly used throughout the hydraulic fracturing process with specific examples provided for each category class. Adapted with permission from Colborn T et al. (2011). Reprinted by permission of Taylor & Francis LLC (http://www.tandfonline.com).

et al. 2014; McKenzie et al. 2012; Roy et al. 2014; Steinzor et al. 2013), in some cases exceeding levels observed in heavily polluted inner cities (Helmig et al. 2014).

Endocrine-Disrupting Chemicals and Oil and Gas Operations

EDC activity of chemicals used in oil and natural gas operations. Our laboratory has tested the estrogen and androgen receptor activities of 12 chemicals commonly used in oil and gas operations using a luminescence-based reporter gene bioassay in human cancer cells. We measured stimulation of receptors (agonist) or inhibition of positive control–induced expression (antagonist). We found 1 estrogen receptor agonist, 11 estrogen receptor antagonists, and 10 androgen receptor antagonists; several chemicals exhibited multiple receptor activities (Kassotis et al. 2014).

A 2011 analysis reported approximately 120 known or suspected EDCs out of 353 oil and gas operation chemicals with Chemical Abstract Service (CAS) numbers (Colborn et al. 2011). Importantly, only half of the known oil and gas operation chemicals had CAS numbers at that time, greatly limiting the health assessment for other chemicals used in these processes (Waxman et al. 2011). Still other chemicals remain proprietary information (Shonkoff et al. 2014; Wiseman 2011). For example, a recent study found that 67%, 37%, and 18% of assessed wells were fractured with ≥ 1, 5, or 10 proprietary chemicals, respectively (Souther et al. 2014).

EDC activity in water near oil and natural gas operations. We assessed the estrogen and androgen receptor activities of water samples collected from five sites in a drilling-dense region of Garfield County, Colorado, that had experienced industry-related spills or preventable discharges relative to surface and groundwater collected immediately outside of the drilling-dense region (Kassotis et al. 2014). Analysis of these samples revealed that surface and groundwater from Garfield County spill sites contained significantly elevated estrogen agonist, estrogen antagonist, and androgen antagonist activities relative to those at reference sites (Kassotis et al. 2014). Independent analytical water testing at these sites identified chemicals that we or others have shown to exhibit these same agonist and antagonist activities (discussed by Kassotis et al. 2014). Other researchers have reported estrogen agonist and androgen antagonist activities associated with oil sands and oil production wastewater (He et al. 2011; Thomas et al. 2004, 2009; Tollefsen et al. 2007).

Concentration of oil and natural gas operation chemicals in water. Hydraulic fracturing wastewater is reported to contain hundreds of organic chemicals (polyethylene glycols, ethoxylated surfactants, BTEX compounds, biocides, polycyclic aromatic hydrocarbons, aromatic amines, and more), with total dissolved organic carbon as high as 5.5 g/L, and many individual compounds present at > 500 mg/L and up to grams per liter concentrations (Kahrilas et al. 2015; Maguire-Boyle and Barron 2014; Orem et al. 2014; Thurman et al. 2014). A recent report analyzed publicly available data on FracFocus, an industry disclosure website (http://www.fracfocus.org/), and reported benzene ≤ 4.1% and naphthalene and ethylbenzene ≤ 0.45% of total fracturing fluid volume, resulting in milligrams per liter concentrations for these and other chemicals (Schaeffer and Bernhardt 2014).

Surface spills have been reported to contaminate groundwater with chemicals from oil and gas operations (Gross et al. 2013). Groundwater at surface spill sites contained 1.4, 2.2, 0.2, and 2.6 mg/L benzene, toluene, ethylbenzene, and xylene, respectively, and these concentrations decreased over time and distance from the spill sites (Gross et al. 2013). Sampling of groundwater in Pavillion, Wyoming, by the U.S. EPA in a region where no specific accident or spill had occurred revealed concentrations of BTEX, naphthalene, ethylene glycols, and other oil and gas chemicals at concentrations ranging from 0.01 to 8 mg/L (DiGiulio et al. 2011). Because some of these chemicals have been shown to disrupt multiple hormone receptors *in vitro* at concentrations in the micrograms per liter range (Kassotis et al. 2014), these groundwater samples contained concentrations of these chemicals within the bioactive range in our reporter gene assays. To date, few comprehensive analyses have been performed of oil and gas operation–derived chemicals in drinking-water samples.

Potential Endocrine-Related Health Effects of Oil and Gas Operation Chemicals

Oil and gas operation chemicals and health effects. Evidence of potential harm from exposure to hazardous chemicals, pollutants, and emissions used in oil and natural gas operations has been reported. These reports have most often been case series involving natural experiments using quasi-experimental design and have investigated domestic animals and wildlife (Bamberger and Oswald 2012). Researchers have also begun to document in both reports and white papers the content and quantities of hazardous chemicals, pollutants, and emissions associated with these operations (Eastern Research Group and Sage Environmental Consulting 2011; Ethridge 2010; Steinzor et al. 2013; Witter et al. 2008). Concurrent with these environmental testing projects, surveys of local residents were also performed, and the reports suggested that

living in close proximity to oil and gas operations has the potential to affect human and environmental health (Ferrar et al. 2013a; Rabinowitz et al. 2015; Steinzor et al. 2013; Subra 2009, 2010). At the present time, a limited number of epidemiology studies have been conducted to explore the relationship between health effects and exposure to oil and gas operation chemicals as described herein and as reviewed by Webb et al. (2014) and Werner et al. (2015).

The biological plausibility of health effects associated with exposure to hazardous chemicals, pollutants, and emissions used in oil and natural gas operations has also been explored. Many of these chemicals have documented adverse health effects in humans, are designated priority pollutants by the U.S. EPA, and/or are known or suspected EDCs (Colborn et al. 2011; Waxman et al. 2011). For example, exposure to naphthalene, a constituent of crude oil and a chemical used by industry for hydraulic fracturing processes (Waxman et al. 2011) and that has been reported in air and water near operations (Colborn et al. 2014; DiGiulio et al. 2011; Wolf Eagle Environmental 2009), can result in altered steroid hormone levels, increased reproductive abnormalities, and impaired sexual maturation in animal models and *in vitro* (Hansen et al. 2008; Pollino et al. 2009; Thomas and Budiantara 1995; Tintos et al. 2006), albeit generally at greater concentrations than those reported near these sites.

Occupational exposures. As with all environmental exposures, those who work around or with hazardous chemicals face significantly higher exposure risk than does the general population. The National Institute of Occupational Health and Safety (NIOSH) has published two studies for the oil and natural gas extraction industry: one about work crew exposures to respirable crystalline silica, and the other about work crew exposures to VOCs (Esswein et al. 2013, 2014). In both cases, these pilot data indicated that some workers' exposures exceeded NIOSH and/or ACGIH safe levels (reported therein) for crystalline silica, flammable hydrocarbon emissions, and benzene.

Reproductive effects. Exposure to VOCs including but not limited to benzene, toluene, ethylbenzene, xylenes, and formaldehyde, all chemicals used in and produced by oil and natural gas operations (Colborn et al. 2011; Waxman et al. 2011), is associated with reproductive health effects in both humans and animals. These effects include impaired fertility and fecundity via reduced semen quality and impaired menstrual cycles as well as increased risk of miscarriage, stillbirth, preterm birth, and birth defects, as reviewed by Webb et al. (2014). A list of other adverse endocrine health effects due to exposure to single

chemicals used in and produced by oil and gas operations has been assembled and is available online (http://endocrinedisruption.org/chemicals-in-natural-gas-operations/chemicals).

Adverse pregnancy outcomes. McKenzie et al. (2014) used spatial analysis to evaluate the likelihood of adverse pregnancy outcomes in a cohort of 12,842 live births for mothers living within 10 miles of drilling well operations compared with mothers with no drilling wells within 10 miles. Significantly increased risks for congenital heart defects [adjusted odds ratio (AOR) = 1.3; 95% confidence interval (CI), 1.2, 1.5] and neural tube defects (AOR = 2.0; 95% CI: 1.0, 3.9) were observed, but no association with oral clefts (AOR = 0.82; 95% CI: 0.55, 1.2) was observed. In contrast, a study on low birth weight that used a similar design showed mixed results (McKenzie et al. 2014; Stacy et al. 2015). In two case–control studies, maternal or paternal occupational exposure to glycol ethers (hormonally active chemicals used in fracturing fluids; Kassotis et al. 2014; U.S. EPA 2015; Waxman et al. 2011) and other chemicals (pesticides, polychlorinated compounds, phthalates, bisphenol A, alkylphenolic compounds, heavy metals, and miscellaneous agents) during pregnancy was associated with congenital malformations (Cordier et al. 1997).

Cancer. In a health impact assessment, McKenzie et al. (2012) used spatial modeling based on residence proximity (≤ 0.5 miles vs. > 0.5 miles) to oil and gas operations in Colorado and found an elevated cumulative cancer risk for people living near drilling wells (10 per 1,000,000 vs. 6 per 1,000,000). Two studies calculated standardized incidence ratios. One study was a cancer cluster analysis that compared the rates for several cancers in a drilling-dense Texas town with state rates using 3 years of cancer incidence data. Mokry et al. (2010) reported a statistically significantly elevated rate for breast cancer [(standardized incidence ratio (SIR) = 1.3; 95% CI: 1.1, 1.5]. The other study compared Pennsylvania counties before and after launching drilling operations. Fryzek et al. (2013) found a slightly increased rate of one cancer, central nervous system tumors (SIR = 1.13; 95% CI: 1.02, 1.25), after unconventional drilling operations began in northeast Pennsylvania (Fryzek et al. 2013).

Limitations and data gaps. Limitations of the above-mentioned studies are the lack of both direct exposure assessment and information on residential mobility of study participants. To date, no longitudinal study has enrolled a cohort of residents in a community that has an active oil and natural gas extraction industry so that biomarkers can be obtained in a timely manner. Known and suspected risk factors need to be collected to fully model

the exposure risk. The critical route/timing of exposure for hazardous chemicals associated with oil and natural gas operations has yet to be established. Drilling wells release different amounts of air pollutants at different stages of the development and production processes (Brown et al. 2014; Colborn et al. 2014; Helmig et al. 2014; McKenzie et al. 2012), and residents, including pregnant women, may be exposed to these pollutants throughout extraction or only during specific stages. Drinking-water exposure may show considerable heterogeneity owing to the hydrogeology of undergroundwater flow associated with released natural and man-made chemicals, and limited data are available on contamination of drinking water in areas that have oil and natural gas operations.

Recommendations

The endocrine system is designed to respond to extremely low concentrations of hormones, making it uniquely equipped to assess exposure to low levels of exogenous hormonally active contaminants. Although toxicological studies often assess adverse outcomes from high-exposure scenarios relevant to occupational exposure, endocrinological studies can assess outcomes from low-level exposure that may be more relevant to humans living near oil and natural gas operations. By combining existing *in vivo* EDC studies with knowledge of the hormone receptor activity profile of chemicals used in oil and natural gas operations, we can identify adverse health outcomes in areas where humans and animals are exposed to these chemicals for epidemiological assessment. We can then use a modified Bradford-Hill approach to assess causality between environmental exposures and adverse health outcomes, as suggested by Zoeller et al. (2014). The risks related to potential exposure and adverse outcomes in humans and wildlife populations have not been afforded complete evaluations in part because of exemptions from parts of six key federal regulatory acts that traditionally act to safeguard U.S. water sources, including the Safe Drinking Water Act and the Clean Water Act (Clean Water Act 1972; Deutch et al. 2011; Safe Drinking Water Act 1974).

Based on the hypothesis that exposure to oil and natural gas chemicals contributes to negative health outcomes, we offer the following recommendations to evaluate the risks posed to humans and wildlife: *a*) integrate endocrine-centric end points into human health assessments in areas of unconventional drilling operations; *b*) perform biomonitoring studies for chemicals and their metabolites in humans; *c*) develop an effect-directed screening approach to assess endocrine-related effects of mixtures; *d*) perform controlled laboratory animal studies of exposure to complex mixtures of oil and natural gas chemicals to

assess adverse health outcomes; and *e*) perform *in vitro* bioassays to assess receptor interactions with complex mixtures.

Endocrine health assessments. We suggest incorporating an endocrine-centric component into overall human and environmental health assessments. An endocrine-centric health component would assume additivity of chemicals, an assumption that has been shown to be reasonable for chemicals acting through similar mechanisms of action (Payne et al. 2000; Rajapakse et al. 2002; Silva et al. 2002). This approach would assess common adverse endocrine end points that have been shown to result from disruption of specific hormone receptors alone and in combination, including *a*) reproductive effects (infertility, subfertility, reduced sperm counts, miscarriage, preterm birth, birth weight, puberty), *b*) developmental irregularities (cryptorchidism, hypospadias, neural tube defects, congenital heart defects), and *c*) cancer, particularly hormone-responsive types such as testicular, breast, prostate, and brain cancers (reviewed by Bergman et al. 2013; Diamanti-Kandarakis et al. 2009; Vandenberg et al. 2012; Zoeller et al. 2012).

Measurement of chemicals in humans and wildlife (biomonitoring). One of the major limitations in human risk assessment of oil and natural gas operations is the paucity of chemical exposure information, considering the number of chemicals used and the proprietary disclosure rules. Until now, most research has focused on airborne emissions (reviewed by Moore et al. 2014) and water contamination (reviewed by Rozell and Reaven 2012; Vengosh et al. 2014). Although epidemiological studies have begun to assess adverse health outcomes near drilling operations (McKenzie et al. 2014), to our knowledge, no researchers have yet published data on concentrations of oil and gas operation chemicals in humans or wildlife.

Chemical characterization is required to determine appropriate biomonitoring candidates. Recent work has detailed analytical approaches for characterizing the various classes of compounds present in hydraulic fracturing wastewater (Ferrer and Thurman 2015). We suggest that oil and gas wastewater be used to determine the presence of chemicals that can result in the observed agonist and/or antagonist responses. Initial identification should occur via reverse matching to known compound lists such as the National Institute of Standards and Technology (NIST) Spectral Search Program for the NIST/U.S. EPA/National Institutes of Health (NIH) Mass Spectral Library. These compounds can be further reverse-matched to known oil and gas operation chemicals (Colborn et al. 2011, 2014; U.S. EPA 2015; Waxman et al. 2011). Because this step may miss proprietary compounds not currently

reported by industry, it should be used as a supplement to reverse-matching databases. These compounds can then be confirmed by comparing them with authentic standards. These chemicals can be further tested in bioassays to determine receptor activities and their likely presence and contribution to activities in water. These data can then guide the development of analytical methods for target compounds and their metabolites serving as biomonitoring candidates in humans living near extraction operations.

Using effects-directed analysis to identify chemicals responsible for EDC activity. Analytical identification of hormonally active chemicals present in both water and air must be performed to better characterize source and exposure and to assess risk. Whenever possible, analysis of complex environmental samples should be performed using an effects-directed analysis approach (Burgess et al. 2013; Liscio et al. 2014; Rostkowski et al. 2011) coupled with a response–balance approach (Cargouët et al. 2004; Schriks et al. 2010; Sun et al. 2008).

This effects-directed/response–balance approach should target the most hormonally active samples from drilling regions (as well as from reference sites to eliminate background activity/chemicals) for chemical fractionation and testing. These procedures should include orthogonal separations and screening of the resulting fractions in bioassays to refine and isolate bioactive chemicals. Refined fractions can then be analyzed using the mass spectrometry (MS) tools described below and recently reported (Ferrer and Thurman 2015) to help identify chemicals responsible for observed activities. Once candidate chemicals have been identified, authentic standards may be used to confirm the MS identification and the bioactivity observed in bioassays. This method has been used successfully to identify novel bioactive compounds and represents the best approach for characterizing the EDCs that are most responsible for observed activities (Liscio et al. 2014; Rostkowski et al. 2011). Finally, biological activity can be coupled with chemical concentrations obtained from environmental monitoring to determine relative contributions to observed receptor activities, as has been described by others (Cargouët et al. 2004; Schriks et al. 2010; Sun et al. 2008).

EDC-centric laboratory animal health assessments. Laboratory animal models can and should be used to test for causal relationships between exposure and negative health outcomes that might be expected in drilling-dense regions. Humans and wildlife living in these regions are likely exposed to oil and gas operation chemicals during different developmental windows, and known critical periods such as prenatal, perinatal, childhood, and puberty should be targeted. Studies of adult exposure should also be performed to assess occupational exposure and chronic exposure at environmentally relevant levels encountered by nearby residents. We further recommend that the route of exposure remain as relevant as possible. Likely exposure to chemicals may occur through oral, dermal, and/or inhalation routes, and parameters such as volatility and partition coefficients will help determine which exposure routes are of the highest concern for individual chemicals. Route of exposure is crucial to understanding health effects because varying routes of exposure can result in very different bioavailability of EDCs, as has recently been described for bisphenol A (Gayrard et al. 2013; Hormann et al. 2014; vom Saal and Welshons 2014). Adverse health outcomes that should be targeted are described above in both the section entitled "Potential Endocrine-Related Health Effects of Oil and Gas Operation Chemicals" as well as in our recommendation regarding endocrine health assessments and are known to result from exposure to EDCs (reviewed by Bergman et al. 2013; Diamanti-Kandarakis et al. 2009; Vandenberg et al. 2012; Zoeller et al. 2012); many protocols have been described for the evaluation of these end points (Diamanti-Kandarakis et al. 2009; Schug et al. 2013; U.S. EPA 2009a, 2009b, 2009c; Zoeller et al. 2012). These data can provide important information for further refining human epidemiological studies as well as studies on pets and wildlife populations, which have recently been shown to be affected by endocrine health concerns (Bamberger and Oswald 2012, 2014, 2015; Grant et al. 2015; Papoulias and Velasco 2013; Slizovskiy et al. 2015).

Bioassays for complex mixtures. With approximately 1,000 chemicals used in and produced by oil and gas operations (U.S. EPA 2015), there is a critical need for methods to assess the EDC activity of these complex mixtures. Methods of assessing the activity and potential health risks of mixtures that can appropriately address the interplay between receptor systems are limited. Observed outcomes *in vivo* can often be the result of disruption of several hormone receptor systems by single chemicals or by mixtures. Statistical modeling (Orton et al. 2012), *in vitro* and *in vivo* assays (Silva et al. 2002), quantitative structure analysis (Nishihara et al. 2000), gene expression (Richter et al. 2014), and other tools have been used to assess a number of laboratory-defined mixtures that interact with single hormone receptors.

Modeling complex mixtures can greatly reduce the number of independent tests that need to be performed when assessing toxicity. For example, Bertin et al. used a neural networking model to assess mixture toxicity, achieving a predictive model with approximately 10% of actual interactions tested (Bertin et al. 2013). However, despite clear successes with relatively uncomplicated mixtures, analysis of more complicated mixtures appears to be beyond current capabilities (Kortenkamp et al. 2014; Orton et al. 2012) owing to insufficient knowledge of interreceptor interactions and indirect chemical–receptor interactions (Kortenkamp et al. 2014). An additional concern involves indirect interactions between chemicals and receptors. For example, interaction with the aryl hydrocarbon receptor can result in the activation of cytochrome P450 enzymes, which are well known to alter endogenous and exogenous chemical metabolism and therefore exposure (Anzenbacher and Anzenbacherová 2001; Markowitz et al. 2003). Inactive chemicals can be metabolized into active metabolites, resulting in mixtures of inactive chemicals that can act as agonists or antagonists in mixtures only (Gauger et al. 2007). Improved characterization of these interactions will provide a clearer understanding of the utility models can provide towards assessing *in vivo* outcomes, as well as their limitations.

Because it is not possible to test all combinations of chemicals *in vitro* and/or *in vivo*, we recommend performing guided *in vitro* and *in vivo* research that focuses on receptor interactions. We suggest that reporter gene assays be used for *in vitro* testing because of their low cost, ease of use, reliability, high sensitivity, and ease of adapting for multiple receptor systems (Naylor 1999; Rajapakse et al. 2002; Silva et al. 2002; Soto et al. 2006). Similar assays including yeast receptor screens [yeast estrogen screen (YES), yeast androgen screen (YAS), etc.] tend to be less robust and less sensitive, albeit less susceptible to toxicity, whereas cell proliferation assays (E-SCREEN, A-SCREEN, etc.) are equally sensitive and, unlike reporter gene assays, can measure nongenomic effects through cell-surface receptors; however, they are generally less applicable for diverse receptor testing (Leusch et al. 2010). Current high-throughput assay options such as Tox21 or ToxCast^{TM} are of great use as diverse first-pass screens for individual compounds, although it is unclear whether they will be helpful in the assessment of complex mixtures (Filer et al. 2014; Tice et al. 2013). Rather than the single-receptor tests used by these systems, assessing chemicals and mixtures of chemicals in controlled multiple-receptor systems is critical to understanding and accounting for receptor interplay.

Improvement of the utility of *in vitro* assay systems should take place in several steps. First, receptor interaction can be assessed through testing positive controls in both the presence and the absence of other receptors. Ideally, this testing should be done across several cell lines to identify chemical impingement on receptor interactions and

tissue-specific comodulators. Once multiple-receptor experiments are carried out with single chemicals, simple mixtures with clearly defined receptor activity profiles can be introduced to determine how simultaneous interactions with several receptors can modulate responses. Further work should be coupled with *in vivo* experiments to understand these interactions in a whole-animal model and to confirm *in vitro* multiple-receptor results.

Potential Implications

Recent analyses of the potential contributions of EDC exposures to adverse endocrine health outcomes, such as obesity, cancers (particularly hormone-dependent), reproduction/infertility, metabolic diseases, and developmental abnormalities, suggest that EDC exposures account for an estimated 1.8% to 40% of societal health care costs (Hunt and Ferguson 2014; Olsson 2014; Trasande 2014). More recently, a suite of studies estimated the potential health care costs for the European Union (EU) due to EDC exposures: neurobehavioral deficits and disorders (> 150 billion euros; Bellanger et al. 2015), obesity and diabetes (> 18 billion euros; Legler et al. 2015), and male reproductive disorders and diseases (> 15 billion euros; Hauser et al. 2015). Altogether, the median cost to the EU for EDCs with the highest probability of causation was estimated at 157 billion euros per year (Trasande et al. 2015). Whereas exposure to oil and gas operation chemicals individually would likely result in only a fraction of these costs, increasing exposure to additional hormonally active chemicals is a cause for concern given the additive nature of many of these receptor systems. As such, there are potentially large financial implications for exposure to EDCs from their use in oil and gas operations.

Conclusions

Herein, we have provided a series of recommendations that will allow scientifically defensible, accurate assessments of the potential endocrine-related risks from chemical exposure associated with oil and natural gas operations. We present these recommendations in light of the growing body of information regarding both chemical concentrations in the environment and adverse health outcomes reported in humans and in wildlife. We suggest that these approaches will lead to improved information for resource management decisions and will ultimately protect and improve human health.

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WildEarth Guardians Exhibit 5

New Mexico Envt. Department, Ozone Attainment Initiative at 5 (September 26, 2019), available at: https://www.env.nm.gov/air-quality/o3-initiative/ (last accessed July 16, 2020).

New Mexico Environment Department

Ozone Attainment Initiative
Air Quality Bureau, Control Strategies
September 26, 2019

New Mexico Ozone Attainment Initiative Development

Our mission is to protect the inhabitants and natural beauty of New Mexico by preventing the deterioration of air quality.

The NMED will use the following during the development of the Ozone Attainment Initiative (OAI):

☐ Science: We will use the best available science to inform our decision-making.

☐ Innovation: We will employ creative engineering and technological solutions.

☐ Collaboration: We will engage with communities and interested stakeholders in our OAI development strategy.

☐ Compliance: We will ensure compliance with National Ambient Air Quality Standards and state regulations.

Outline

- ☐ What is Ozone?
- ☐ What are the health effects of ground level ozone?
- ☐ What is the Ozone Attainment Initiative?
- ☐ Why do we need the OAI?
- ☐ How will NMED implement the OAI?
- ☐ Where are the focus areas?
- ☐ What is the projected timeline?
- ☐ How can stakeholders get involved?

Smog

Denver Colorado

A layer of smog hovers over Los Angeles

New York City

Ground-level Ozone Formation

The main pollutants that form ozone are oxides of nitrogen (NOx) and volatile organic compounds (VOC).

Ground level ozone, is not emitted directly into the air, but is created by chemical reactions between the "precursor" pollutants of nitrogen oxides (NOx) and volatile organic compounds (VOC) in the presence of sunlight.
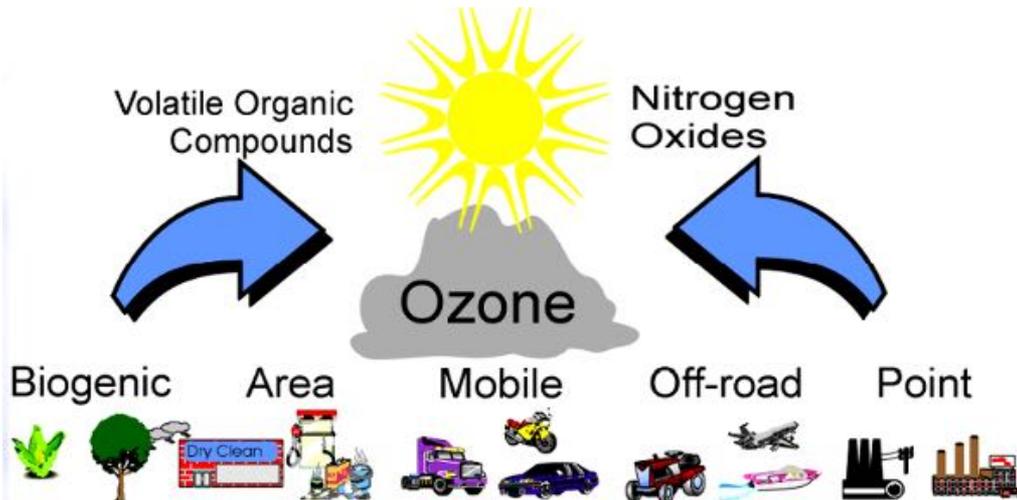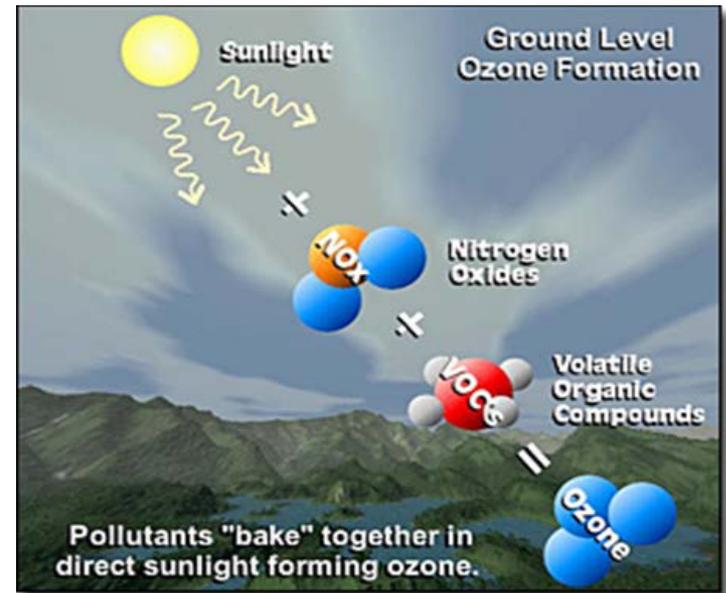
Ozone Pollution Health Effects

- Effects seen across a wide range of health outcomes
- Sensitive groups include:
  - Asthmatic children and other people with lung disease
  - All children and older adults, especially people active outdoors
  - Outdoor workers

https://www.epa.gov/ozone-pollution-and-your-patients-health/health-effects-ozone-patients-asthma-and-other-chronic

Seriousness of effect

Death

Emergency department visits, hospital admissions

Doctor visits, school absences

Respiratory symptoms, medication use, asthma attacks

Lung function decrements, inflammation and permeability, susceptibility to infection, cardiac effects

Number of people affected

NAAQS and Nonattainment

National Ambient Air Quality Standards (NAAQS)

- Standards for criteria pollutants
- Established by the U.S. Environmental Protection Agency (EPA)
- Nonattainment Area= Can be an area that violates/exceeds one of the NAAQS

Pollutant	Type	Standard	Averaging	Form
Ozone (O$_3$)	Primary and Secondary	0.070 ppm (70 ppb)	8-hour	Annual 4th high daily maximum 8-hr. avg., averaged over 3 yrs.*

*EPA's calculation methodology can be found at:
https://www.epa.gov/air-trends/air-quality-design-values

What is the Ozone Attainment Initiative (OAI)?

Monitoring data show several areas in the State approaching the level of the National Ambient Air Quality Standard (NAAQS) for Ozone

The OAI aims to:

☐ Protect the attainment/unclassifiable status of all areas in the state

☐ Ensure the health and welfare of the residents of the state for future generations

Why do we need the OAI?

74-2-5.3 NMSA 1978

- If the EIB finds that sources cause or contribute to ozone concentrations in excess of ninety-five percent of a national ambient air quality standard for ozone, then

- NMED shall adopt a plan to control oxides of nitrogen and volatile organic compounds.

Affected Monitoring Stations*
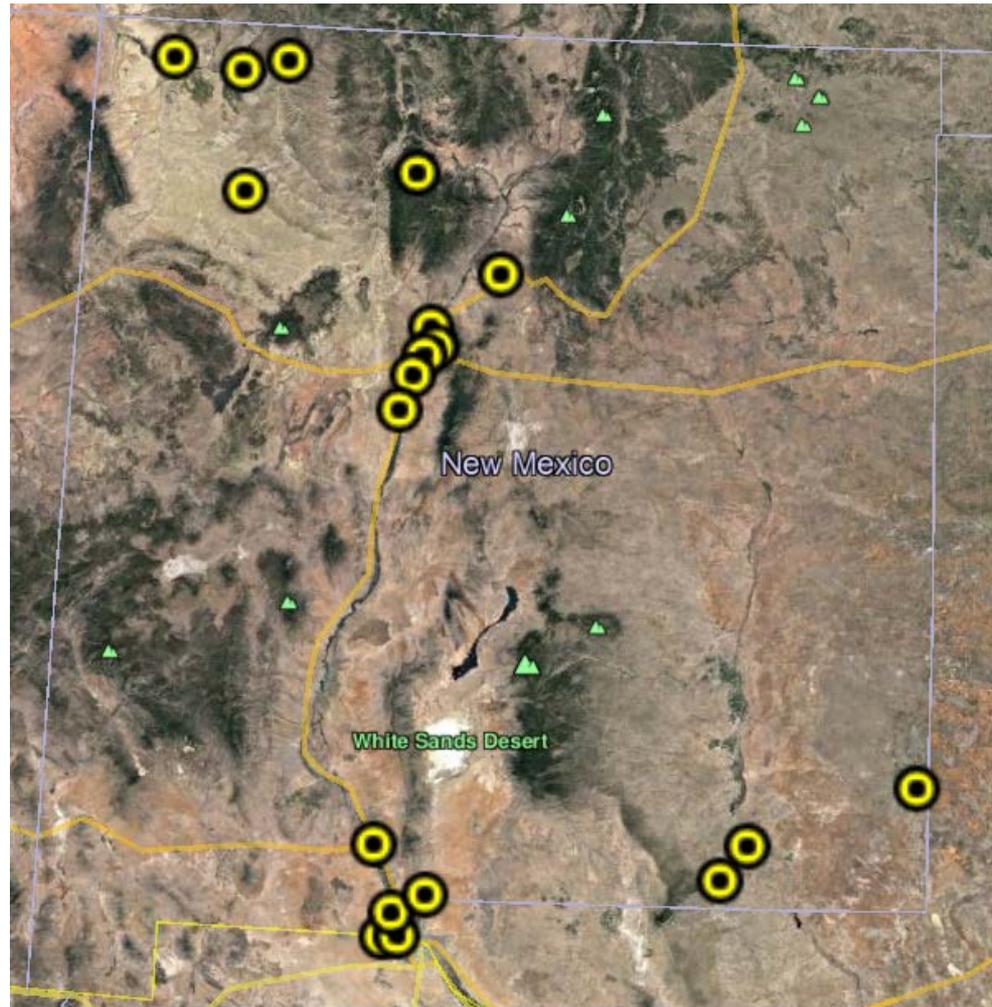
- Includes CABQ/EHD O_3 monitoring sites. Each monitoring station includes several air monitors that each monitor a different pollutant.

Focus Areas
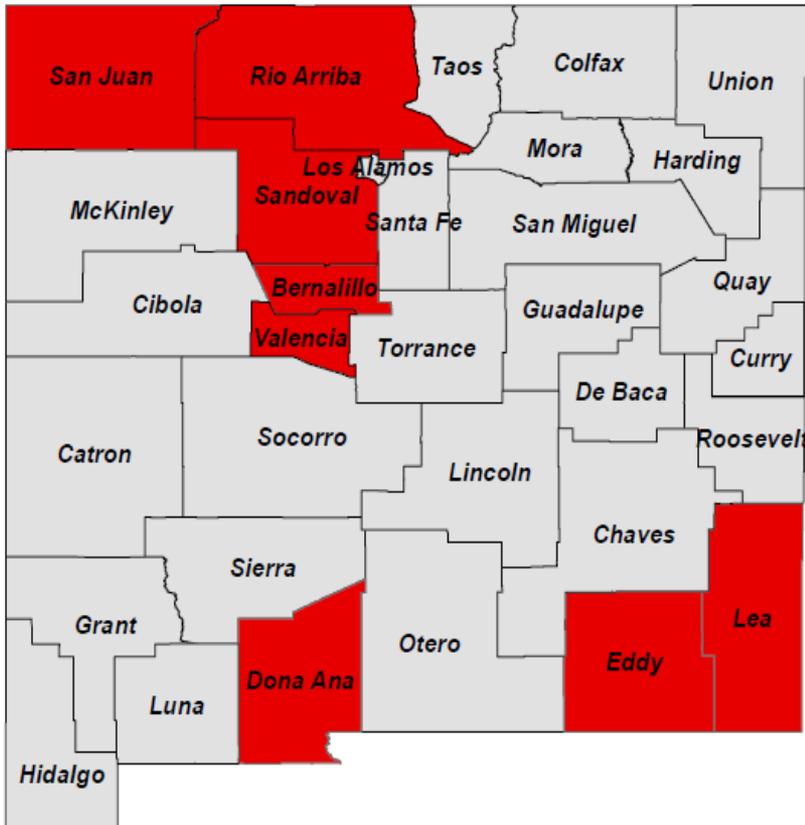
*Parallel planning is occurring for Bernalillo County through the Albuquerque/Bernalillo County Department of Environmental Health

☐ Counties within 95% of the standard:

- San Juan (Navajo Lake, 70 ppb)
- Doña Ana (several monitors, 74 ppb)
- Eddy (Carlsbad, 74 ppb)
- Lea (Hobbs, 70 ppb)
- Rio Arriba (Coyote, 67 ppb)
- Sandoval (Bernalillo, 68 ppb)
- Valencia (Los Lunas, 67 ppb)

NMED Ozone Monitoring Data by County
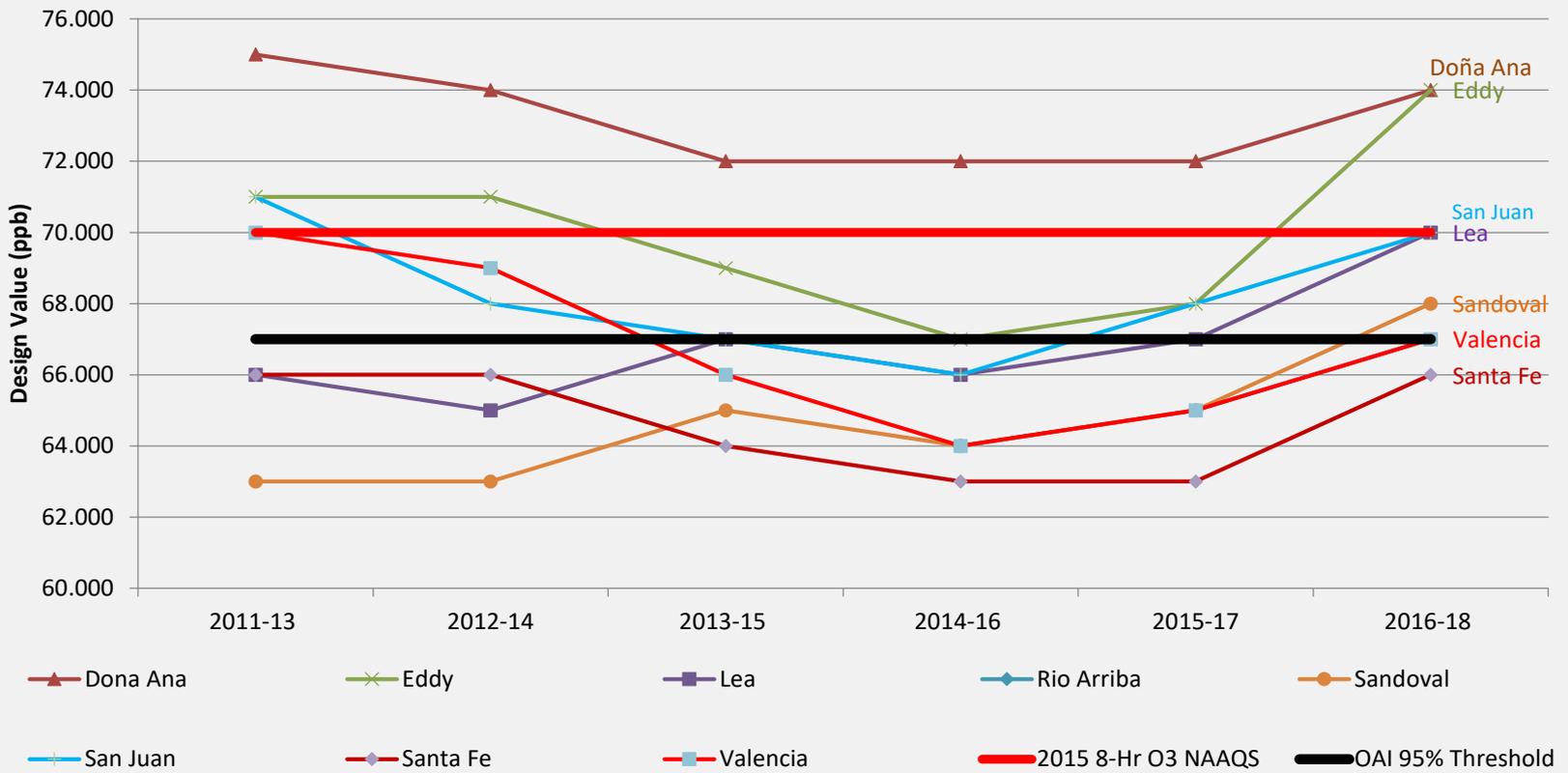
95% of the 70 ppb standard ≥ 67 ppb

How Will NMED Implement the OAI?

- **Data Gathering**
  - Emissions Inventories, Modeling and Continued Monitoring
    - O_3 and NOx Concentrations
    - Source sector contributions
    - Ozone formation and its transport
- **Mandatory and/or Voluntary Measures**
  - Normal NMED rulemaking process
  - EPA's Ozone Advance Program
- **Robust stakeholder involvement**
  - Stay informed through the OAI Listserv!

Ozone Advance

Helping States, Tribes, & Local Governments

Currently, 38 areas are actively participating in Advance. These areas are located in 21 states and 9 of the 10 EPA Regions. They include 21 Ozone Advance areas, 7 PM Advance areas, and 10 areas that are participating in both Ozone and PM Advance.

- Is a collaborative effort by EPA, states, tribes and local governments to encourage emission reductions to help them continue to meet the NAAQS
- Take near-term steps to improve local air quality and ensure continued health protection
- Flexibility, participant determine their own goals and the measures
- Actions taken could better position an area to handle nonattainment requirements.

https://www.epa.gov/advance

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Why are Early Efforts Important

- Local steps to reduce air pollution voluntarily, before becomes a requirement
- Improving air quality to ensure continued health protection
- Proactive efforts could better position areas to stay in attainment.
- Areas working voluntarily to reduce air pollution have more flexibility to choose measures that make sense to them
    - Once a nonattainment designation has occurred, less flexibility is available

Projected Timeline*

- **2018**
  - **Spring**
    - Kick off OAI planning meeting; and
    - Development of outreach and educational materials.
- **2019**
  - **Summer**
    - Initial public outreach including education and initial input request.
  - **Fall/Winter**
    - Conduct modeling;
    - Research and review mandatory or voluntary control measures; and
    - Additional public outreach.

- **2020**
  - **Winter/Spring**
    - Gather input; and
    - More public comment opportunities.
  - **Summer**
    - Analyze input;
    - Develop rules; and
    - Other measures for inclusion in programs.
  - **Fall/Winter**
    - OAI Plan drafted and released with formal comment period; and
    - EIB hearing to adopt proposed plan/rules.

*Note that NMED is in the initial stages of planning, which only includes the educational component and planning for public outreach. No rules/programs have yet been discussed.

Path Forward

☐ Modeling and Data Analyses

- ◘ Identify source categories causing elevated ozone
- ◘ Predict effectiveness of a proposed strategy or control measure

☐ Control and pollution reduction measures

- ◘ Once sources and types are identified, a list of potential air quality improvements and/or emission reduction options can be developed

How can stakeholders get involved?

☐ NMED is committed to a robust, transparent process where feedback and suggestions are encouraged.

☐ Provide input!

▫ Attend public meetings

▫ Share comments and suggestions

☐ Stay current

▫ OAI Listserv: public.govdelivery.com/accounts/NMED/subscriber/new

▫ OAI webpage: www.env.nm.gov/air-quality/o3-initiative/

▫ Air Monitoring Network: https://www.env.nm.gov/air-quality/air-monitoring-network-2/

19 | # Questions or comments?

Thank you. We look forward to working with our stakeholders.

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OAI Doña Ana County Contact
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WildEarth Guardians Exhibit 6

EPA Radiation Waste Material from Oil and Gas Drilling, https://www.epa.gov/radtown/radioactive-waste-material-oil-and-gas-drilling (last accessed July 10, 2020).

An official website of the United States government.

We've made some changes to EPA.gov. If the information you are
looking for is not here, you may be able to find it on the EPA Web
Archive or the January 19, 2017 Web Snapshot.

Close

EPA United States
Environmental Protection
Agency

Radioactive Waste Material From Oil and Gas Drilling

Radiation Facts

- Naturally radioactive materials that are brought to the surface and
  concentrated by industrial processes are called Technologically
  Enhanced Naturally-Occurring Radioactive Material (TENORM).
- Wastes generated from oil and gas drilling must be properly
  managed to keep radionuclides in these wastes from spreading to
  surrounding areas.

Rocks in and around certain oil- and gas-bearing formations may contain natural
radioactivity. Drilling through these rocks or bringing them to the surface can
generate waste materials that contain radioactivity.

- Once oil and gas have been extracted from the formation, workers and
  members of the public may be exposed to radionuclides that are brought to
  the surface.
- Because materials have been relocated to the surface and/or are
  concentrated because of industrial processes, they are called
  Technologically Enhanced Naturally-Occurring Radioactive Material
  (TENORM).

On this page:

- About Radioactive Waste Material From Oil and Gas Drilling
- What you can do
- Where to learn more

About Radioactive Waste Material From Oil and Gas Drilling

A modern day drilling rig used for unconventional drilling. Source: U.S. Environmental Protection Agency (EPA)

Radionuclides are found naturally in almost all soils, rocks, surface water and groundwater. Bringing natural resources from below the surface to above the ground also brings up materials that naturally contain radionuclides. These naturally radioactive materials are called TENORM. Radionuclides commonly found in TENORM are radium, radon, uranium, potassium and thorium. The level of radioactivity in TENORM can vary widely.

TENORM can be found in solids, liquids, sludges and/or gases. It's possible for TENORM to come from different parts of the oil and gas extraction processes. Here are a few examples:

- **Drill cuttings:** When drilling for oil and gas, rock is ground into small pieces using a sharp bit. These pieces of rock, called drill cuttings, can contain radioactive elements that are found inside the rock.
- **Flowback and produced water:** These terms describe the water that comes back to the surface during and after drilling. Flowback water is the solution that returns to the surface after injecting materials into the well for fracking. Industrial water, sand and chemicals mix with water in the formation to create flowback water. Produced water is the salty liquid that is brought to the surface with oil and gas after the well is developed and put into production.
- **Pipe scale:** When water is pumped in and out of well and storage tanks, a coating called pipe scale builds up around the inside of the pipe. Pipe scale is made up of the natural minerals found in water, which sometimes include radionuclides. Radioactivity in pipe scale can be quite high.

- **Sludges, sediments, and filters:** Sludge is an oily, loose material from produced water that often ends up in water storage tanks. Sediments are the more solid material, often present in water storage tanks. Filters can contain TENORM that is captured as liquid and gas passes through.

Wastes generated from oil and gas drilling must be properly managed to keep the radionuclides in these wastes from spreading to surrounding areas. One factor that affects the movement of radionuclides in the environment is how well they dissolve in water (solubility). For example, radium is more soluble than thorium. Therefore, under certain conditions, radium can spread more easily through the groundwater.

Employees who work at drilling sites are the most likely group to be exposed to TENORM from oil and gas drilling and production. Some states have worker safety programs in place to ensure workplace safety. To learn more about oil and gas drilling sites in your area, contact your state geological survey or health department.

What You Can Do

- **Obey safety instructions.** It's important to follow any posted safety instructions near oil and gas drilling or production-sites.
- **Never handle, dispose of or re-use abandoned equipment used at these sites.** Do not go near abandoned oil and gas drilling sites.

Where to Learn More

The U.S. Environmental Protection Agency (EPA)

While there is not a single, comprehensive, federal TENORM regulation, The EPA has developed standards for natural resource extraction through several laws. Laws include:

- Clean Air Act
- Clean Water Act
- Safe Drinking Water Act
- Resource Conservation and Recovery Act (RCRA)
- Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA)

Technologically Enhanced Naturally-Occurring Radioactive Materials (TENORM)
This webpage discusses processes and industries that may generate TENORM.

TENORM: Oil and Gas Production Wastes
This webpage provides detailed information about TENORM in oil and gas production wastes.

The U.S. Department of Labor (DOL), Occupational Safety and Health Administration (OSHA)

OSHA provides tools and resources related to worker safety at oil and gas drilling and production-sites.

Oil and Gas Well Drilling and Servicing eTool
This tool can be used as a resource to identify possible workplace hazards and solutions in the oil and gas welling industry.

Health Hazard Information Bulletin: Potential Health Hazards Associated with Handling Pipe used in Oil and Gas Production
This 1989 report discusses potential health hazards associated with materials used in oil and gas production.

The U.S. Department of the Interior (DOI), the U.S. Geological Survey (USGS)

The USGS generates reports and information related to oil and gas deposits and geological data.

Naturally-occurring Radioactive Materials (NORM) in Produced Water and Oil-Field Equipment— An Issue for the Energy Industry (PDF)
 (4 pp, 2.6 Mb, About PDF)
This 1999 fact sheet provides information about naturally-occurring radioactive materials in produced water and equipment.

The Conference of Radiation Control Program Directors (CRCPD)

The CRCPD is a nonprofit non-governmental professional organization dedicated to radiation protection.

State Radiation Protection Programs   EXIT
This webpage provides links and contact information for each state's Radiation Control Program office.

E-42 Task Force Report Review of TENORM In the Oil & Gas Industry (PDF) (131 pp, 1,080 K, About PDF)   EXIT
This report, generated by the Conference of Radiation Control Program Director's E-42 task force, examines and reviews TENORM radiological, environmental, regulatory, and health and safety issues.

LAST UPDATED ON MARCH 1, 2019

WildEarth Guardians Exhibit 7

J. Nobel, America's Radioactive Secret, Rolling Stone (Jan. 21, 2020), available at: https://www.rollingstone.com/politics/politics-features/oil-gas-fracking-radioactive-investigation-937389/.

America's Radioactive Secret

Justin Nobel

54-69 minutes

January 21, 2020 7:00AM ET

Oil-and-gas wells produce nearly a trillion gallons of toxic waste a year. An investigation shows how it could be making workers sick and contaminating communities across America

Brine trucks at an Injection well in Cambridge, OH.

George Etheredge for Rolling Stone

Justin Nobel is writing a book about oil-and-gas radioactivity for Simon & Schuster. This story was supported by the journalism nonprofit Economic Hardship Reporting Project

In 2014, a muscular, middle-aged Ohio man named Peter took a job trucking waste for the oil-and-gas industry. The hours were long — he was out the door by 3 a.m. every morning and not home until well after dark — but the steady $16-an-hour pay was appealing, says Peter, who asked to use a pseudonym. "This is a poverty area," he says of his home in the state's rural

southeast corner. "Throw a little money at us and by God we'll jump and take it."

In a squat rig fitted with a 5,000-gallon tank, Peter crisscrosses the expanse of farms and woods near the Ohio/West Virginia/Pennsylvania border, the heart of a region that produces close to one-third of America's natural gas. He hauls a salty substance called "brine," a naturally occurring waste product that gushes out of America's oil-and-gas wells to the tune of nearly 1 trillion gallons a year, enough to flood Manhattan, almost shin-high, every single day. At most wells, far more brine is produced than oil or gas, as much as 10 times more. It collects in tanks, and like an oil-and-gas garbage man, Peter picks it up and hauls it off to treatment plants or injection wells, where it's disposed of by being shot back into the earth.

One day in 2017, Peter pulled up to an injection well in Cambridge, Ohio. A worker walked around his truck with a hand-held radiation detector, he says, and told him he was carrying one of the "hottest loads" he'd ever seen. It was the first time Peter had heard any mention of the brine being radioactive.

The Earth's crust is in fact peppered with radioactive elements that concentrate deep underground in oil-and-gas-bearing layers. This radioactivity is often pulled to the surface when oil and gas is extracted — carried largely in the brine.

In the popular imagination, radioactivity conjures images of nuclear meltdowns, but radiation is emitted from many common natural substances, usually presenting a fairly minor risk. Many industry representatives like to say the radioactivity in brine is so

insignificant as to be on par with what would be found in a banana or a granite countertop, so when Peter demanded his supervisor tell him what he was being exposed to, his concerns were brushed off; the liquid in his truck was no more radioactive than "any room of your home," he was told. But Peter wasn't so sure.

"A lot of guys are coming up with cancer, or sores and skin lesions that take months to heal," he says. Peter experiences regular headaches and nausea, numbness in his fingertips and face, and "joint pain like fire."

He says he wasn't given any safety instructions on radioactivity, and while he is required to wear steel-toe boots, safety glasses, a hard hat, and clothes with a flash-resistant coating, he isn't required to wear a respirator or a dosimeter to measure his radioactivity exposure — and the rest of the uniform hardly offers protection from brine. "It's all over your hands, and inside your boots, and on the cuticles of your toes, and any cuts you have — you're soaked," he says.

So Peter started quietly taking samples of the brine he hauled, filling up old antifreeze containers or soda bottles. Eventually, he packed a shed in his backyard with more than 40 samples. He worried about further contamination but says, for him, "the damage is already done." He wanted answers. "I cover my ass," he says. "Ten or 15 years down the road, if I get sick, I want to be able to prove this."

Through a grassroots network of Ohio activists, Peter was able to transfer 11 samples of brine to the Center for Environmental

Research and Education at Duquesne University, which had them tested in a lab at the University of Pittsburgh. The results were striking.

Radium, typically the most abundant radionuclide in brine, is often measured in picocuries per liter of substance and is so dangerous it's subject to tight restrictions even at hazardous-waste sites. The most common isotopes are radium-226 and radium-228, and the Nuclear Regulatory Commission requires industrial discharges to remain below 60 for each. Four of Peter's samples registered combined radium levels above 3,500, and one was more than 8,500.

"It's ridiculous that these drivers are not being told what's in their trucks," says John Stolz, Duquesne's environmental-center director. "And this stuff is on every corner — it is in neighborhoods. Truckers don't know they're being exposed to radioactive waste, nor are they being provided with protective clothing.

"Breathing in this stuff and ingesting it are the worst types of exposure," Stolz continues. "You are irradiating your tissues from the inside out." The radioactive particles fired off by radium can be blocked by the skin, but radium readily attaches to dust, making it easy to accidentally inhale or ingest. Once inside the body, its insidious effects accumulate with each exposure. It is known as a "bone seeker" because it can be incorporated into the skeleton and cause bone cancers called sarcomas. It also decays into a series of other radioactive elements, called "daughters." The first one for radium-226 is radon, a radioactive gas and the second-leading cause of lung cancer in the U.S.

Radon has also been linked to chronic lymphocytic leukemia. "Every exposure results in an increased risk," says Ian Fairlie, a British radiation biologist. "Think of it like these guys have been given negative lottery tickets, and somewhere down the line their number will come up and they will die."

Peter's samples are just a drop in the bucket. Oil fields across the country — from the Bakken in North Dakota to the Permian in Texas — have been found to produce brine that is highly radioactive. "All oil-field workers," says Fairlie, "are radiation workers." But they don't necessarily know it.

Tanks, filters, pumps, pipes, hoses, and trucks that brine touches can all become contaminated, with the radium building up into hardened "scale," concentrating to as high as 400,000 picocuries per gram. With fracking — which involves sending pressurized fluid deep underground to break up layers of shale — there is dirt and shattered rock, called drill cuttings, that can also be radioactive. But brine can be radioactive whether it comes from a fracked or conventional well; the levels vary depending on the geological formation, not drilling method. Colorado and Wyoming seem to have lower radioactive signatures, while the Marcellus shale, underlying Ohio, Pennsylvania, West Virginia, and New York, has tested the highest. Radium in its brine can average around 9,300 picocuries per liter, but has been recorded as high as 28,500. "If I had a beaker of that on my desk and accidentally dropped it on the floor, they would shut the place down," says Yuri Gorby, a microbiologist who spent 15 years studying radioactivity with the Department of Energy. "And if I dumped it down the sink, I could

go to jail."

Brine storage tanks at an injection well near Belpre, Ohio. The state is home to 225 injection wells. Felicia Mettler, a resident of Torch, Ohio, started a volunteer group that monitors brine trucks. One injection well sees more than 100 trucks a day, she says. Photograph by George Etheredge for Rolling Stone

George Etheredge for Rolling Stone

The advent of the fracking boom in the early 2000s expanded the danger, saddling the industry with an even larger tidal wave of waste to dispose of, and creating new exposure risks as drilling moved into people's backyards. "In the old days, wells weren't really close to population centers. Now, there is no separation," says City University of New York public-health

expert Elizabeth Geltman. In the eastern U.S. "we are seeing astronomically more wells going up," she says, "and we can drill closer to populations because regulations allow it." As of 2016, fracking accounted for more than two-thirds of all new U.S. wells, according to the Energy Information Administration. There are about 1 million active oil-and-gas wells, across 33 states, with some of the biggest growth happening in the most radioactive formation — the Marcellus. And some regulations have only gotten weaker. "Legislators have laid out a careful set of exemptions that allow this industry to exist," says Teresa Mills of the Buckeye Environmental Network, an Ohio community-organizing group. "There is no protection for citizens at all — nothing."

In an investigation involving hundreds of interviews with scientists, environmentalists, regulators, and workers, *Rolling Stone* found a sweeping arc of contamination — oil-and-gas waste spilled, spread, and dumped across America, posing under-studied risks to the environment, the public, and especially the industry's own employees. There is little public awareness of this enormous waste stream, the disposal of which could present dangers at every step — from being transported along America's highways in unmarked trucks; handled by workers who are often misinformed and underprotected; leaked into waterways; and stored in dumps that are not equipped to contain the toxicity. Brine has even been used in commercial products sold at hardware stores and is spread on local roads as a de-icer.

"Essentially what you are doing is taking an underground

radioactive reservoir and bringing it to the surface where it can interact with people and the environment," says Marco Kaltofen, a nuclear-forensics scientist at Worcester Polytechnic Institute. "Us bringing this stuff to the surface is like letting out the devil," says Fairlie. "It is just madness."

The extent of any health impacts are unknown, mostly because there hasn't been enough testing. Many doctors just aren't aware of the risks. For a time, in Pennsylvania, doctors were even banned from discussing some toxic fracking exposures with patients — the controversial "medical gag rule" was struck down by the state's Supreme Court in 2016. Also, cancer from radiation often emerges years after exposure, making it hard to pinpoint a cause. "It's very difficult," says Geltman, "to say the exposure is from the oil industry and not other things — 'You smoke too much, drink too much' — and the oil-and-gas industry is a master of saying, 'You did this to yourself.'"

But a set of recent legal cases argues a direct connection to occupational exposure can be made. Expert testimony in lawsuits by dozens of Louisiana oil-and-gas industry workers going back decades and settled in 2016 show that pipe cleaners, welders, roughnecks, roustabouts, derrickmen, and truck drivers hauling dirty pipes and sludge all were exposed to radioactivity without their knowledge and suffered a litany of lethal cancers. An analysis program developed by the Centers for Disease Control and Prevention determined with up to 99 percent certainty that the cancers came from exposure to radioactivity on the job, including inhaling dust and radioactivity accumulated on the workplace floor, known as "groundshine."

Their own clothes, and even licking their lips or eating lunch, added exposure. Marvin Resnikoff, a nuclear physicist and radioactive-waste specialist who served as an expert witness, says that in every case the workers won or the industry settled. "I can tell you this industry has tremendous resources and hired the best people they could, and they were not successful," he says. "Once you have the information, it is indisputable."

Radioactivity was first discovered in crude oil, from a well in Ontario, as early as 1904, and radioactivity in brine was reported as early as the 1930s. By the 1960s, U.S. government geologists had found uranium in oil-bearing layers in Michigan, Tennessee, Oklahoma, and Texas. In the early 1970s, Exxon learned radioactivity was building up in pumps and compressors at most of its gas plants. "Almost all materials of interest and use to the petroleum industry contain measurable quantities of radionuclides," states a never-publicly released 1982 report by the American Petroleum Institute, the industry's principal trade group, passed to *Rolling Stone* by a former state regulator.

Rolling Stone discovered a handful of other industry reports and articles that raised concerns about liability for workers' health. A 1950 document from Shell Oil warned of a potential connection between radioactive substances and cancer of the "bone and bone marrow." In a 1991 paper, scientists with Chevron said, "Issues such as risk to workers or the general public…must be addressed."

"They've known about this since the development of the gamma-ray log back in the 1930s," says Stuart Smith, referencing a method of measuring gamma radiation. A New

Orleans-based lawyer, Smith has been trying cases pertaining to oil-and-gas radioactivity for 30 years and is the author of the 2015 book *Crude Justice.* In Smith's first case, in 1986, a six-month-pregnant Mississippi woman was sitting on the edge of her bathtub and her hip cracked in half. Tests showed the soil in her vegetable garden had become contaminated with radium from oil-field pipes her husband had cleaned in their yard. "They know," Smith says. "All of the big majors have done tests to determine exactly what risks workers are exposed to."

"Protecting workers, individuals, and the community who are near oil and natural-gas operations is of paramount importance to the industry," says Cornelia Horner, a spokeswoman with the American Petroleum Institute. But the organization did not reply to specific questions about workers' exposure to radioactivity. ExxonMobil and Chevron recommended *Rolling Stone* direct its questions to the American Petroleum Institute.

Curtis Smith, a spokesman with Shell, says, "This subject is the focus of litigation that at least one Shell expert recently testified to as part of a formal deposition.…Our top priorities remain the safety of our employees and the environment. While the risk of exposure to radioactive elements in some phases of our operations is low, Shell has strict, well-developed safety procedures in place to monitor for radioactivity as well as a comprehensive list of safety protocols should radioactivity be detected."

Oil-and-gas waste pits like this one in Lycoming County, Pennsylvania, vent radioactive radon gas, the second-leading cause of lung cancer in the U.S. Two recent studies show elevated levels of radon in homes near fracking operations. Photo credit: Joshua B. Pribanic/"Public Herald"

Joshua B. Pribanic/"Public Herald"

But the radioactivity in oil-and-gas waste receives little federal oversight. "They swept this up and forgot about it on the federal side," says Smith, the attorney. When asked about rules guarding oil-and-gas workers from contamination, the Department of Labor's Occupational Safety and Health Administration pointed to a set of sparse letters and guidance documents, some more than 30 years old. OSHA conducted "measurements of external radiation doses to workers in the oil-and-gas industry," a representative says. "The agency's experience is that radiation doses" are "well below the dose limits" that would require the agency's regulation.

"The Nuclear Regulatory Commission does not have statutory authority to regulate naturally occurring radioactive material," says NRC spokesman David McIntyre. The agency has

authority over "materials stemming from the nuclear fuel cycle," he says, adding, "My understanding is that the Environmental Protection Agency is the federal regulator for…oil-and-gas wastes."

"There is no one federal agency that specifically regulates the radioactivity brought to the surface by oil-and-gas development," an EPA representative says. In fact, thanks to a single ecemption the industry received from the EPA in 1980, the streams of waste generated at oil-and-gas wells — all of which could be radioactive and hazardous to humans — are not required to be handled as hazardous waste.

In 1988, the EPA assessed the exemption — called the Bentsen and Bevill amendments, part of the Resource Conservation and Recovery Act — and claimed that "potential risk to human health and the environment were small," even though the agency found concerning levels of lead, arsenic, barium, and uranium, and admitted that it did not assess many of the major potential risks. Instead, the report focused on the financial and regulatory burdens, determining that formally labeling the "billions of barrels of waste" as hazardous would "cause a severe economic impact on the industry." Effectively, the EPA determined that in order for oil-and-gas to flourish, its hazardous waste should not be defined as hazardous.

So responsibility has been largely left to the states — a patchwork of laws that are outdated, inconsistent, and easy for the industry to avoid. Of 21 significant oil-and-gas-producing states, only five have provisions addressing workers, and just three include protections for the public, according to research by

Geltman, the public-health expert. Much of the legislation that does exist seems hardly sufficient. For example, in Texas, the nation's largest oil-and-gas producer, Department of State Health Services spokeswoman Lara Anton says the agency "does not monitor oil-field workers for radiation doses," nor are workers, including brine haulers, required to wear protective equipment like Tyvek suits or respirators.

The first state to enact any protections at all was Louisiana, in the late 1980s. "It was the only environmental issue in Louisiana anyone ever sprang on me I didn't know anything about," says chemical physicist Paul Templet, who as the state's lead environmental regulator at the time ordered a study on oil-and-gas radioactivity. The results horrified him.

Brine-spreading is used to suppress dust on dirt roads, but "there appears to be a complete lack of data indicating the practice is effective," a 2018 study found.

Courtesy of Babst Calland

The levels of radium in Louisiana oil pipes had registered as much as 20,000 times the limits set by the EPA for topsoil at uranium-mill waste sites. Templet found that workers who were cleaning oil-field piping were being coated in radioactive dust and breathing it in. One man they tested had radioactivity all over his clothes, his car, his front steps, and even on his newborn baby. The industry was also spewing waste into coastal waterways, and radioactivity was shown to accumulate in oysters. Pipes still laden with radioactivity were donated by the industry and reused to build community playgrounds. Templet sent inspectors with Geiger counters across southern Louisiana. One witnessed a kid sitting on a fence made from piping so radioactive they were set to receive a full year's radiation dose in an hour. "People thought getting these pipes for free from the oil industry was such a great deal," says Templet, "but essentially the oil companies were just getting rid of their waste."

Templet introduced regulations protecting waterways and setting stricter standards for worker safety. The news reverberated across the industry, and *The New York Times* ran a front-page story in 1990 headlined "Radiation Danger Found in Oil Fields Across the Nation". Another *Times* story that year reported that the radiation measured in oil-and-gas equipment "exposes people to levels that are equal to and at times greater than

workers receive in nuclear power plants," and that pending lawsuits "may ultimately decide whether oil companies can be held responsible for billions of dollars in expenses associated with cleaning up and disposing radioactive wastes at thousands of oil-and-gas sites around the nation."

But the issue soon faded from the news. Discussion around it has remained mostly in the confines of arcane reports by regulators. Even in academia, it is an obscure topic. "There's no course that teaches this," says Julie Weatherington-Rice, an Ohio scientist with the environmental-consulting firm Bennett & Williams who has tracked oil-and-gas waste for 40 years. "You literally have to apprentice yourself to the people who do the work." The lack of research and specialization has made it hard to reach a consensus on the risks and has facilitated the spread of misinformation. There is a perception that because the radioactivity is naturally occurring it's less harmful (the industry and regulators almost exclusively call oil-and-gas waste NORM — naturally occurring radioactive material, or TENORM for the "technologically enhanced" concentrations of radioactivity that accumulate in equipment like pipes and trucks). But the radioactivity experts *Rolling Stone* spoke to dismiss the "naturally occurring" excuse. "It makes no sense," says Kaltofen, the nuclear-forensics scientist. "Arsenic is completely natural, but you probably wouldn't let me put arsenic in your school lunch."

As for the "banana red herring," as Kaltofen calls it — the idea that there's no more radioactivity in oil-and-gas waste than in a banana — "I call bullshit," he says. They emit two different types

of radiation. The potassium-40 in bananas predominantly emits beta particles that barely interact with your body; radium emits alpha particles, which are thousands of times more impactful and can swiftly mutate cells. He compares them this way: "If I pick up a .45-caliber bullet and throw it at you, or if I put the same bullet in a .45-caliber pistol and fire it at you, only one of these things will cause you serious harm."

An oft-cited 2015 study on TENORM by Pennsylvania's Department of Environmental Protection determined there are "potential radiological environmental impacts," but concluded there was "limited potential for radiation exposure to workers and the public." But Resnikoff, the nuclear physicist, wrote a scathing critique of the report, saying it downplayed the radioactive gas radon, misinterpreted information on radium, and ignored the well-documented risks posed by the inhalation or ingestion of radioactive dust.

And this past summer, Bemnet Alemayehu, a radiation health physicist with the Natural Resources Defense Council, toured oil fields in Ohio, West Virginia, and Pennsylvania with *Rolling Stone*, taking samples, including some of Peter's brine. Alemayehu's report is due out later this year, but he says, "The data I am seeing is that some oil-and-gas workers" — including maintenance workers and haulers like Peter — "should be treated as radiation workers."

Brine haulers are a ghost fleet. No federal or state agency appears to know how many drivers like Peter are out there, how long they've been working, how much radioactivity their bodies have accumulated, or where this itinerant workforce might be

living.

But the Department of Transportation does have jurisdiction over the roads, and there are rules on hazardous materials. Trucks with loads that contain more than the DOT radioactivity limit could be required to be placarded with a radioactivity symbol, meet strict requirements for the container carrying the radioactive substance, and uphold hazmat-training requirements for the drivers. The standard brine truck cited in Pennsylvania's 2016 TENORM Report would be 980 times the DOT's limit when it comes to the total accumulated amount of radium-226 in the truck, known as the consignment limit. But the truck's average radium concentration must also exceed a certain level for regulations to kick in, and according to a Texas-based TENORM expert, many Pennsylvania brine trucks might meet or just exceed that level because of the concentrated scale that can build up in a truck, but the DOT wouldn't necessarily know. Testing, says a DOT spokesperson, is the responsibility of the operator at the wellhead who dispatches the brine to the hauler, and the DOT is not required to verify or confirm the analysis at all.

An overturned brine truck near Coolville, OH in 2017. Photo courtesy of Felicia Mettler

Ted Auch, an analyst with the watchdog group FracTracker Alliance, estimates there are at least 12,000 brine trucks operating in Ohio, Pennsylvania, and West Virginia. He says he has never seen one with a radioactivity placard. "There are all sorts of examples for how often these things crash," says Auch. In 2016, a brine truck overturned on a bad curve in Barnesville, Ohio, dumping 5,000 gallons of waste. The brine water flowed across a livestock field, entering a stream and then a city reservoir, forcing the town to temporarily shut it down. (The EPA safe drinking-water limit for radium is 5 picocuries per liter). In a 2014 crash in Lawrence Township, Ohio, a brine truck traveling south on Bear Run Road flipped over a guardrail and rolled down a steep bank, striking a home.

In the tiny town of Torch, Ohio, elementary school archery instructor Felicia Mettler co-founded Torch CAN DO, a volunteer group that monitors for spills and crashes of brine trucks. One injection well they track in the area sees more than 100 brine trucks a day, about one every 14 minutes. "This is why it's so important we document everything," she says. "I don't think we're gonna stop it today, I don't think we're gonna stop it five years from now, but someday it's gonna help."

Even without crashing, the trucks are a potential hazard. Haulers often congregate at local restaurants and truck stops where half a dozen or more brine trucks may be lined up in the parking lot, says Randy Moyer, a former brine hauler in Pennsylvania who says he quit the job when burning rashes and

odd swelling broke out across his body after only four months. "I warn waitresses who serve guys getting out of these waste trucks," says Gorby, the former DOE engineer — a driver sloshed with brine could be shedding dust particles with radium. "The consensus of the international scientific community is that there is no safe threshold for radiation," says Resnikoff. "Each additional exposure, no matter how small, increases a person's risk of cancer."

In Pennsylvania, regulators revealed in 2012 that for at least six years one hauling company had been dumping brine into abandoned mine shafts. In 2014, Benedict Lupo, owner of a Youngstown, Ohio, company that hauled fracking waste, was sentenced to 28 months in prison for directing his employees to dump tens of thousands of gallons of brine into a storm drain that emptied into a creek that feeds into the Mahoning River. While large bodies of water like lakes and rivers can dilute radium, Penn State researchers have shown that in streams and creeks, radium can build up in sediment to levels that are hundreds of times more radioactive than the limit for topsoil at Superfund sites. Texas-based researcher Zac Hildenbrand has shown that brine also contains volatile organics such as the carcinogen benzene, heavy metals, and toxic levels of salt, while fracked brine contains a host of additional hazardous chemicals. "It is one of the most complex mixtures on the planet," he says.

Officials found the creek in the Lupo incident to be "void of life" after the contamination, prosecutors said. But downstream, no one notified water authorities or tested water supplies for

possible radioactivity, says Silverio Caggiano, a near 40-year veteran of the Youngstown fire department and a hazardous-materials specialist with the Ohio Hazmat Weapons of Mass Destruction Advisory Committee. "If we caught some ISIS terrorist cells dumping this into our waterways, they would be tried for terrorism and the use of a WMD on U.S. citizens," says Caggiano. "However, the frac industry is given a pass on all of this."

In Ohio, laws that enabled local communities to enforce zoning of oil-and-gas activities were systematically stripped during the 2000s and 2010s. Language snuck into one 2001 Ohio budget bill exempted the oil-and-gas industry from having to disclose safety information to fire departments and first responders. "A truck carrying brine for injection is the worst of the worst," says Caggiano. "And it is going through your freeways, through your neighborhoods, through your streets, past your homes, past your schools, and the drivers are not trained in how to handle hazardous waste and don't have to have a single piece of paper telling a fire chief like me what the hell they are carrying — it scares the fuck out of me."

Siri Lawson became ill after brine was spread on the road near her home in rural Pennsylvania. Photograph by George Etheredge for Rolling Stone

George Etheredge for Rolling Stone

In the summer of 2017, Siri Lawson noticed a group of Amish girls walking down the side of a dirt road near the horse farm where she lives with her husband in Farmington Township, Pennsylvania. The girls, dressed in aprons and blue bonnets, had taken off their shoes and were walking barefoot. Lawson was horrified. She knew the road had been freshly laced with brine.

Radioactive oil-and-gas waste is purposely spread on roadways around the country. The industry pawns off brine — offering it for free — on rural townships that use the salty solution as a winter

de-icer and, in the summertime, as a dust tamper on unpaved roads.

Brine-spreading is legal in 13 states, including the Dakotas, Colorado, much of the Upper Midwest, northern Appalachia, and New York. In 2016 alone, 11 million gallons of oil-field brine were spread on roads in Pennsylvania, and 96 percent was spread in townships in the state's remote northwestern corner, where Lawson lives. Much of the brine is spread for dust control in summer, when contractors pick up the waste directly at the wellhead, says Lawson, then head to Farmington to douse roads. On a single day in August 2017, 15,300 gallons of brine were reportedly spread.

"After Lindell Road got brined, I had a violent response," reads Lawson's comments in a 2017 lawsuit she brought against the state. "For nearly 10 days, especially when I got near the road, I reacted with excruciating eye, nose, and lung burning. My tongue swelled to the point my teeth left indentations. My sinus reacted with a profound overgrowth of polyps, actually preventing nose breathing."

The oil-and-gas industry has "found a legal way to dispose of waste," says Lawson, 65, who worked as a horse trainer but is no longer able to ride professionally because of her illnesses. Sitting in her dining room, surrounded by pictures she has taken to document the contamination — brine running down the side of a road, an Amish woman lifting her dress to avoid being sprayed — she tells me the brine is spread regularly on roads that abut cornfields, cow pastures, and trees tapped for maple syrup sold at a local farmer's market.

"There is nothing to remediate it with," says Avner Vengosh, a Duke University geochemist. "The high radioactivity in the soil at some of these sites will stay forever." Radium-226 has a half-life of 1,600 years. The level of uptake into agricultural crops grown in contaminated soil is unknown because it hasn't been adequately studied.

"Not much research has been done on this," says Bill Burgos, an environmental engineer at Penn State who co-authored a bombshell 2018 paper in *Environmental Science & Technology* that examined the health effects of applying oil-field brine to roads. Regulators defend the practice by pointing out that only brine from conventional wells is spread on roads, as opposed to fracked wells. But conventional-well brine can be every bit as radioactive, and Burgos' paper found it contained not just radium, but cadmium, benzene, and arsenic, all known human carcinogens, along with lead, which can cause kidney and brain damage.

And because it attaches to dust, the radium "can be resuspended by car movement and be inhaled by the public," Resnikoff wrote in a 2015 report. Research also shows that using brine to suppress dust is not only dangerous but pointless. "There appears to be a complete lack of data indicating the practice is effective," reads a 2018 paper published in the *European Scientific Journal.* In fact, it notes, the practice is "likely counterproductive for dust control." As Lawson puts it, "It is a complete fucking myth that this works. After brine, the roads are dustier."

But the new buzzword in the oil-and-gas industry is "beneficial

use" — transforming oil-and-gas waste into commercial products, like pool salts and home de-icers. In June 2017, an official with the Ohio Department of Natural Resources entered a Lowe's Home Center in Akron and purchased a turquoise jug of a liquid de-icer called AquaSalina, which is made with brine from conventional wells. Used for home patios, sidewalks, and driveways — "Safe for Environment & Pets," the label touts — AquaSalina was found by a state lab to contain radium at levels as high as 2,491 picocuries per liter. Stolz, the Duquesne scientist, also had the product tested and found radium levels registered about 1,140 picocuries per liter.

"AquaSalina is 400-million-year-old ancient seawater from the Silurian Age" that "contains a perfect natural balance of chlorides uniquely suited for snow and ice management," Dave Mansbery, owner of Duck Creek Energy, the Ohio-based company that produces AquaSalina, tells *Rolling Stone*. "We recycle and repurpose this natural water to a higher purpose." He told regional news station WKRC that he soaked his sore feet in AquaSalina.

Mansbery said that he tested for heavy metals and saw "no red flags." Asked if he tested for radioactive elements, he stated, "We test as required by the state law and regulatory agencies."

"Every time you put this solution onto your front steps you are basically causing a small radioactive spill," says Vengosh, the geochemist, who has examined AquaSalina. "If you use it in the same place again and again, eventually you will have a buildup of radioactivity in the sediment and soil and create an ecological dead zone." But Ohio's Department of Health concluded

AquaSalina poses a "negligible radiological health and safety risk."

"Reading their study shows it's about equal to eating a banana a week," says Mansbery. "Sorry, AquaSalina does not fit the narrative sought by many haters of the oil-and-gas industry."

CPI Road Solutions, an Indianapolis-based snow- and ice-management company, sells hundreds of thousands of gallons of AquaSalina each winter to the Pennsylvania Turnpike Commission and Ohio Department of Transportation, says Jay Wallerstein, a company VP. Supporters tout that the product has been approved by Pacific Northwest Snowfighters, the nation's most-respected organization for evaluating de-icing products. But Snowfighters official Jay Wells says, "PNS has not tested AquaSalina for radioactive elements" and that "radium-226 is not a standard test for de-icing products."

Meanwhile, Ohio is pushing forward with legislation to *protect* the practice of brine-spreading. State Senate Bill 165 would slash environmental safeguards and make it easier for products like AquaSalina to be developed. In Pennsylvania, Lawson's case had led the state's DEP to acknowledge brine-spreading violated environmental laws, and the practice was halted last year. But Pennsylvania House Bill 1635 and Senate Bill 790 unsuccessfully tried to greenlight brine-spreading again, and even restrict the DEP's ability to test products. In October, the state Senate passed the bill without debate; its fate remains up in the air in the state's House of Representatives.

On a sunny day in September 2018, I meet with Kerri Bond

and her sister, Jodi, at an injection well next to a shopping plaza in Guernsey County, Ohio. As people dine on fast food and shop for the latest iPhone, trucks unload brine into giant tanks where it will wait to be shot back into the earth. The sisters, both nurses, had grown up wandering the region's woods and creeks. "We thought it was Shangri-la," says Kerri. In 2012, a leasing company held a meeting at a church in town, she recalls. "They told everyone they were going to be millionaires. People were high-fiving." Residents signed documents enabling the Denver-based energy company Antero Resources to begin fracking on their land. As with many people who live near fracking operations, which involve storing and mixing toxic chemicals plus a torrent of carcinogenic emissions when drilling begins, Kerri and Jodi quickly started to notice problems.

"A truck carrying brine for injection is the worst," says Ohio fire chief Silverio Caggiano. "Drivers don't have to have a single piece of paper telling me what they are carrying. It scares the f— out of me." Photograph by George Etheredge for Rolling Stone

George Etheredge for Rolling Stone

Animals on Kerri's farm dropped dead — two cats, six chickens, and a rooster. A sheep birthed babies with the heads fused together. Trees were dying. One evening Kerri was watching a show about Chernobyl's radioactive forests, and she felt like she recognized Ohio. She bought a hand-held radiation detector on Amazon and recorded radiation three to seven times the normal level for southeastern Ohio in her backyard, she says. In 2016, an Ohio Department of Health official visited and said not to worry as long as people weren't exposed to these levels on a regular basis, she recalls. "Hey, dude," Bond told him, "we are living here."

Ohio, because of its geology, favorable regulations, and nearness to drilling hot spots in the Marcellus, has become a preferred location for injection wells. Pennsylvania has about a

dozen wells; West Virginia has just over 50. Ohio has 225. About 95 percent of brine was disposed of through injection as of 2014. Government scientists have increasingly linked the practice to earthquakes, and the public has become more and more suspicious of the sites. Still, the relentless waste stream means new permits are issued all the time, and the industry is also hauling brine to treatment plants that attempt to remove the toxic and radioactive elements so the liquid can be used to frack new wells.

In Ohio, no public meetings precede the construction of these treatment facilities, many locals remain unaware they exist, and the Ohio Department of Health does not regularly monitor them. They are under the exclusive oversight of the Ohio Department of Natural Resources.

To store radioactive waste, or recycle, treat, process, or dispose of brine and drill cuttings, companies simply submit an application that is reviewed by the chief of the ODNR. They're called "Chief's Order" facilities, and Ohio has authorized 46 of them. Companies have to submit a radiation protection plan as part of the application, and ODNR spokesman Steve Irwin says all facilities are inspected regularly. But worker protections and knowledge of the risks still seem to be lacking.

In 2014, at a now-defunct Ohio company operating under Chief's Order, EnviroClean Services, inspectors discovered a staff clueless of basic radiation safety, operating without protective gear, with no records or documentation for the waste they were receiving, and no instrument to measure it except a pocket Geiger counter that appeared to have never been used.

One entry on the form documenting the inspection asks for an "Evaluation of individuals' understanding of radiation safety procedures." The inspector noted: "Unable to evaluate — no radiation safety procedures being used."

Last April, I met with an oil-and-gas waste-treatment-plant operator at a restaurant beside a dusty truck stop in the panhandle of West Virginia. Cody Salisbury left Las Vegas as a teenager and bartended his way across the country before ending up in the Texas oil fields, he says, chowing down barbecue wings as we talk in a quiet corner booth, his phone buzzing repeatedly. "It comes as a sludge, a nasty mess, and we separate the solids, the oil, and the water," says Salisbury, not divulging other treatment details but alluding to a secret sauce. He is upgrading a waste plant and has helped build two others in Ohio. The opening of one, just a few hundred feet from a nursing home, was attended by Ohio Sen. Rob Portman, who applauded the "regulatory relief" that made it possible.

Salisbury and all of the workers at his plants wear dosimeter badges, which measure external radiation exposure, and they've always registered low numbers, he says. Most oil-and-gas waste facilities in Ohio issue dosimeters to their workers, says an ODNR representative, and they haven't observed anyone that's exceeded the annual occupational-exposure limit. But dosimeters, says Kaltofen, the nuclear-forensics scientist, don't register alpha particles — the type of radiation emitted by radium — and aren't able to track what a person may have inhaled or ingested. So they aren't providing insight into the key exposures these workers are likely incurring.

"These guys are so proud of their jobs," says Weatherington-Rice, the Ohio-based scientist, "and they're working with this stuff and they go home and they've got this on their clothes — they can end up contaminating their family as well. This is how this stuff works."

I ask Salisbury if he and the workers have to wear radiation protective gear, and he shakes his head: "There's not enough radioactivity in it — I ain't never seen anyone wearing a respirator." When asked if he is concerned about radon, he says he has never heard anything about it. "There's more radioactivity coming off a cigarette, a banana, a granite countertop," he says.

Even at facilities touted to be the best of the best, there still could be risks. Peter, the Ohio brine hauler, tells me about the Clearwater plant in West Virginia, a $300 million fracking-waste treatment facility completed in 2018 and run by a partnership between Antero and the French water- and waste-management company Veolia. Kevin Ellis, an Antero vice president, described the facility as the "best project like this in the world. Bar none. Period."

The plant was abruptly "idled" in September after less than two years of operation because of a steep drop in gas prices. One day last year, before it closed, Peter and I drove out toward the hulking facility. As we approached, I saw thick plumes of whitish-gray steam rising out of a series of cooling towers. An engineering report the plant filed with the state showed emissions from treatment tanks were being vented to the atmosphere, after first being routed to a thermal oxidizer, a

piece of equipment that can destroy hazardous pollutants — but not radon, says Resnikoff.

Neither Veolia nor Antero replied to questions on whether they were testing the steam for radioactivity. When asked if the agency was monitoring for such things, West Virginia Department of Environmental Protection official Casey Korbini said, "The WVDEP permits are in accordance with federal and state air-quality statutes, and radionuclides are not a regulated pollutant under these statutes." He added, "This does not mean that radionuclides are prohibited; they are simply not regulated."

"Son of a bitch, he's loaded," says Jack Kruell on a rainy evening this past spring. Kruell, a 59-year-old contractor, is watching a dump truck headed toward Pennsylvania's Westmoreland Sanitary Landfill, just down the road from his home in Belle Vernon, about 25 miles from Pittsburgh. It's been accepting fracking waste since 2010.

The end of the line for much of the radioactive solid waste produced from extraction, like drill cuttings and the sludge filtered out of brine, is the local dump. Kruell used to keep a pair of Geiger counters on the spice rack in his kitchen to monitor the regularly above-normal levels.

There are facilities that treat drill cuttings and sludges, "downblending" them with less-radioactive waste to obtain a brew with a radiation content low enough to be accepted at regional landfills. Otherwise, they have to be sent to a low-level radioactivity waste site out in Utah, says Troy Mazur, a radiation safety officer I speak to from Austin Master Services, a

downblending facility in Martin's Ferry, Ohio. "I would not like to divulge too much about our process internally," says Mazur. "There is waste that comes in that goes directly to a low-level radioactivity site," he says. "It is all based on an economic decision."

Pennsylvania resident Jack Kruell kept a pair of Geiger counters

on his spice rack to monitor the radioactivity from a dump near his home outside Pittsburgh. Photograph by George Etheredge for Rolling Stone

George Etheredge for Rolling Stone

A 2013 report co-authored by Resnikoff calculated that sending solid oil-and-gas waste like drill cuttings to a low-level radioactive-waste facility could mean as much as a 100-fold increase in cost, so there's an incentive for companies to get the waste into a regional landfill.

A letter from a whistle-blowing employee of Westmoreland to one of Kruell's neighbors last April told of "numerous overlooked DEP violations" and "dumping of frackwater material and sludge in excess of legal limits."

The company "is getting away with everything that they can," the letter said. "I am writing to you because I know your quality of life is being affected and I don't want you to get a raw deal." The Westmoreland Sanitary Landfill did not reply to questions from *Rolling Stone.*

But what worries Kruell most is a metallic dust he has noticed speckling his bushes and grass, and the pain he gets when he mows his lawn. "The day after I cut the grass, I have pain in my bones so bad I can't move," says Kruell. "Like someone taking a drill bit and drilling into your bone without anesthetic."

"These are the people who I worry about most," says Weatherington-Rice, because metals like radium can easily become airborne with small clay particles in dust. "You put it up on top of the landfill and put a wind over it, what do you think is

going to happen?" she says. "Radioactive metals and other heavy metals are going to settle out over communities and people downwind. They are all hazardous, and they will all kill you eventually if you get enough of them in you."

There are at least five landfills in West Virginia that accept drill cuttings, at least five in New York, 10 in Ohio, and 25 in Pennsylvania. Most of the drill cuttings are from fracking and can be radioactive. "We have never knowingly buried very large quantities of known low-level radioactive waste in a generic, municipal solid-waste landfill originally designed for household garbage," Bill Hughes, an industrial electrician who served 15 years on a board overseeing the municipal landfill in West Virginia's Wetzel County, wrote to the West Virginia Department of Environmental Protection. The dangers involved, he said, "might not be known for generations." In 2018, when I met Hughes, who is now deceased, he told me the issue of dealing with the industry's radioactive drill cuttings "blindsided" state agencies. "They really weren't sure how to regulate this," he said.

The foul discharge of water passing through Westmoreland, called "leachate," flowed downhill through a sewer pipe and into the Belle Vernon sewage-treatment plant, where superintendent Guy Kruppa says it was killing the microbes needed to digest the sewage. His facility has no ability to remove the radioactivity, he says. This means, as long as his plant was receiving the contaminated leachate, insufficiently treated sewage and radioactivity was being spewed into the Monongahela River, which runs through downtown Pittsburgh.

"What this place is, essentially, is a permit to pollute," says Kruppa. "It's a free pass to go ahead and dump it in the river, because we don't test for that stuff, we don't have to. It's a loophole. They found a way to take waste that no one else will take to the landfill and get rid of it in liquid form. Essentially, we are the asshole of the fracking industry."

Kruppa tried for months to make the Pennsylvania DEP act on the dilemma, but to no avail. "DEP has no evidence…that would indicate levels of heavy metals or radioactive elements in leachate," says spokeswoman Lauren Fraley. The agency is not worried about the leachate entering Pennsylvania rivers. She says the DEP concluded there was "no immediate or significant harm to human health or the environment, given the enormous volume of water in the receiving river."

But in May, a county judge ordered the landfill to stop sending the sewage plant its leachate. And there are risks even when there's a large body of water to dilute the contamination: A 2018 study found that in Pennsylvania's Allegheny River, oil-and-gas waste was accumulating in the shells of freshwater mussels.

"We are putting things in the river and don't know what we're doing, and we might be putting people at risk," says Kruppa. "At times it seems like I am the only one not playing ball here, and everyone else, including the DEP, is turning their heads and telling us there's no problem."

Despite dire climate warnings, the U.S. oil-and-gas industry is in the midst of an epic boom, what a 2018 Department of Energy paper calls an "oil-and-gas production renaissance."

Pipelines, power plants, and shipping terminals are being developed across the nation at a dizzying pace.

But in the excitement of this boom there is little mention of the pipes, pumps, and filters in these plants that will become coated with radioactivity. Or of the fountain of radioactive brine and drill cuttings spewing forth from wells. Or of the workers being exposed, the land being contaminated.

"One question I ask these companies," says Smith, the New Orleans lawyer, "'What have you done to go out and find all the radioactive waste you have dumped all over the United States for the past 120 years?' And the answer is nothing."

A 2016 lawsuit by environmental groups forced the EPA to reassess its monitoring of oil-and-gas waste, which it had not done since before the fracking boom. But in 2019 the agency concluded "revisions…are not necessary at this time."

When I checked in with Peter around the holidays he had collected a new batch of samples and said anxiety levels among brine haulers were at an all-time high. "The other drivers are getting scared," he says. "Guys are wanting to get tested."

"The workers are going to be the canaries," says Raina Rippel of the Southwest Pennsylvania Environmental Health Project, a nonprofit public-health organization that supports residents impacted by fracking. "The radioactivity issue is not something we have adequately unpacked. Our elected leaders and public-health officials don't have the knowledge to convey we are safe."

But knowledge is out there. Radium can be detected in urine; a

breath test can pick up radon. Because radium builds up in bone, even a body buried in a cemetery could convey details of someone's exposure, says Wilma Subra, a Louisiana toxicologist who first started tracking oil-and-gas radioactivity in the 1970s.

"There is a massive liability that has been lying silently below the surface for all these years," says Allan Kanner, one of the nation's foremost environmental class-action lawyers, whose recent cases have included PFAS contamination and the Deepwater Horizon oil spill. "The pieces haven't all really been put together, because the industry has not really been telling the story and regulators haven't been telling the story and local doctors aren't informed, but at some point I expect you will see appropriate and reasonable litigation emerge on this."

If so, it could have a devastating impact on the fossil-fuel industry, especially if tighter regulations were put in place and oil-and-gas waste was no longer exempted by the EPA from being defined as hazardous waste. "The critical component of the profit margin for these companies is that they can get rid of the waste so cheaply," says Auch of FracTracker Alliance. "If they ever had to pay fair-market value, they wouldn't be able to exist."

"It has been argued," says Liz Moran, with the New York Public Interest Research Group, "that if you close the loophole, you would put the industry out of business." When asked what would happen to the industry if the EPA exemption were removed, University of Cincinnati legal scholar Jim O'Reilly, author of 53 textbooks on energy development and other topics, replied with

a single word: "Disaster."

Radioactivity "is the way into the Death Star," says Melissa Troutman, an analyst with the environmental group Earthworks. The industry is afraid of two things, she says, "losing money, and losing their social license." The high cost of drilling relies on a continual infusion of capital, and "the number of operational risks and bottlenecks continues to grow," states a 2018 article by the energy consultancy group Wood Mackenzie. But while the industry is continuously supported by Wall Street cash, social license may be a more difficult coffer to refill.

Paul Templet, the former secretary of the Louisiana Department of Environmental Quality and the first state official to tackle oil's radioactivity issue, is now 79 years old and lives with his wife in an adobe house in New Mexico. But he has to return to Louisiana once every couple of months to serve as an expert in lawsuits over oil-field contamination. In recent years, a growing group of landowners has discovered that the oil-and-gas wells that brought them riches also tarnished their property with heavy metals and radioactivity. "Almost everywhere we test we find contamination," says Templet. There are now more than 350 of these legacy lawsuits moving forward in the state. Proceedings are sealed, and it is difficult to tally sums across all cases, but Templet says it's fair to say that what began as a little nibble on the industry's pocketbook has turned into a forceful tug. "They've known for 110 years, but they haven't done anything about it," says Templet. "It's the secret of the century."

[CORRECTION: This story originally stated that the average brine truck in Pennsylvania exceeds Department of

Transportation radioactivity limits, which would mean that by not following certain haz-mat guidelines these trucks were breaking the law. Upon further reporting, we found that while the standard Pennsylvania brine truck would be 980 times above the DOT limit when it comes to the total accumulated amount of radium in the truck, known as the consignment limit, the truck's average radium concentration must also exceed a certain level for regulations to kick in. It is not clear whether the average brine truck would exceed that limit — built-up, concentrated radioactive scale in a truck could push it over, but that data isn't available. Testing is the responsibility of the operator at the wellhead, and the DOT is not required to verify or confirm the analysis. The story has been changed to reflect this new information.]

[CORRECTION: A photograph of a truck crash that was originally published with this story was misidentified as a brine truck. It has been replaced.]

WildEarth Guardians Exhibit 8:

C. Danforth et al., An Integrative Method for Identification and Prioritization of Constituents of Concern in Produced Water from Onshore Oil and Gas Extraction, Environment International 134 (2020).

An integrative method for identification and prioritization of constituents of concern in produced water from onshore oil and gas extraction

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ARTICLE INFO

ABSTRACT

In the United States, onshore oil and gas extraction operations generate an estimated 900 billion gallons of produced water annually, making it the largest waste stream associated with upstream development of petroleum hydrocarbons. Management and disposal practices of produced water vary from deep well injection to reuse of produced water in agricultural settings. However, there is relatively little information with regard to the chemical or toxicological characteristics of produced water. A comprehensive literature review was performed, screening nearly 16,000 published articles, and identifying 129 papers that included data on chemicals detected in produced water. Searches for information on the potential ecotoxicological or mammalian toxicity of these chemicals revealed that the majority (56%) of these compounds have not been a subject of safety evaluation or mechanistic toxicology studies and 86% lack data to be used to complete a risk assessment, which underscores the lack of toxicological information for the majority of chemical constituents in produced water. The objective of this study was to develop a framework to identify potential constituents of concern in produced water, based on available and predicted toxicological hazard data, to prioritize these chemicals for monitoring, treatment, and research. In order to integrate available evidence to address gaps in toxicological hazard on the chemicals in produced water, we have catalogued available information from ecological toxicity studies, toxicity screening databases, and predicted toxicity values. A Toxicological Priority Index (ToxPi) approach was applied to integrate these various data sources. This research will inform stakeholders and decision-makers on the potential hazards in produced water. In addition, this work presents a method to prioritize compounds that, based on hazard and potential exposure, may be considered during various produced water reuse strategies to reduce possible human health risks and environmental impacts.

1. Introduction

Produced water is the largest volumetric waste stream in oil and gas production; it is a combination of water that occurs from within or proximate to the hydrocarbon-bearing zone as well as any injected fluid used to stimulate or maintain production activities (Fakhru'l-Razi et al., 2009). This wastewater has complex chemistry (Stringfellow and Camarillo, 2019) and is generated during all types of petroleum hydrocarbon extraction activities, including conventional and unconventional production. As oil and gas production expands, so does the challenge to manage the estimated hundreds of billion gallons of wastewater generated per year from these activities (Veil, 2015). While approximately

90% of produced water is reinjected deep into the subsurface for enhanced recovery or disposal, there are increased efforts to recycle produced water in the oilfield (Liden et al., 2018). In addition, in arid-prone areas there are incentives to consider alternative management strategies of produced water, including for agricultural purposes. However, there remain outstanding questions as to the chemical composition and potential human and ecological hazards of produced water.

Produced water characteristics from both conventional and unconventional oil and gas development vary by formation and geology, time since well-emplacement, and types of chemicals used in operation. Generally, produced water contains dissolved and dispersed oil compounds, salts, metals, naturally occurring radioactive materials, stimulation

and production chemicals, as well as the degradants and transformation compounds from these additives (Hoelzer et al., 2016). Currently, the majority of oil and gas producing states require disclosure of hydraulic fracturing additive chemicals, and most of these states allow for, or require, the use of FracFocus—a chemical registry for hydraulic fracturing in the United States—to meet these reporting requirements. The concentrations of produced water constituents can differ by orders of magnitude (Estrada and Bhamidimarri, 2016; Fakhru'l-Razi et al., 2009). Individual chemicals and their concentrations can be difficult to quantify or even identify. Many of the compounds associated with either hydraulic fracturing fluids or those identified in produced water lack established analytical methods (Oetjen et al., 2017; U.S. EPA, 2018). Advanced research-based analytical methods have been used to detect and quantify organic compounds in produced water, including homologous series of surfactants (Nell and Helbling, 2018; Thurman et al., 2017, 2014), biocides (Nell and Helbling, 2018), and compounds that are suspected additives but which are unreported to FracFocus (Hoelzer et al., 2016; Sitterley et al., 2018). Overall, there is not a comprehensive understanding of produced water composition (Ferrer and Thurman, 2015; Nell and Helbling, 2018; Oetjen et al., 2017).

Current Federal Effluent Limitation Guidelines (ELG), under Title 40 of the Code of Federal Regulation (CFR), limit the direct discharge of produced waters to surface water, with an exception for western states, where the only defined ELG is for oil and grease at 35 mg/L (40 CFR §435.53, 1995). Produced water discharge may include a wide array of treatment options, ranging from robust, multi-step treatment systems that use ultra-filtration and reverse osmosis units (CDPHE, 2011) to those that discharge water that has been minimally treated using oil/water separators (CDPHE, 2012). The U.S. EPA study of offsite Centralized Waste Treatment (CWT) facilities, which can be authorized to treat produced water for discharge throughout the United States under 40 CFR §437, concluded that CWTs without multi-step treatment are often deficient and may not remove many of the pollutants found in produced water (U.S. EPA, 2018). There are considerable ambiguities in how produced water should comply with existing federal regulations under the Clean Water Act (CWA) and many practices of disposal of produced water that do not involve surface water discharge, such as road de-icing, dust suppression, and irrigation, are not subject to the CWA (U.S. EPA, 2019a).

Practices that intentionally discharge produced water to the environment have the potential to increase risks to human health and the environment by introducing a new exposure pathway to an understudied wastewater (Faber et al., 2019). To date, the majority of studies on chemical hazards associated with onshore produced water have focused on hydraulic fracturing chemicals used in the stimulation process rather than the produced water generated by it and other development practices (Colborn et al., 2011; Elsner and Hoelzer, 2016; Gordalla et al., 2013; Rogers et al., 2015; Yost et al., 2016a, 2017).

Research on toxicity of produced water itself has been challenging due to lack of access to oil and gas wastewater samples (Santos et al., 2019). One research team at the University of Alberta has conducted integrated studies on the characterization and toxicity of flowback and produced water from a hydraulically fractured gas well in the Upper Devonian-aged Duvernay Formation (Blewett et al., 2017a, 2017b; He et al., 2018, 2017). Their work has indicated that there are potential impacts on a variety of aquatic organisms from additives and their transformation products, as well as from naturally occurring organic and inorganic constituents. Additionally, the findings indicate that some toxicity effects are partially associated with particulate matter, likely due to organic sorption to the particulates, and not from salinity alone.

Prior to their finalized 2016 report examining potential impacts from the hydraulic fracturing water cycle on drinking water (U.S. EPA, 2016), U.S. EPA released draft reports on the study, which included approximately 130 chemicals in flowback or produced water identified in literature reviews (U.S. EPA, 2015). These data were used by some research groups to assess the potential hazard of produced water by reviewing associated chemical toxicity data. Elliot et al. (2017)

searched the REPROTOX database, which is comprised of reproductive and developmental toxicity data and reported that some toxicity information was available for only 55% of these compounds. Yost et al. (2016) conducted a review of chronic oral toxicity values and found that only 62% of the chemicals have some toxicity values available.

Our aim was to develop an integrative method to identify and prioritize chemical constituents in produced water, thereby addressing existing gaps in our knowledge on the potentially hazardous chemicals in produced water. First, we performed a comprehensive literature search to aggregate available information on chemical constituents detected in onshore produced water in North America. Next, data on the potential ecotoxicological and human health hazards were identified for these chemicals and used to create a prioritized list of the produced water constituents of concern. Finally, we determined whether analytical methods for the chemicals of concern are available to support future exposure assessment efforts. Collectively, our approach represents a comprehensive framework to identify potential constituents of concern in produced water in order to prioritize these chemicals for monitoring, treatment, and research based on available and predicted toxicological hazard data.

2. Methods

2.1. A literature search for chemicals identified in produced water

A comprehensive literature search was designed to identify studies that performed a chemical analysis of flowback or produced water generated onshore during oil and gas development. Searches were conducted electronically using Web of Science and PubMed for all years through March 8, 2018. Search keywords and logic are reported in SI Table 1. Additional articles were identified using cited references from review articles. A list of review articles can be found in SI Table 2. Two independent reviewers screened titles and abstracts for relevance using DistillerSR. To be considered for inclusion, the studies had to present primary results for chemical analysis of flowback or produced water from onshore oil and gas production sites in Canada, Mexico, or the United States and be in the English language. Two independent reviewers resolved discrepancies regarding inclusion through discussion; if needed, a third reviewer was also consulted. The articles that met inclusion criteria underwent full text review and data extraction for chemical data, including Chemical Abstract Service (CAS) number and concentration, if reported in the study. Often, CAS Registry Numbers were not included in the literature; if provided by the author, CAS numbers were extracted as reported and their authenticity confirmed using the U.S. EPA CompTox Chemistry Dashboard ("Chemistry Dashboard," 2019). Otherwise, the Chemistry Dashboard was used to look up CAS numbers by chemical name.

2.2. Cross walks

To understand what information was available for each chemical, the aggregated list of chemicals derived from the literature review was compared by CAS number to a variety of databases. These databases included:

i. Quantitative measures of dose-effect from databases identified by the U.S. EPA Office of Solid Waste and Emergency Response (OSWER) Directive 9285.7–53 (U.S. EPA, 2003);

ii. Chemistry Dashboard database of toxicity values (ToxValDB) (Williams et al., 2017);

iii. Select chemical lists compiled by regulatory authorities, including the list of National Primary Drinking Water Standards (NPDWS) (U.S. EPA, 2009), the U.S. EPA Priority Pollutant List (PPL) compiled under the Clean Water Act (40 CFR §423, Appendix A, 2015), and hazardous waste defined under Appendix VIII of Part 261 of the Resource Conservation and Recovery Act (RCRA);

iv. Chemicals listed under the U.S. EPA-approved test methods for the analysis of environmental media (Hazardous Waste Test Methods/SW-846), those listed in Title 40 of the Code of Federal Regulations Part 136, which establishes the guidelines for test procedures for the analysis of pollutants (40 CFR §136, 2017), and those listed on the National Environmental Methods Index (NEMI), which is a database of analytical and field methods for environmental monitoring ("National Environmental Methods Index," 2017); and

v. Chemicals reported in FracFocus from January 2013 to January 24, 2018 (FracFocus, 2018).

2.3. Collection and analysis of toxicity data for produced water chemicals

Chemicals that were considered in the toxicity prioritization analyses were restricted to constituents that (1) had been detected in produced water more than once, (2) had reported concentration data, and (3) were known to have some toxicity data available, specifically those chemicals that were included in the Toxicity Value Database (ToxValDB) (Williams et al., 2017) and the Toxicity Forecaster (ToxCast) program ("Chemistry Dashboard," 2019; "Toxicity Forecasting," 2019). Chemicals that did not have these attributes were not included in further analyses. For the list of included chemicals, available toxicity data were collected, analyzed, and integrated for the purposes of prioritization of potential toxicity. These data were collected from three sources: the Ecotoxicology Knowledge-base (U.S. EPA, 2019b), the Chemistry Dashboard, and the Conditional Toxicity Value (CTV) Predictor (Wignall et al., 2018). These three sources reported hazards based on ecotoxicity testing, bioactivity from high throughput *in vitro* screening, and regulatory toxicity values for human health, respectively.

2.3.1. ECOTOX database

The ECOTOX database is maintained by the U.S. EPA's National Health and Environmental Effects Research Laboratory's Mid-Continent Ecology Division and includes toxicity data for aquatic organisms and terrestrial plants and wildlife (U.S. EPA, 2019b). These data are primarily from peer-reviewed literature. Data included in the ECOTOX database are for single chemicals with verifiable CAS numbers that demonstrate a biological effect on a live, whole organism. Concentration data are converted into units of parts per million where information reported in the literature make such conversions possible. All available data for the half-maximal effective concentration (EC50) were extracted and analyzed here; however, the original references for those data were not examined. EC50 for aquatic organisms was chosen as the representative endpoint for ecotoxicological hazard data as this was the richest dataset (i.e. most data available for each chemical) in the ECOTOX database over other effective concentrations or endpoints (e.g., EC15 or LD50) or for terrestrial organisms. While the database contains species-level information, data were aggregated for each chemical by species group. For example, green algae (*Pseudokirchneriella subcapitata*) and diatoms (*Skeletonema costatum*) were considered collectively as the species group "algae." To establish a representative characteristic effective concentration for each chemical, the lower quartile (Q1) of EC50 was calculated across all effects for the most sensitive species group after removing outliers. Outliers were detected and removed using the ROUT (Robust regression and **Out**lier removal) method (Motulsky and Brown, 2006) in GraphPad Prism version 8.0.1 for Windows (GraphPad Prism 8, 2019). If less than four results were available for a chemical, then instead of the Q1, the lowest value was used. This approach represents a reasonably, but not overly, conservative estimate of the potential hazard that may not have considered all sensitive species or endpoints. The robustness of the results to a number of these assumptions was assessed using sensitivity analyses, described below in Section 2.5.

2.3.2. EPA chemistry dashboard

The ToxCast screening library contained 4746 substances that had been tested in a panel of *in vitro* assays with a variety of cell types, design,

or bioactivity type. For each chemical and assay type, whether the chemical were active and at what half-maximal concentration (AC50), was reported in the ToxCast database. These data were accessed through the Chemistry Dashboard and, similar to the EC50 data, AC50 for all available assays were analyzed collectively. Chemicals that did not show activity below the highest tested concentration were considered inactive and not included for that component in ToxPi. A representative concentration of AC50 for each chemical was determined in the same manner as described above for ecotoxicology data (Section 2.3.1). *In vitro* assay data for chemicals with a boiling point less than 200 degrees Fahrenheit were excluded, as the compound volatility may lead to artificially low concentrations in the assay or may create false negative results. In addition to the representative AC50 value, the percent of active assays was used as another indicator of potential hazard.

2.3.3. CTV predictor

The Conditional Toxicity Value (CTV) predictor (Wignall et al., 2018) is a web-based quantitative structure activity relationship (QSAR) model-based *in silico* approach for developing human health quantitative risk estimates for chemicals where there are none. The CTV predictor generates quantitative predictions for a variety of toxicity values (oral and inhalation exposures), with an uncertainty of an order of magnitude or less. Here, only chemicals within the applicability domain were considered. Additionally, if a chemical were part of the "training set" with existing published, peer-reviewed regulatory toxicity values, then the regulatory value was used instead of the QSAR-generated value. Furthermore, only toxicity values for oral exposure were included for this data set as the primary potential route of exposure to chemicals in produced water was assumed to be ingestion over inhalation.

2.4. Data integration and prioritization using ToxPi

The Toxicological Prioritization Index (ToxPi) is an analytical framework that can be used to integrate multiple lines of evidence from a variety of sources into a dimensionless index score, as described elsewhere (Marvel et al., 2018; Reif et al., 2010). In this analysis, ToxPi was used to calculate a weighted combination of each data source to illustrate how each component (or slice) contributed to the overall toxicity profile for each chemical. The higher the ToxPi score, the higher the potential toxicity of that chemical relative to the others in the study based on the components considered for that analysis. The visual representation of the index score allows for a rapid understanding of the underlying weight-of-evidence scheme employed in the analysis. To harmonize quantitative data, data are scaled or inverted, where appropriate, so that the compound with the lowest toxicity value is represented by the smallest, positive non-zero number in the set. To normalize ToxPi scores, each slice was scaled so that the data were distributed linearly. The scaling equations are presented in the Supplemental Information (SI Table 3). By default, component data that are missing for a particular chemical are considered to be zero by ToxPi. Therefore, where data were missing, the minimum values for that component data set (i.e. least toxic value) of all individual assays was imputed; this assumes chemicals with missing data caused a minimal effect or activity (To et al., 2018). In this analysis, toxicity data were used for each chemical to build component slices in three domains. Each slice was derived using characteristic concentrations for the toxic effect the chemical had on aquatic organisms (ECOTOX), cell-based high throughput screening assays (ToxCast), or by using known or calculated human toxicity values. The three domains were: *in vivo* endpoints, *in vitro* assays, and known or conditional toxicity values (CTV domain). The definition and notation of ToxPi is presented in Fig. 1.

2.5. Sensitivity analysis

To understand the impacts of data analysis or inclusion decisions for the three data sets, the following sensitivity analyses were performed: (1) for missing values, using no values (blanks) instead of the minimum
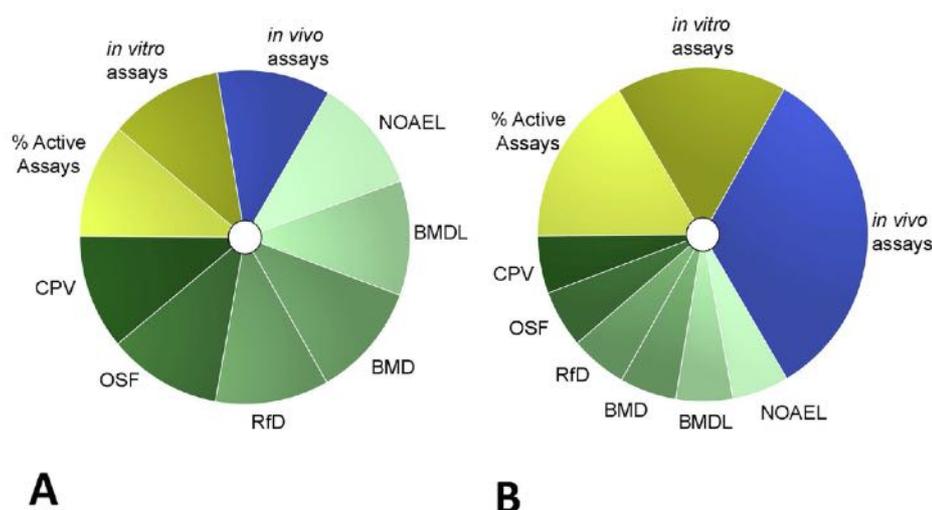
Fig. 1. ToxPi definitions and notations. A: original analysis where equal weighting was given for each endpoint; B: alternative weighting, where each domain was given equal weight. Each chemical was analyzed using unweighted (A) and weighted (B) combinations of data from multiple domains, which are represented by slices of a similar color: *in vivo* ecotoxicology endpoints (blue), *in vitro* high throughput screening assays (yellow), and known or conditional human health toxicity values (green). Individual slices represent data from related assays, endpoints, or analyses. The distance of each slice from the center indicates the normalized value of the component. The angle of the slice represents how that component is weighted relative to the other components in the overall ToxPi calculation. Cancer potency value (CPV), Oral slope factor (OSF), Reference dose (RfD), Rfd Benchmark dose (BMD), RfD Benchmark dose lower limit (BMDL), RfD No observed adverse effect level (NOAEL). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

in the analysis; (2) for both the ecotoxicity data and *in vitro* activity data, using median values (Q2) or geometric mean versus the lower quartile and minimum values in the main analysis for characteristic half-maximal concentrations; (3) including only data-rich chemicals defined as those having at least five out of nine component slices; and (4) using different weighting schemes in ToxPi that gave equal weight to each endpoint ("unweighted," Fig. 1A) versus giving equal weight to each domain in the main analysis ("weighted," Fig. 1B). Additionally, chemicals listed on the EPA's Priority Pollutants List (PPL), which are known to be hazardous, were included in the ToxPi analysis as reference chemicals to benchmark our methodology.

3. Results

3.1. Identification of chemicals in produced water through comprehensive literature review

Based on the literature search, a total of 15,661 records were returned (11,996 from Web of Science and 3,665 from PubMed), with an additional 33 studies identified through review articles (SI Table 2). After title/abstract screening, 302 articles were assessed for full-text eligibility and a final total of 129 articles were included for data extraction (Fig. 2, SI Table 4). These papers detailed chemical analysis for 173 sources of produced water (by state and hydrocarbon development type) collected from 27 locations in North America: 24 States in the USA, 2 Canadian Provinces, and 1 Mexican State (SI Fig. 1). The majority of produced water reported in these studies was sourced from unconventional developments (112). Produced water collected from conventional developments (35) and coalbed methane (26) were represented more similarly. The source of produced water in these studies was predominately from the Marcellus basin in Pennsylvania, even though the majority of produced water volume is generated in areas such as Texas, California, and New Mexico (SI Fig. 1). From the comprehensive literature search, a total of 1,198 unique chemicals were identified as having been detected in produced water (SI Table 4). Of these, 296 chemicals satisfied the additional criteria of being detected more than once and having associated concentration data; 122 chemicals had the further criteria of having at least two types of toxicity data (Fig. 3, SI Table 5).

3.2. Comparison of produced water chemicals to other databases

The initial literature review identified 1,198 chemical constituents in produced water for which there were a CAS number identified (SI
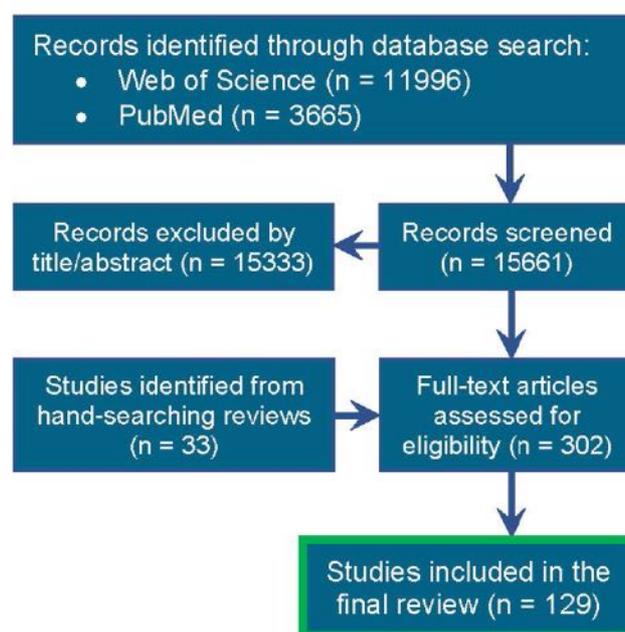
Fig. 2. Flow diagram of the literature search strategy.

Table 4). The following sections describe their presence on selected databases; the results are summarized in Fig. 3.

3.2.1. Quantitative toxicity values

To perform a human health risk assessment for particular contaminants of concern in the environment, decision makers need appropriate chemical-specific toxicity values, which are a quantitative measure of dose-effect. These values can be reassessed or updated over time; therefore, the OSWER Directive 9285.7–53 (U.S. EPA, 2003) suggests a hierarchy of sources to identify appropriate toxicity values, defined as follows: Tier 1 toxicity information from the U.S. EPA's Integrated Risk Information System (IRIS), Tier 2 information from the U.S. EPA's Provisional Peer Reviewed Toxicity Values (PPRTV), and Tier 3 from "other sources." Priority is given to those sources that use similar methods to develop toxicity information as in Tiers 1 and 2. Examples of other sources include the California EPA's toxicity value database (CalEPA), the Agency for Toxic Substances and Disease Registry (ATSDR) Minimal Risk Levels (MRL), and the U.S. EPA Health

1198 Compounds in Produced Water
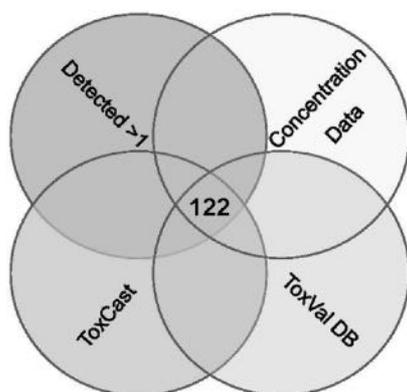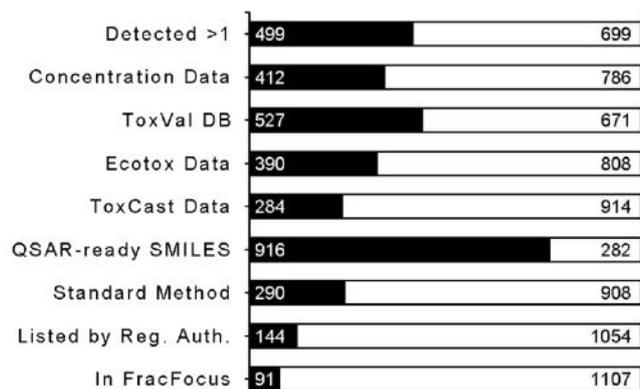
Fig. 3. Selection of data-rich chemicals for ToxPi rank analysis, based on available data.
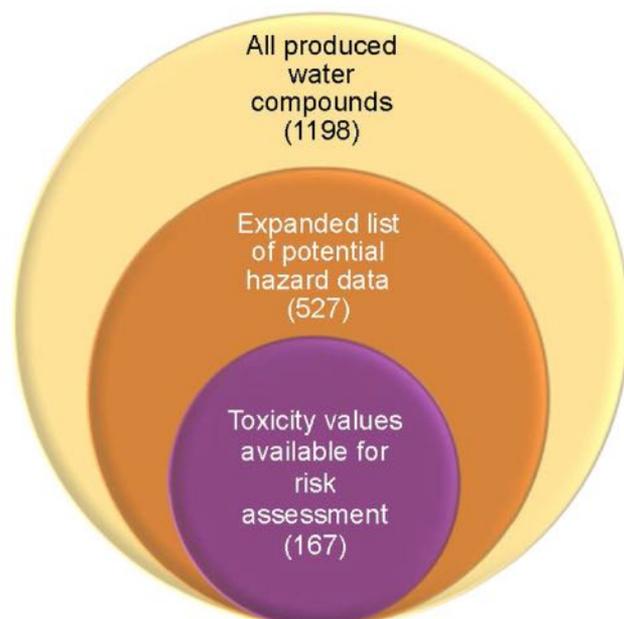
Fig. 4. Cross reference of produced water constituents to available toxicity data. The majority of constituents in produced water (56%) have no data available on the databases searched here to understand or indicate potential toxicological hazard.

Effects Assessment Summary Tables (HEAST). To identify which produced water chemicals found in the literature had chemical-specific toxicity values that may be considered appropriate for a risk assessment, the above databases, as well as the EPA's Office of Pesticide

Programs (OPP), were cross-referenced. Of the 1,198 constituents identified in produced water, we found that 167 have existing toxicity values (14%) that can be used for a risk assessment in the United States (Fig. 4).

3.2.2. ToxVal database

Next, the list of produced water constituents was compared to the Chemistry Dashboard database of expanded toxicity Values (ToxValDB), which is a collection of databases that summarize *in vivo* data (Williams et al., 2017). Presence on the ToxValDB list indicates the availability of toxicity dose-effect values collected from multiple databases, including the databases listed above, but also European databases, including ECHA (European Chemicals Agency), and ecotoxicity data. When cross-referenced to this list, there were 527 chemicals identified in produced water with some associated toxicity data in one of these public databases, indicating that more than half (56%) of chemicals identified in produced water lack publically available toxicity dose-effect related values (Fig. 4).

3.2.3. Lists made by regulatory authorities

To further understand which produced water constituents may be regulated currently at the federal level, we compared constituents to some key chemicals lists compiled by regulatory authorities, including NPDWS, the PPL, and hazardous waste defined under RCRA. The NPDWS are legally enforceable standards for public water systems that impose maximum concentrations or treatment techniques determined to be protective of public health. The PPL was compiled from a list of chemicals that were known to be toxic, however, these chemicals were highlighted for the PPL because they were measurable, had been detected and reported in water at a frequency of 2.5%, and are "produced in significant quantities." Chemicals that are listed under the NPDWS and PPL are all likely to cause adverse effects to human health at concentrations above standards. Finally, the Resource Conservation and Recovery Act is the law that governs the disposal of hazardous and non-hazardous solid waste. Hazardous waste is considered to be ignitable, corrosive, reactive, or toxic. Chemicals listed under Appendix VIII (40 CFR §261, Appendix VIII, 2010) may be considered hazardous to human health or the environment if improperly managed. Of the chemicals identified in produced water, there were 46 (3.8%) chemicals listed under the NPDWS, 76 (6.3%) on the PPL, and 81 (6.8%) that are listed under RCRA. However, it should be noted that produced water, along with other exploration and production (E&P) wastes have been exempt from Federal Hazardous Waste Regulations since 1980 (U.S. EPA, 2002).

3.2.4. Standard analytical methods

Chemical analysis that is performed on waste or wastewater in a regulatory context, such as those described above, is limited to a proscribed set of methods. The produced water chemicals were cross-referenced by CAS number to chemicals that can be analyzed by U.S. EPA-approved test methods. For the 1,198 chemicals identified in this review, 290 (24%) can be identified through standard analytical methods.

3.2.5. FracFocus

Only 91 (7.6%) chemicals that were reported in FracFocus were found in the constituents identified in produced water.

3.3. Collection and analysis of toxicity data for chemicals in produced water

Ecotoxicology data are summarized in Fig. 5. The Q1 of the EC50 was calculated for 37 out of the 92 chemicals that had dose-response data by species group. Because the remaining 55 chemicals had limited data—less than four studies per species group—quartiles were not calculated. Here, the lowest EC50 for the most sensitive species group of the remaining chemicals, which represents an entire study rather than a single assay, was included as the characteristic concentration in the analysis.
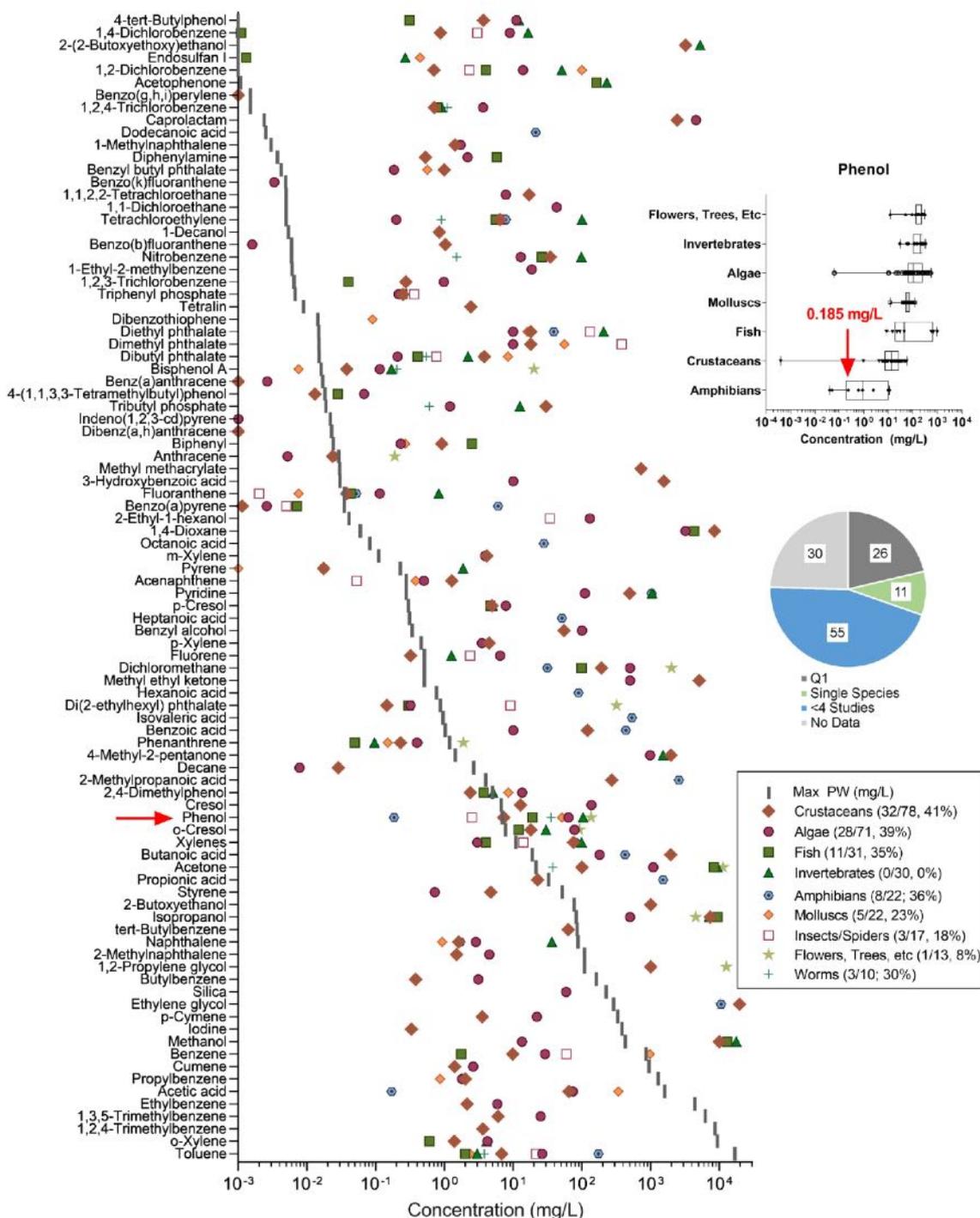
Fig. 5. Characteristic concentrations for EC50 (lower quartile or minimum concentration) for aquatic organisms by species group, compared to maximum concentration measured in produced water (mg/L). Inset displays an example box and whisker plot of EC50 that was used to determine quartiles across all effects by phenol on each species group. The lower quartile concentration for the most sensitive species group was chosen for each chemical (i.e. amphibians for phenol) as the characteristic concentration for ToxPi analysis. The pie chart indicates the available data for the chemicals included in this analysis.

Data from *in vitro* assays in the ToxCast screening are summarized in Fig. 6. The Q1 of the AC50 was calculated for 73 chemicals. The minimum AC50 was selected for 30 chemicals that had less than four active assays. Thirteen chemicals were inactive at the maximum concentration assayed, and six chemicals had a boiling point below 200 °F.

Finally, "conditional" and existing toxicity values were predicted or identified using the CTV Predictor (toxvalue.org, Wignall et al., 2018). The availability of toxicity values for the chemicals in produced water are listed in Table 1.

3.4. Data integration and prioritization using ToxPi

Data from various toxicity data streams detailed above, ecotoxicity, *in vitro* methods, and predicted/existing toxicity values, were integrated using the ToxPi approach. The results of the ToxPi evaluation are summarized in Fig. 7 and SI Fig. 2. The toxicity prioritization schemes (weighted and unweighted), identified 57 chemicals as the top-third most hazardous compounds, relative to the restricted list of 122 chemicals (Table 2). There were twenty-three chemicals that ranked in the top-third of both weighting schemes (Table 3). The weighted scheme
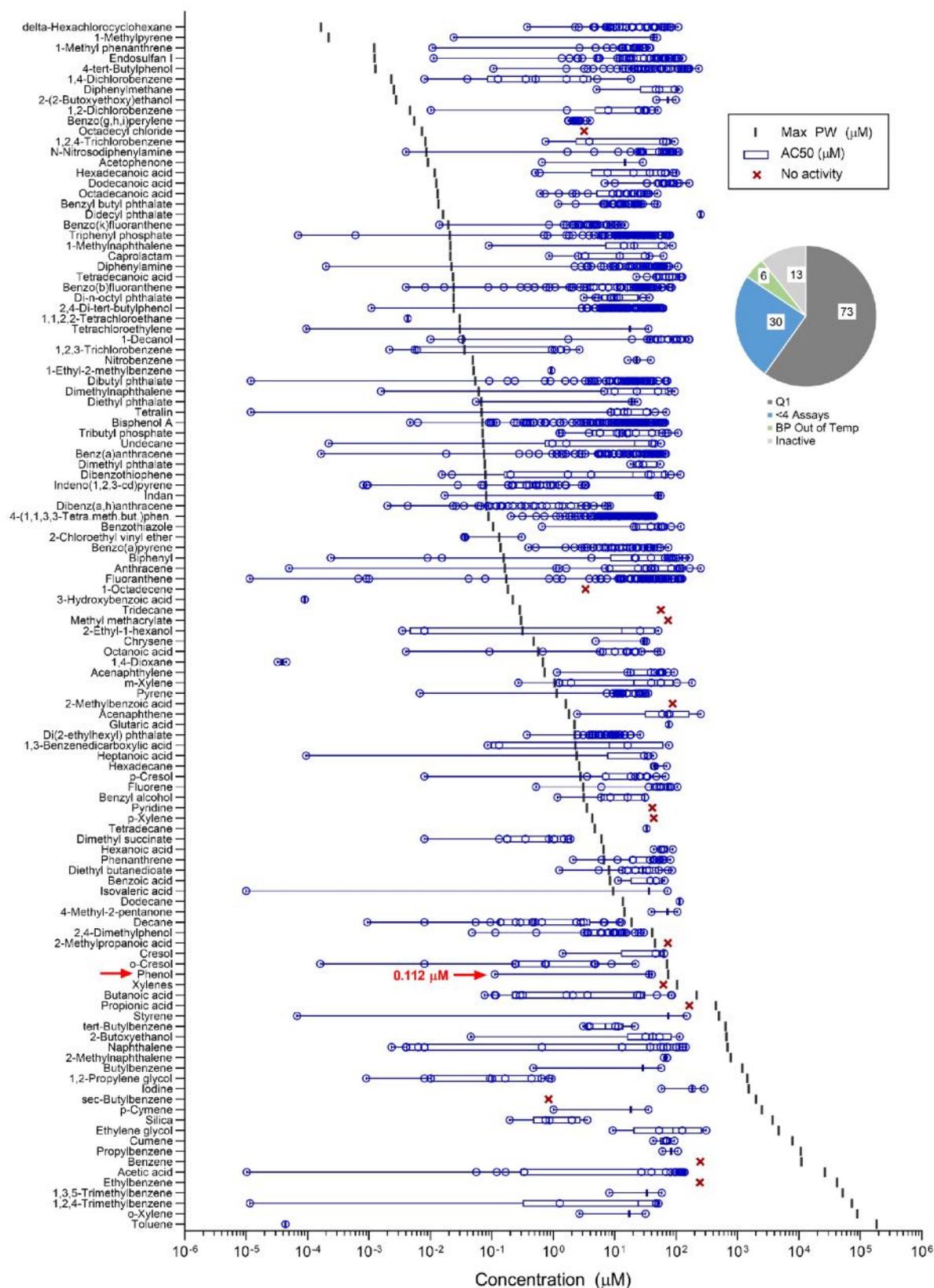
Fig. 6. Characteristic concentrations for AC50 (lower quartile or minimum concentration) for ToxPi analysis, compared to maximum concentration measured in produced water (μM). For *in vitro* assays, the characteristic effective concentration was calculated as the Q1 of AC50 across all active assays, if greater than four assays. Else, the minimum value was chosen. An example compound (phenol) is called out. The pie chart indicates the available data for the chemicals included in this analysis.

Table 1
Availability of conditional (predicted) and known toxicity values for the restricted set of 122 chemicals. Existing toxicity values were collected by the CTV Predictor from the following sources: IRIS, Office of Pesticide Programs (OPP), Superfund Regional Screening Levels (CDC/ATSDR, PPRTV, HEAST), and California EPA Office of Environmental Health Hazard.

Toxicity value	"Conditional" predicted	Existing	No value
Cancer potency value (CPV)	46	16	60
Oral slope factor (OSF)	37	23	62
Reference dose (RfD)	29	62	31
Rfd Benchmark dose (RfD BMD)	39	24	59
RfD Benchmark dose lower limit (RfD BMDL)	44	10	68
RfD No observed adverse effect level (RfD NOAEL)	53	34	35

gives equal weight to ecotoxicology, high-throughput *in vitro* activity, and human health hazards. However, because there are more endpoints for human health hazards (the CTV domain), in the unweighted scheme, the ToxPi is dominated by human health hazards. While weighting data is somewhat subjective—which underscores the need for careful consideration of data inputted and assumptions of each ToxPi analysis—the facility to change weighting schemes allows the user to prioritize receptors of higher concern for the context of the analysis. When these two methodologies are considered concurrently, the 23 chemicals identified potentially represent the more data-rich chemicals with known toxicological hazard.

3.5. Sensitivity analysis

To assess how the ranking of chemicals based on ToxPi scores may be impacted by the types and amounts of data included in the assessment (data-rich versus data-poor chemicals) or how the characteristic concentrations were calculated (Q1 and minimum value vs Q2 and geometric mean), a sensitivity analysis was performed by comparing the ToxPi ranking and values for multiple analyses (Fig. 8). The sensitivity analysis showed that the overall ToxPi ranking was largely stable regardless of the choices made on input parameters of weighting. When comparing imputing of minimum (least toxic) values for missing values, the overall rank change was three or less rank-changes for 69% of the chemicals, and within ten rank places for 94% of the chemicals. Completing the ToxPi analysis with median values and geometric means gives an over-all rank change by three or less places for 51% of the chemicals and ten or less places for 84% of the chemicals. The analysis was found to be most sensitive to changes in how the domain is weighted or if data were removed by only considering chemicals that are data-rich. Here, the ToxPi rankings fluctuated more by chemical (16% and 17% moved three or less places, and 26% and 76% moved ten or less places for weighted and data-rich analyses, respectively).

4. Discussion

This study presents a method for identification and prioritization of constituents of concern in produced water from onshore oil and gas extraction. This unique approach identified the potential universe of chemicals associated with an understudied, industry-specific wastewater, and considered multiple lines of toxicity evidence for those constituents. The results of this analysis will be highly informative to measuring and mitigating exposure to constituents of concern in produced water. The method is particularly appropriate to survey toxicity of identified constituents, given the large number of compounds reported in produced water, as well as address a lack of data available on the chemical hazard of many of the chemicals detected. Given the variability in produced water composition, the nearly 1,200 chemicals identified through our comprehensive literature review are not likely be
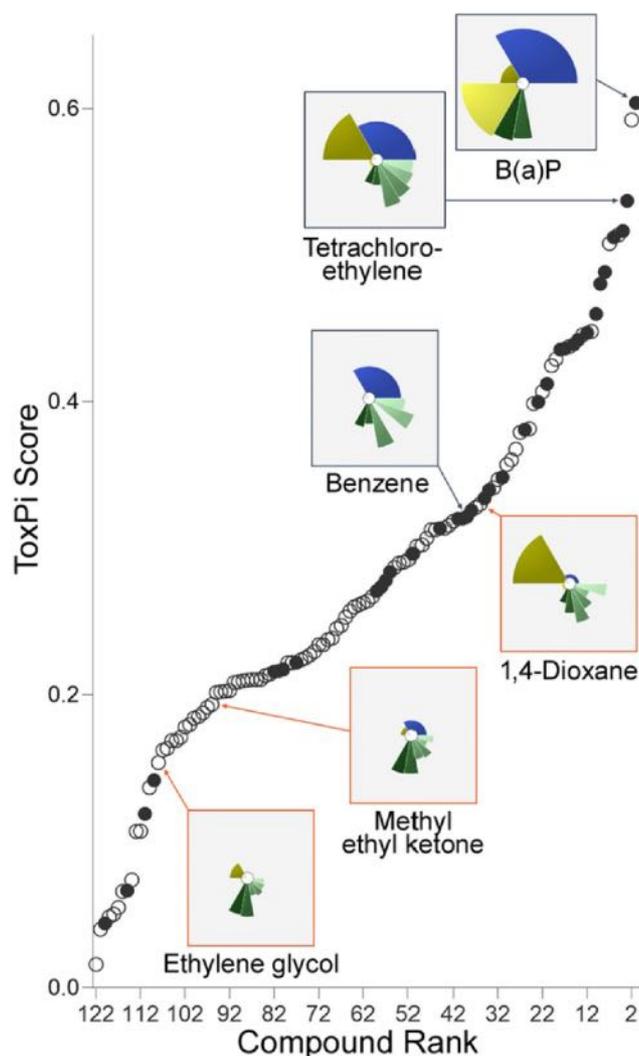
Fig. 7. Distribution dot plot of ToxPi Scores for all 122 chemicals using the weighted analysis. The dots represent an individual chemical, whereas the 36 chemicals also listed on the EPA's Priority Pollutant List (PPL) are denoted by a solid dot. Example ToxPi profiles are represented in the insets.

present in each wastewater sample. However, this and other analyses indicate that there is not a comprehensive understanding of what constituents are of primary concern in regional-specific wastewaters (Luek and Gonsior, 2017; Oetjen et al., 2017; U.S. EPA, 2016). This lack of understanding represents a major hurdle for designing fit-for-purpose treatment and monitoring strategies for alternative management of specific produced water.

4.1. Chemical constituents in produced water

While this literature review identified 1,198 chemicals in produced water with CAS numbers, there are additional constituents of potential concern, such as isomers or homologous series of various compounds (Thurman et al., 2017), which cannot be represented by a single CAS number, and therefore were not included in this study. For the purposes of this study, requiring a CAS number allowed for rapid cross-reference to numerous other databases and facilitated identification of associated data. It is likely that substances without CAS numbers have even more limited toxicity information.

Our literature review found that only 14% of chemicals identified in produced water have existing toxicity values for risk assessment in the United States. While this percentage is much smaller than what has been reported by others (Elliott et al., 2017; Yost et al., 2016a), it is

Table 2
Top third of chemicals as ranked by two ToxPi analyses. Bolded chemicals were found in both weighting schemes.

Rank	CAS	Domain weighted	CAS	Unweighted
1	**50-32-8**	**Benzo(a)pyrene**	319-86-8	delta-Hexachlorocyclohexane
2	**959-98-8**	**Endosulfan I**	959-98-8	**Endosulfan I**
3	**127-18-4**	**Tetrachloroethylene**	127-18-4	**Tetrachloroethylene**
4	53-70-3	Dibenz(a,h)anthracene	126-73-8	Tributyl phosphate
5	**124-18-5**	**Decane**	98-95-3	Nitrobenzene
6	56-55-3	Benz(a)anthracene	79-34-5	1,1,2,2-Tetrachloroethane
7	207-08-9	Benzo(k)fluoranthene	124-18-5	**Decane**
8	**205-99-2**	**Benzo(b)fluoranthene**	50-32-8	**Benzo(a)pyrene**
9	**106-46-7**	**1,4-Dichlorobenzene**	64-19-7	**Acetic acid**
10	193-39-5	Indeno(1,2,3-cd)pyrene	143-07-7	**Dodecanoic acid**
11	**126-73-8**	**Tributyl phosphate**	110-75-8	2-Chloroethyl vinyl ether
12	191-24-2	Benzo(g,h,i)perylene	104-76-7	**2-Ethyl-1-hexanol**
13	**64-19-7**	**Acetic acid**	112-30-1	**1-Decanol**
14	129-00-0	Pyrene	123-91-1	**1,4-Dioxane**
15	206-44-0	Fluoranthene	108-88-3	Toluene
16	**87-61-6**	**1,2,3-Trichlorobenzene**	111-76-2	2-Butoxyethanol
17	**108-88-3**	**Toluene**	503-74-2	**Isovaleric acid**
18	**79-34-5**	**1,1,2,2-Tetrachloroethane**	79-09-4	Propionic acid
19	140-66-9	4-(1,1,3,3-Tetramethylbutyl)phenol	544-63-8	Tetradecanoic acid
20	80-05-7	Bisphenol A	56-55-3	**Benz(a)anthracene**
21	**98-95-3**	**Nitrobenzene**	107-92-6	Butanoic acid
22	**108-95-2**	**Phenol**	544-76-3	Hexadecane
23	**91-20-3**	**Naphthalene**	1120-21-4	Undecane
24	100-42-5	Styrene	629-59-4	Tetradecane
25	132-65-0	Dibenzothiophene	71-43-2	**Benzene**
26	**319-86-8**	**delta-Hexachlorocyclohexane**	75-09-2	Dichloromethane
27	**112-30-1**	**1-Decanol**	106-65-0	Dimethyl succinate
28	**104-76-7**	**2-Ethyl-1-hexanol**	124-07-2	Octanoic acid
29	99-06-9	3-Hydroxybenzoic acid	123-25-1	Diethyl butanedioate
30	**503-74-2**	**Isovaleric acid**	108-95-2	**Phenol**
31	120-12-7	Anthracene	53-70-3	Dibenz(a,h)anthracene
32	**143-07-7**	**Dodecanoic acid**	205-99-2	Benzo(b)fluoranthene
33	104-51-8	Butylbenzene	57-55-6	1,2-Propylene glycol
34	84-74-2	Dibutyl phthalate	112-40-3	Dodecane
35	85-68-7	Benzyl butyl phthalate	629-50-5	Tridecane
36	122-39-4	Diphenylamine	111-14-8	Heptanoic acid
37	**123-91-1**	**1,4-Dioxane**	91-20-3	Naphthalene
38	117-81-7	Di(2-ethylhexyl) phthalate	106-46-7	1,4-Dichlorobenzene
39	**71-43-2**	**Benzene**	87-61-6	1,2,3-Trichlorobenzene
40	83-32-9	Acenaphthene	57-10-3	Hexadecanoic acid

important to note that those studies considered only about 130 potential constituents in produced water, which had been primarily identified through targeted analytical methodologies because they were known to be of toxicological concern. Currently, only 24% (290) of the 1,198 chemicals identified in produced water can be detected through standard analytical methods. This limited chemical characterization prohibits thorough understanding of potential effects on human health, which is important given that some regions across the country are considering—or have implemented—alternative strategies to reuse the wastewater, including some that involve agricultural use. This bias toward "known knowns," as compared to the nearly 1,200 chemical constituents identified through the literature search, highlights the need to use a combination of targeted, suspect-screening, and non-targeted analytical methodologies to characterize the chemical composition of complex wastewaters and to identify a wider range of potential contaminants of concern.

Our analysis additionally indicated that many of the chemicals used in hydraulic fracturing are not present in produced water. However, this analysis does not account for likely transformation of compounds or degradants of hydraulic fracturing additives; meaning, it is difficult to estimate the percentage of geogenic versus anthropogenic compounds that are detected in produced water. Furthermore, while there have been very positive advancements in disclosure, a full understanding of chemicals used in operations remains limited due to trade secret provisions. Konschnik and Dayalu (2016) found that approximately 18.9% of CAS numbers were "intentionally withheld from public disclosure" in their analysis of FracFocus (Konschnik and Dayalu,

2016). Additionally, there are no requirements for the disclosure of chemicals used for oil and gas activities outside of well simulation (i.e. hydraulic fracturing) (Stringfellow et al., 2017).

4.2. Prioritization of produced water chemicals

This study devised a method to identify and integrate multiple sources of available toxicity hazard data in order to ascertain and prioritize constituents of concern. Known chemicals of concern were included in the ToxPi analysis to gain understanding as to how they may be distributed in the final ranking (Fig. 7). There were 36 chemicals listed on the EPA's Priority Pollutants List (PPL) in the subset of 122 chemicals used for the ToxPi analysis (SI Table 5). While these reference chemicals are classified as hazardous, they are being compared to chemicals that are being ranked based on a different set of considerations. Whereas PPL chemicals are selected based on toxicity to humans as well as production volume and detection frequency, the chemicals in this framework were ranked by toxicity to humans, ecotoxicity, and *in vitro* activity. Therefore, it is not unexpected that the reference chemicals are distributed throughout the ToxPi rankings. PPL chemicals, however, are more weighted at the top of the ToxPi ranking.

To address potential bias based on availability of data, two different weighting schemes—one weighted by endpoint and one weighted by domain—were considered concurrently. It was assumed that chemicals that are in the top-third of both are most likely to be a priority. The ToxPi evaluation, using these data and assumptions, yielded twenty-three chemicals of concern (Table 3). One finding of this work is the

Table 3
Characteristics of the chemicals in top third for both ToxPi weighting schemes.

CASRN	Compound	# of samples	Age of PW (range)	Type	Reported to FracFocus	Toxicity Value[§]	Citation
50-32-8	Benzo(a)pyrene	32	1–90 d	U		Yes	(Bell et al., 2017; Chittick and Srebotnjak, 2017; Hayes, 2009; Hayes and Severin, 2012; He et al., 2017; Regnery et al., 2016; Shih et al., 2015)
959-98-8	Endosulfan I	4	0–90 d	U			(Hayes, 2009; Shih et al., 2015)
127-18-4	Tetrachloroethylene	5	1 d – 38 mo	U		Yes	(Akob et al., 2015; Hayes, 2009; Hayes and Severin, 2012; NYSDEC, 2015; Shih et al., 2015)
53-70-3	Dibenz(a,h)anthracene	13	1–90 d	U		Yes	(Bell et al., 2017; Chittick and Srebotnjak, 2017; Hayes, 2009; Hayes and Severin, 2012; Shih et al., 2015)
124-18-5	Decane	18	1 wk – 18 mo	U	Breaker		(Hoelzer et al., 2016; Maguire-Boyle and Barron, 2014; Strong et al., 2014; Wesolowski et al., 1987)
56-55-3	Benz(a)anthracene	76	1–90 d	U		Yes	(Bell et al., 2017; Chittick and Srebotnjak, 2017; Hayes and Severin, 2012; He et al., 2017; Regnery et al., 2016; Shih et al., 2015)
205-99-2	Benzo(b)fluoranthene	40	1–90 d	U		Yes	(Bell et al., 2017; Chittick and Srebotnjak, 2017; Hayes, 2009; Hayes and Severin, 2012; He et al., 2017; Shih et al., 2015)
106-46-7	1,4-Dichlorobenzene	2	ns	U		Yes	(Shih et al., 2015)
126-73-8	Tributyl phosphate[†]	50	PW	CBM	Defoamer	Yes	(Orem et al., 2014, 2007; Pashin et al., 2014a)
64-19-7	Acetic acid	11	14–328 d	U, C, CBM	Corrosion inhibitor/iron control		(Cluff et al., 2014; Hayes, 2009; Lester et al., 2015; Shih et al., 2015; Sirivedhin and Dallbauman, 2004; U.S. EPA, 2016)
87-61-6	1,2,3-Trichlorobenzene	4	14–90 d	U		Yes	(Hayes, 2009; Shih et al., 2015)
108-88-3	Toluene	734	1 d to > 2 yrs	U, C, CBM, EOR	Paraffin Inhibitor	Yes	(Akob et al., 2015; Carey et al., 1992; Chittick and Srebotnjak, 2017; Cluff et al., 2014; Dahm et al., 2011; DiGiulio and Jackson, 2016; Hayes, 2009; Hayes and Severin, 2012; Hoelzer et al., 2016; Maguire-Boyle and Barron, 2014; NYSDEC, 2015; Rogers et al., 1992; Rosenblum et al., 2017; Shih et al., 2015; Sirivedhin and Dallbauman, 2004; Thacker et al., 2015; U.S. EPA, 2016; Wesolowski et al., 1987; Ziemkiewicz et al., 2014; Ziemkiewicz and Thomas He, 2015)
79-34-5	1,1,2,2-Tetrachloroethane	2	PW	C		Yes	(Sirivedhin and Dallbauman, 2004)
98-95-3	Nitrobenzene	3	PW	C, CBM		Yes	(Sirivedhin and Dallbauman, 2004)
108-95-2	Phenol	49	1 d to > 10 yrs	U, C, EOR	Proppant, Other	Yes	(Carey et al., 1992; DiGiulio and Jackson, 2016; Gieg et al., 2010; Hayes, 2009; Hayes and Severin, 2012; Hoelzer et al., 2016; Lester et al., 2015; NYSDEC, 2015; Shih et al., 2015; U.S. EPA, 2016; Wesolowski et al., 1987)
91-20-3	Naphthalene	712	1 d to > 10 yrs	U, C, CBM	Other[*]	Yes	(Bell et al., 2017; Chittick and Srebotnjak, 2017; Cluff et al., 2014; DiGiulio and Jackson, 2016; Hayes, 2009; Hayes and Severin, 2012; He et al., 2017; Hoelzer et al., 2016; Kassotis et al., 2015; Lyman et al., 2018; NYSDEC, 2015; Orem et al., 2014, 2007; Pashin et al., 2014b, 2014a; Regnery et al., 2016; Shih et al., 2015; Sirivedhin and Dallbauman, 2004; U.S. EPA, 2016; Wesolowski et al., 1987)
319-86-8	delta-Hexachloro-cyclohexane	3	0–14d	U			(Hayes, 2009; Shih et al., 2015)
112-30-1	1-Decanol[†]	4	1–3 wks	U	Acid Corrosion Inhibitors		(Hoelzer et al., 2016; Shih et al., 2015)
104-76-7	2-Ethyl-1-hexanol	4	1–3 wks	U	Corrosion Inhibitor		(Hoelzer et al., 2016; Shih et al., 2015)
503-74-2	Isovaleric acid[†]	6	1–3 wks	U, C, CBM			(Hoelzer et al., 2016; Sirivedhin and Dallbauman, 2004; U.S. EPA, 2016)
143-07-7	Dodecanoic acid[†]	67	1–3 wks	U, CBM			(Hoelzer et al., 2016; Orem et al., 2007; Pashin et al., 2014b, 2014a)
123-91-1	1,4-Dioxane	41	1–90 d	U	Other[*]	Yes	(Hayes and Severin, 2012; Lester et al., 2015; Shih et al., 2015; U.S. EPA, 2016)
71-43-2	Benzene	647	1 d to > 2yrs	U, C, CBM	Carrier Fluid, Surfactant	Yes	(Akob et al., 2015; Chittick and Srebotnjak, 2017; Cluff et al., 2014; Dahm et al., 2011; DiGiulio and Jackson, 2016; Hayes, 2009; Hayes, 2009; Kassotis et al., 2015; Khan et al., 2016; NYSDEC, 2015; Rogers et al., 1992; Rosenblum et al., 2017; Shih et al., 2015; Sirivedhin and Dallbauman, 2004; U.S. EPA, 2016; Wesolowski et al., 1987; Ziemkiewicz et al., 2014; Ziemkiewicz and Thomas He, 2015)

PW – Produced Water; U – Unconventional; C – Conventional; CBM – Coalbed Methane; EOR – Enhanced Oil Recovery.
* Other – multiple usages listed.
† No U.S. EPA-approved analytical test method exists for this chemical.
§ Quantitative toxicity values available from the databases described in the U.S. EPA Office of Solid Waste and Emergency Response (OSWER) Guidance document under Directive 9285.7–53 (U.S. EPA, 2003).
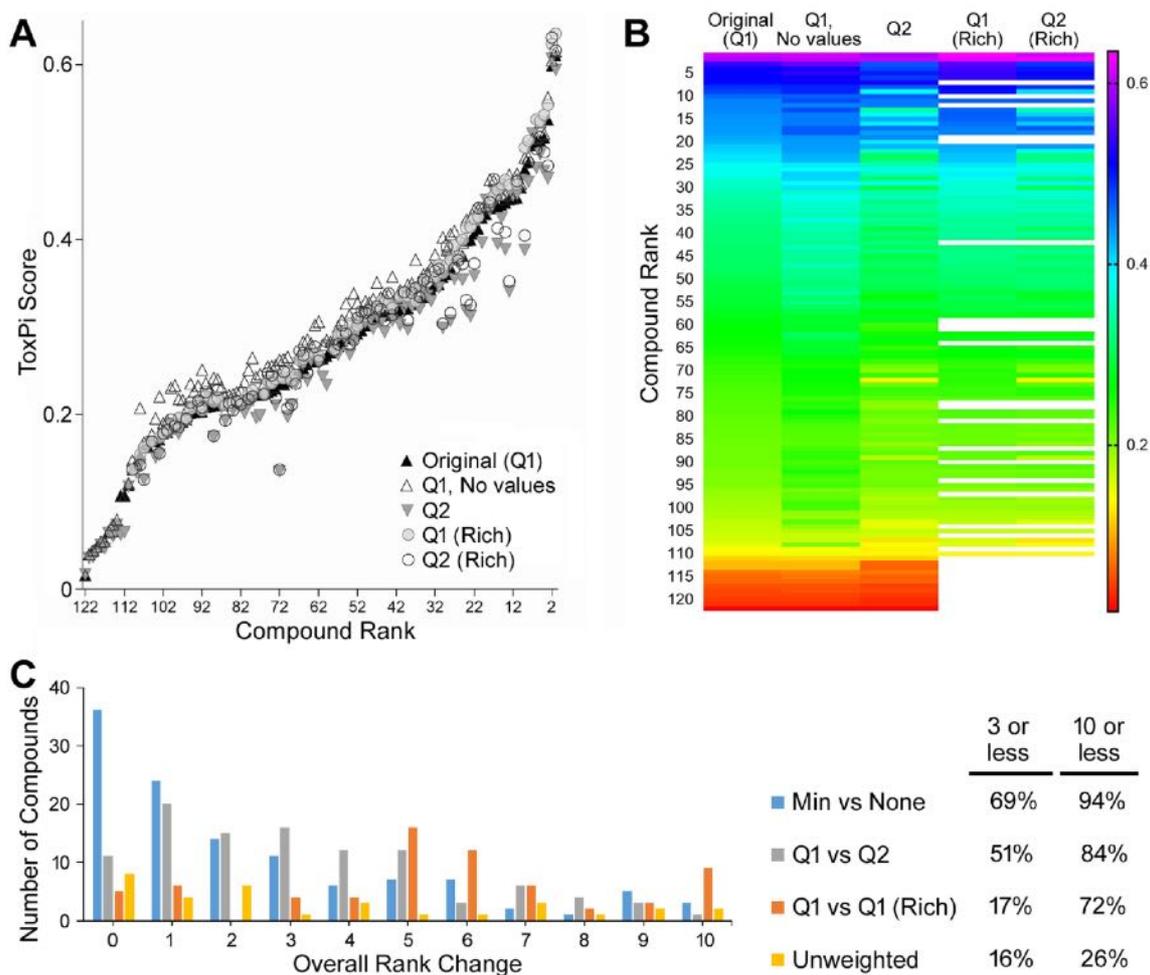
Fig. 8. Sensitivity of ToxPi analysis. A: Sensitivity analysis comparing the rank versus ToxPi score of original weighted ToxPi analysis (Original, Q1) to imputing missing data using no values instead of the minimum in the main analysis (Q1, No values); using median values or geometric mean instead of the lower quartile and minimum values for both the ecotoxicity data and *in vitro* activity data for characteristic half-maximal concentrations (Q2); and including only data-rich chemicals defined as those having at least five out of nine component slices (Q1 and Q2 Rich). The rank derived in the original analysis was held constant to understand how the overall ToxPi score changed. B: A heat map of the same data derived in the sensitivity analysis to visualize change in rank order. C: Additionally, the sensitivity analysis examined how the overall rank changed using different weighting schemes in ToxPi that gave equal weight to each endpoint (unweighted) versus giving equal weight to each domain in the main analysis with using an unweighted analysis. The histogram indicates the total number of chemicals that moved rank (0–10) places.

identification of many compounds with known profiles of toxicity, including 1,4-dioxane, nitrobenzene, 1,1,2,2-tetrachloroethane, and toluene. Implications of those compounds identified with high ToxPi scores indicate that some chemicals of known hazard are present in some produced water samples. Additionally, acetic acid was identified as a chemical of concern. While acetic acid is the primary component of vinegar, it is harmful to aquatic life at low concentrations. Acetic acid was found at elevated concentrations (1,600 mg/L) in produced water (Lester et al., 2015), a level which exceeds demonstrated acute and chronic ecotoxicity effects (Locke et al., 2009) and can further impact aquatic systems through eutrophication.

Apparent throughout this analysis is the identification of legacy pollutants that may be reintroduced to the environment through produced water discharges, including the presence of endosulfan, an organochlorine insecticide that was banned in the US in 2010, and tetrachloroethylene, which is a suspected human carcinogen. It is unclear how these legacy pollutants became associated with produced water. One possibility is that they are present in the make-up water used to create stimulation fluids (Yost et al., 2016b). Tetrachloroethylene, which is a commonly used industrial solvent (Cichocki et al., 2016), may be used to maintain drilling or other equipment. Regardless of the process, it is clear that some of these legacy contaminants are present in produced water and are another factor that should be considered in

assessing potential risks associated with reuse applications that introduce this wastewater to the environment.

An important limitation of this ranking analysis is the restricted geographic area from which produced water samples were collected. As noted, the majority of samples came from the Marcellus Shale play. The implication is that the extent to which the type and quantity of compounds of concern are present in produced water across the country is not well understood. More representative sampling would have provided a broader perspective on chemicals that may be of concern nationally or regionally where treatment for discharge is being considered. The framework described here can be applied to create a more targeted prioritization effort once regional constituents are identified. The flexibility, and potential concern, of the ToxPi approach in this application is that the selection of ToxPi evaluation criteria are inherently subjective. Different types of data—including physicochemical properties to consider fate and transport, as well as those chemicals that are persistent, bioaccumulative, and toxic—can be included and adjusted, leading to identification of different priority chemicals for various contexts and applications. This is helpful when a search for a particular set of chemicals, such as those that exhibit aquatic toxicity, is warranted, but may be a weakness if evaluation criteria are not considered carefully, potentially leading to misidentification of the highest priority chemicals of concern. Additionally, when considering particular chemicals of concern

for a context-specific risk assessment, a review of all the original studies included in each of the databases should be completed to assess data quality, reliability, and applicability.

The bioactivity data underlying the ToxPi hazard evaluation also provides an initial step toward performing risk assessments for produced water. For context, we compared the maximum concentrations reported in produced water to the bioactivity data for ecotoxicity (Fig. 5) as well as from ToxCast (Fig. 6). However, we elected not to include a "margin of exposure" in the ToxPi evaluation, as produced water is a highly-variable, under-characterized waste stream, and there is no assurance that the reported concentrations are in any way representative of the typical or even maximal concentrations across all sources of produced water. Thus, in the context of site-specific risk evaluations, our ToxPi hazard evaluation methodology represents an example methodology that can also be applied in a fit-for-purpose, context-specific case. For instance, after the chemical constituents in produced water are characterized and potential receptors (ecological or human) identified, then the underlying bioactivity data can be used to provide a screening-level indication of what chemicals may be of greater or lesser concern from a risk-based perspective. However, even in this case, many chemicals potentially present in produced water do not have either bioactivity data or toxicity values, so whole effluent assessments could have an important role in establishing hazard and risk.

Thus, while providing useful insights, prioritizing chemicals and focusing on a subset of constituents does not eliminate potential concern from the broader list of chemicals. Moreover, a demonstrated need exists for a more robust analytical evaluation of wastewater and new methods to characterize the potential impacts of its release, which will also allow for smarter monitoring and better development of treatment regimes. This, and other knowledge gaps associated with human exposure to oil and gas development was highlighted in a recent literature review and research planning document developed by the Health Effects Institute (2019). In addition to targeted and non-targeted chemical characterization, whole-effluent toxicity evaluation techniques, such as novel high-throughput "toxicogenomics" assays (Gao et al., 2015; Lan et al., 2016) or effects-directed assessments combined with toxicity identification evaluation (Burgess et al., 2013) may be useful to characterize the potential toxicological hazard of "unknown unknown" chemicals. Evaluation of analytical and treatment options for compounds identified through this work is an obvious next step in characterizing mitigation strategies to reduce potential risks from compounds identified in produced water.

5. Conclusions

We have developed a methodology to address the critical issue of identifying and prioritizing constituents of concern in produced water by combining a comprehensive literature search process to rapidly and methodically collect useful literature on chemicals that have been identified in produced water, with a quantitative integration method to evaluate toxicity data for those constituents across multiple domains. One of the more salient findings of this work is the lack of sufficient toxicity data for 86% of compounds identified in the limited analysis of produced water. Our results also provide a systematic basis for prioritizing chemicals for further study. Furthermore, this method can be extended to allow for additional types of data to be considered, including physicochemical properties to consider chemical fate and transport, as well as what may be persistent in the environment, bioaccumulative, and/or toxic. This flexibility will facilitate context-specific application of the approach, investigating ways to reuse produced water while also being informed about risk and risk management needs. Overall, additional research investigating both "known unknowns" and "unknown unknowns" is vital in order to update existing, and potentially expanding, regulatory programs for produced water, particularly as interest grows in the intentional treatment and release of produced water for disposal or reuse outside of the oilfield.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envint.2019.105280.

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WildEarth Guardians Exhibit 9

Search Results, New Mexico Oil Conservation Division, OCD Permitting, Spill Search Database, (search parameters for Incident Date Range January 1, 2020 – June 30, 2020; Spill Material: Produced Water.

Incident Number	Operator Name	Severity	Lease Type	Incident Date	Material Spilled	Volume Spilled	Unit Of Volume	Spill Cause	Spill Source	County
nRM2018244476	MEWBOURNE OIL CO	Major	Private	6/29/20	Produced Water	100	BBL	Equipment Failure	Other (Specify)	Eddy (15)
nRM2018253989	DEVON ENERGY PRODUCTION COMPANY, LP	Major	Federal	6/28/20	Produced Water	650	BBL	Other	Pump	Lea (25)
nRM2018232278	RIDGEWAY ARIZONA OIL CORP.	Major	State	6/28/20	Produced Water	300	BBL	Other	Flow Line - Production	Roosevelt (41)
nRM2018256434	Spur Energy Partners LLC	Minor	Private	6/26/20	Produced Water	7	BBL	Equipment Failure	Pump	Lea (25)
nRM2017850577	MEWBOURNE OIL CO	Minor	Federal	6/24/20	Produced Water	5	BBL	Lightning	Tank (Any)	Eddy (15)
nRM2017852330	SOLARIS WATER MIDSTREAM, LLC	Major	Private	6/24/20	Produced Water	556	BBL	Equipment Failure	Other (Specify)	Eddy (15)
nRM2017750863	SOLARIS WATER MIDSTREAM, LLC	Major	Federal	6/23/20	Produced Water	120	BBL	Equipment Failure	Valve	Eddy (15)
nRM2017555009	MEWBOURNE OIL CO	Major	Federal	6/21/20	Produced Water	200	BBL	Corrosion	Other (Specify)	Eddy (15)
nRM2017854640	CIMAREX ENERGY CO. OF COLORADO	Major	Federal	6/20/20	Produced Water	112	BBL	Equipment Failure	Pump	Eddy (15)
nRM2018258355	DEVON ENERGY PRODUCTION COMPANY, LP	Minor	Federal	6/20/20	Produced Water	9	BBL	Equipment Failure	Valve	Lea (25)
nRM2017853957	CIMAREX ENERGY CO. OF COLORADO	Minor	Federal	6/18/20	Produced Water	13	BBL	Human Error	Well	Lea (25)
nRM2017527514	MEWBOURNE OIL CO	Major	Private	6/18/20	Produced Water	50	BBL	Corrosion	Other (Specify)	Lea (25)
nRM2017752399	Spur Energy Partners LLC	Minor	Federal	6/18/20	Produced Water	23	BBL	Other	Other (Specify)	Eddy (15)
nRM2018233009	BP AMERICA PRODUCTION COMPANY	Major	Federal	6/17/20	Produced Water	7	BBL	Equipment Failure	Tank (Any)	San Juan (45)
nRM2017856312	CONOCOPHILLIPS COMPANY	Major	State	6/16/20	Produced Water	56	BBL	Corrosion	Flow Line - Production	Lea (25)
nRM2017643736	WPX Energy Permian, LLC	Minor	Federal	6/16/20	Produced Water	22	BBL	Corrosion	Flow Line - Production	Eddy (15)
nRM2017635527	WPX Energy Permian, LLC	Minor	Federal	6/15/20	Produced Water	12	BBL	Corrosion	Tank (Any)	Eddy (15)

nRM2017855476	JUDAH OIL LLC		Federal	6/15/20	Produced Water	3	BBL	Equipment Failure	Water Tank	Eddy (15)
nRM2017052769	WPX Energy Permian, LLC	Minor	State	6/15/20	Produced Water	10	BBL	Equipment Failure	Valve	Eddy (15)
nRM2017054610	CIMAREX ENERGY CO.	Major	Federal	6/15/20	Produced Water	75	BBL	Equipment Failure	Other (Specify)	Eddy (15)
nRM2017461850	SOLARIS WATER MIDSTREAM, LLC	Minor	Federal	6/15/20	Produced Water	24	BBL	Equipment Failure	Pump	Eddy (15)
nRM2018242652	BTA OIL PRODUCERS, LLC	Major	State	6/14/20	Produced Water	35	BBL	Equipment Failure	Separator	Lea (25)
nRM2017851403	COG OPERATING LLC	Major	Private	6/13/20	Produced Water	138	BBL	Equipment Failure	Flow Line - Production	Eddy (15)
nRM2017041629	Spur Energy Partners LLC	Minor	State	6/13/20	Produced Water	10	BBL	Other	Other (Specify)	Lea (25)
nRM2017440778	Spur Energy Partners LLC	Major	Federal	6/12/20	Produced Water	300	BBL	Other	Other (Specify)	Lea (25)
nRM2017849298	COG OPERATING LLC	Major	Federal	6/12/20	Produced Water	70	BBL	Corrosion	Other (Specify)	Lea (25)
nRM2017849943	COG OPERATING LLC	Minor	Federal	6/12/20	Produced Water	10	BBL	Corrosion	Other (Specify)	Lea (25)
nRM2018237619	OXY USA INC	Major	State	6/11/20	Produced Water	24	BBL	Corrosion	Other (Specify)	Lea (25)
nRM2018235623	OXY USA INC	Minor	Private	6/10/20	Produced Water	1	BBL	Equipment Failure	Gasket	Eddy (15)
nRM2017725462	COG OPERATING LLC	Major	Federal	6/10/20	Produced Water	3	BBL	Other	Other (Specify)	Eddy (15)
nRM2017549520	APACHE CORPORATION	Minor	Private	6/8/20	Produced Water	17	BBL	Corrosion	Other (Specify)	Lea (25)
nRM2016454695	CIMAREX ENERGY CO.	Minor	Federal	6/8/20	Produced Water	6	BBL	Corrosion	Other (Specify)	Eddy (15)
nRM2016453805	ADVANCE ENERGY PARTNERS HAT MESA, LLC	Minor	State	6/7/20	Produced Water	10	BBL	Equipment Failure	Valve	Lea (25)
nRM2017058536	DEVON ENERGY PRODUCTION COMPANY, LP	Minor	Private	6/7/20	Produced Water	22	BBL	Equipment Failure	Flow Line - Production	Lea (25)
nRM2017458969	COG OPERATING LLC	Minor	Federal	6/6/20	Produced Water	14	BBL	Corrosion	Other (Specify)	Lea (25)
nRM2016456845	WPX Energy Permian, LLC	Major	Federal	6/6/20	Produced Water	120	BBL	Corrosion	Other (Specify)	Eddy (15)
nRM2017839486	COG OPERATING LLC	Major	Federal	6/5/20	Produced Water	10	BBL	Equipment Failure	Other (Specify)	Lea (25)
nRM2017547777	APACHE CORPORATION	Major	Private	6/4/20	Produced Water	119	BBL	Corrosion	Flow Line - Injection	Lea (25)

nRM2016457766	HILCORP ENERGY COMPANY	Minor	Federal	6/3/20	Produced Water	21	BBL	Equipment Failure	Pipeline (Any)	San Juan (45)
nRM2016062209	MARATHON OIL PERMIAN LLC	Major	Private	6/2/20	Produced Water	600	BBL	Corrosion	Flow Line - Production	Lea (25)
nRM2016135686	CIMAREX ENERGY CO. OF COLORADO	Minor	Federal	6/1/20	Produced Water	15	BBL	Corrosion	Pump	Eddy (15)
nRM2015754726	CIMAREX ENERGY CO.	Minor	Federal	6/1/20	Produced Water	9	BBL	Equipment Failure	Dump Valve	Lea (25)
nRM2016460654	XTO ENERGY, INC	Major	State	6/1/20	Produced Water	673	BBL	Equipment Failure	Other (Specify)	Eddy (15)
nRM2017035633	GOODNIGHT MIDSTREAM PERMIAN, LLC	Minor	Private	6/1/20	Produced Water	20	BBL	Human Error	Flow Line - Production	Lea (25)
nRM2017057120	LOGOS OPERATING, LLC		Federal	6/1/20	Produced Water	2	BBL	Overflow - Tank, Pit, Etc.	Tank (Any)	Rio Arriba (39)
nRM2016027552	LIME ROCK RESOURCES II-A, L.P.	Major	Federal	5/31/20	Produced Water	1450	BBL	Equipment Failure	Pump	Eddy (15)
nRM2016048371	CONOCOPHILLIPS COMPANY	Major	Federal	5/31/20	Produced Water	26	BBL	Equipment Failure	Pump	Lea (25)
nRM2016059706	Spur Energy Partners LLC	Minor	Private	5/31/20	Produced Water	7	BBL	Equipment Failure	Flow Line - Production	Eddy (15)
nRM2015753993	MEWBOURNE OIL CO	Major	Federal	5/30/20	Produced Water	100	BBL	Equipment Failure	Other (Specify)	Lea (25)
nRM2017141758	CHEVRON U S A INC	Minor	Federal	5/30/20	Produced Water	23	BBL	Human Error	Valve	Eddy (15)
nRM2016949793	COG OPERATING LLC	Minor	State	5/30/20	Produced Water	15	BBL	Corrosion	Flow Line - Production	Lea (25)
nRM2015742721	CIMAREX ENERGY CO. OF COLORADO	Minor	Federal	5/29/20	Produced Water	10	BBL	Corrosion	Other (Specify)	Lea (25)
nRM2015449989	MEWBOURNE OIL CO	Minor	Federal	5/28/20	Produced Water	10	BBL	Equipment Failure	Valve	Lea (25)
nRM2015736485	APACHE CORPORATION	Major	Private	5/28/20	Produced Water	173	BBL	Equipment Failure	Valve	Eddy (15)
nRM2016730091	COG OPERATING LLC	Minor	State	5/27/20	Produced Water	7	BBL	Corrosion	Flow Line - Production	Eddy (15)

nRM2015737274	APACHE CORPORATION	Minor	Private	5/26/20	Produced Water	4	BBL	Equipment Failure	Valve	Lea (25)
nRM2014839790	CIMAREX ENERGY CO.	Minor	State	5/26/20	Produced Water	15	BBL	Corrosion	Pump	Eddy (15)
nRM2014958679	CIMAREX ENERGY CO.	Major	Federal	5/26/20	Produced Water	180	BBL	Corrosion	Other (Specify)	Eddy (15)
nRM2014961908	Grizzly Operating, LLC	Major	Private	5/25/20	Produced Water	49	BBL	Equipment Failure	Valve	Lea (25)
nRM2015542482	OXY USA INC	Minor	Federal	5/24/20	Produced Water	10	BBL	Corrosion	Other (Specify)	Lea (25)
nRM2015743815	CIMAREX ENERGY CO.	Major	Federal	5/24/20	Produced Water	85	BBL	Equipment Failure	Pump	Eddy (15)
nRM2015753153	Spur Energy Partners LLC	Major	Private	5/24/20	Produced Water	40	BBL	Corrosion	Other (Specify)	Eddy (15)
nRM2016146439	DEVON ENERGY PRODUCTION COMPANY, LP	Major	Federal	5/24/20	Produced Water	68	BBL	Corrosion	Flow Line - Production	Lea (25)
nRM2016046152	CONOCOPHILLIPS COMPANY	Minor	Federal	5/22/20	Produced Water	7	BBL	Equipment Failure	Pump	Lea (25)
nRM2018239303	OXY USA INC	Major	Federal	5/22/20	Produced Water	50	BBL	Corrosion	Other (Specify)	Eddy (15)
nRM2016045357	BTA OIL PRODUCERS, LLC	Minor	Federal	5/21/20	Produced Water	16	BBL	Equipment Failure	Valve	Lea (25)
nRM2017030695	OWL SWD OPERATING, LLC	Major	Private	5/21/20	Produced Water	200	BBL	Equipment Failure	Pipeline (Any)	Lea (25)
nRM2014856222	MARATHON OIL PERMIAN LLC	Major	Private	5/21/20	Produced Water	140	BBL	Corrosion	Separator	Eddy (15)
nRM2015755611	COG OPERATING LLC	Minor	Federal	5/20/20	Produced Water	8	BBL	Equipment Failure	Other (Specify)	Lea (25)
nRM2016448841	SIMCOE LLC	Major	State	5/20/20	Produced Water	31	BBL	Human Error	Tank (Any)	San Juan (45)
nRM2015733359	DJR OPERATING, LLC	Minor	Indian	5/19/20	Produced Water	8	BBL	Corrosion	Tank (Any)	Rio Arriba (39)
nRM2014259078	MARATHON OIL PERMIAN LLC	Minor	Federal	5/19/20	Produced Water	20	BBL	Equipment Failure	Other (Specify)	Eddy (15)
nRM2014255492	SOLARIS WATER MIDSTREAM, LLC	Major	Federal	5/18/20	Produced Water	45	BBL	Overflow - Tank, Pit, Etc.	Flow Line - Production	Eddy (15)
nRM2015756964	BTA OIL PRODUCERS, LLC	Major	Federal	5/18/20	Produced Water	276	BBL	Corrosion	Flow Line - Production	Lea (25)
nRM2015757595	COG OPERATING LLC	Minor	Federal	5/17/20	Produced Water	16	BBL	Corrosion	Flow Line - Production	Eddy (15)

nRM2015454866	XTO ENERGY, INC	Major	Federal	5/17/20	Produced Water	35	BBL	Overflow - Tank, Pit, Etc.	Tank (Any)	Eddy (15)
nRM2014052691	WPX Energy Permian, LLC	Major	Federal	5/17/20	Produced Water	160	BBL	Equipment Failure	Flow Line - Production	Eddy (15)
nRM2015546715	OXY USA INC	Major	Federal	5/16/20	Produced Water	50	BBL	Corrosion	Other (Specify)	Eddy (15)
nRM2015553076	OXY USA INC	Minor	Federal	5/15/20	Produced Water	10	BBL	Corrosion	Valve	Eddy (15)
nRM2015059528	XTO ENERGY, INC	Minor	Federal	5/15/20	Produced Water	10	BBL	Equipment Failure	Other (Specify)	Eddy (15)
nRM2014053299	CIMAREX ENERGY CO.	Major	Federal	5/15/20	Produced Water	50	BBL	Equipment Failure	Valve	Lea (25)
nRM2014056076	BTA OIL PRODUCERS, LLC	Major	State	5/15/20	Produced Water	260	BBL	Equipment Failure	Dump Valve	Lea (25)
nRM2014147987	WPX Energy Permian, LLC	Major	Federal	5/14/20	Produced Water	30	BBL	Equipment Failure	Other (Specify)	Eddy (15)
nRM2015439540	MEWBOURNE OIL CO	Major	State	5/13/20	Produced Water	140	BBL	Corrosion	Other (Specify)	Eddy (15)
nRM2015533063	APACHE CORPORATION	Minor	Private	5/13/20	Produced Water	16	BBL	Equipment Failure	Other (Specify)	Lea (25)
nRM2013953582	Spur Energy Partners LLC	Major	Private	5/13/20	Produced Water	42	BBL	Equipment Failure	Valve	Eddy (15)
nRM2014030538	MARATHON OIL PERMIAN LLC	Minor	Federal	5/12/20	Produced Water	12	BBL	Equipment Failure	Flow Line - Injection	Lea (25)
nRM2014056966	CENTENNIAL RESOURCE PRODUCTION, LLC	Major	State	5/12/20	Produced Water	0	BBL	Fire	Other (Specify)	Lea (25)
nRM2013640481	BTA OIL PRODUCERS, LLC	Major	Federal	5/12/20	Produced Water	130	BBL	Equipment Failure	Dump Valve	Lea (25)
nRM2013659360	Spur Energy Partners LLC	Minor	Federal	5/12/20	Produced Water	10	BBL	Corrosion	Water Tank	Eddy (15)
nRM2014755309	GOODNIGHT MIDSTREAM PERMIAN, LLC	Major	State	5/12/20	Produced Water	30	BBL	Equipment Failure	Pump	Lea (25)
nRM2015053388	DEVON ENERGY PRODUCTION COMPANY, LP	Major	Federal	5/12/20	Produced Water	222	BBL	Equipment Failure	Pipeline (Any)	Eddy (15)
nRM2014570121	DEVON ENERGY PRODUCTION COMPANY, LP	Major	Federal	5/11/20	Produced Water	30	BBL	Equipment Failure	Pump	Lea (25)

nRM2013943521	Spur Energy Partners LLC	Minor	Federal	5/11/20	Produced Water	12	BBL	Equipment Failure	Other (Specify)	Eddy (15)
nRM2013931703	Spur Energy Partners LLC		Federal	5/10/20	Produced Water	0	BBL	Corrosion	Flow Line - Production	Eddy (15)
nRM2014569455	DEVON ENERGY PRODUCTION COMPANY, LP	Major	Federal	5/10/20	Produced Water	21	BBL	Equipment Failure	Well	Eddy (15)
nRM2014558079	XTO ENERGY, INC	Minor	Federal	5/10/20	Produced Water	1	BBL	Corrosion	Flow Line - Production	Eddy (15)
nRM2014564602	CONOCOPHILLIPS COMPANY	Major	State	5/10/20	Produced Water	30	BBL	Equipment Failure	Other (Specify)	Lea (25)
nRM2014565278	CONOCOPHILLIPS COMPANY	Major	State	5/9/20	Produced Water	54	BBL	Corrosion	Other (Specify)	Lea (25)
nRM2014567967	COG OPERATING LLC	Minor	State	5/8/20	Produced Water	10	BBL	Equipment Failure	Other (Specify)	Eddy (15)
nRM2013945547	Spur Energy Partners LLC	Major	Private	5/8/20	Produced Water	300	BBL	Human Error	Flow Line - Injection	Eddy (15)
nRM2013949677	Spur Energy Partners LLC	Major	State	5/8/20	Produced Water	23	BBL	Equipment Failure	Pump	Eddy (15)
nRM2013250898	BTA OIL PRODUCERS, LLC	Major	State	5/7/20	Produced Water	650	BBL	Equipment Failure	Pump	Eddy (15)
nRM2013964055	DEVON ENERGY PRODUCTION COMPANY, LP	Minor	Federal	5/7/20	Produced Water	4	BBL	Other	Other (Specify)	Lea (25)
nRM2014262411	XTO ENERGY, INC	Major	Federal	5/7/20	Produced Water	543	BBL	Equipment Failure	Pump	Eddy (15)
nRM2014566661	COG OPERATING LLC	Major	Private	5/6/20	Produced Water	163	BBL	Corrosion	Flow Line - Production	Lea (25)
nRM2015533864	OXY USA INC	Major	Private	5/5/20	Produced Water	145	BBL	Equipment Failure	Other (Specify)	Eddy (15)
nRM2015551293	OXY USA INC	Major	Private	5/5/20	Produced Water	100	BBL	Corrosion	Other (Specify)	Lea (25)
nRM2013950819	Spur Energy Partners LLC	Minor	Private	5/5/20	Produced Water	23	BBL	Corrosion	Pump	Eddy (15)
nRM2014332937	DEVON ENERGY PRODUCTION COMPANY, LP	Major	Federal	5/4/20	Produced Water	84	BBL	Other	Pump	Eddy (15)
nRM2014048215	XTO ENERGY, INC	Minor	Federal	5/4/20	Produced Water	20	BBL	Corrosion	Tank (Any)	Eddy (15)

nRM2013250166	APACHE CORPORATION	Minor	Private	5/4/20	Produced Water	10	BBL	Equipment Failure	Other (Specify)	Lea (25)
nRM2015531569	OXY USA INC	Major	Private	5/4/20	Produced Water	120	BBL	Equipment Failure	Flow Line - Production	Eddy (15)
nRM2012930770	MATADOR PRODUCTION COMPANY	Major	Federal	5/3/20	Produced Water	58	BBL	Equipment Failure	Pump	Eddy (15)
nRM2013660346	XTO ENERGY, INC	Minor	State	5/2/20	Produced Water	8	BBL	Vehicular Accident	Flow Line - Production	Eddy (15)
nRM2013952120	Spur Energy Partners LLC		Federal	5/1/20	Produced Water	10	GAL	Corrosion	Flow Line - Production	Eddy (15)
nRM2013960463	DEVON ENERGY PRODUCTION COMPANY, LP	Minor	Federal	5/1/20	Produced Water	7	BBL	Corrosion	Other (Specify)	Eddy (15)
nRM2013358062	CONOCOPHILLIPS COMPANY	Minor	Federal	4/30/20	Produced Water	8	BBL	Corrosion	Valve	Lea (25)
nRM2013955347	DEVON ENERGY PRODUCTION COMPANY, LP	Minor	Federal	4/29/20	Produced Water	8	BBL	Corrosion	Pump	Eddy (15)
nRM2014059324	DEVON ENERGY PRODUCTION COMPANY, LP	Major	Federal	4/29/20	Produced Water	206	BBL	Vehicular Accident	Other (Specify)	Lea (25)
nRM2012169218	MATADOR PRODUCTION COMPANY	Major	State	4/28/20	Produced Water	117	BBL	Corrosion	Other (Specify)	Lea (25)
nRM2012240751	MARATHON OIL PERMIAN LLC	Minor	Private	4/28/20	Produced Water	13	BBL	Equipment Failure	Pipeline (Any)	Eddy (15)
nRM2015541340	OXY USA INC	Major	Private	4/27/20	Produced Water	50	BBL	Equipment Failure	Gasket	Lea (25)
nRM2012239937	MARATHON OIL PERMIAN LLC	Minor	Private	4/26/20	Produced Water	10	BBL	Equipment Failure	Tank (Any)	Lea (25)
nRM2012238948	MARATHON OIL PERMIAN LLC	Major	Federal	4/25/20	Produced Water	46	BBL	Equipment Failure	Other (Specify)	Lea (25)
nRM2012242719	DEVON ENERGY PRODUCTION COMPANY, LP	Minor	Federal	4/24/20	Produced Water	6	BBL	Equipment Failure	Pump	Lea (25)
nRM2012535502	CENTENNIAL RESOURCE PRODUCTION, LLC	Major	Private	4/24/20	Produced Water	54	BBL	Equipment Failure	Dump Valve	Lea (25)
nRM2012747223	COG OPERATING LLC	Minor	State	4/24/20	Produced Water	6	BBL	Corrosion	Tank (Any)	Lea (25)

nRM2012853960	FOUNDATION ENERGY MANAGEMENT, LLC	Major	State	4/24/20	Produced Water	178	BBL	Corrosion	Tank (Any)	Lea (25)
nRM2012229921	XTO ENERGY, INC	Minor	Federal	4/22/20	Produced Water	16	BBL	Equipment Failure	Separator	Eddy (15)
nRM2011334979	SOLARIS WATER MIDSTREAM, LLC	Major	Federal	4/20/20	Produced Water	342	BBL	Equipment Failure	Pump	Eddy (15)
nRM2012827824	COG OPERATING LLC	Minor	Federal	4/20/20	Produced Water	20	BBL	Corrosion	Tank (Any)	Lea (25)
nRM2011948951	COG OPERATING LLC	Minor	Federal	4/18/20	Produced Water	10	BBL	Corrosion	Other (Specify)	Eddy (15)
nRM2012235693	COG OPERATING LLC	Minor	Federal	4/18/20	Produced Water	4	BBL	Corrosion	Flow Line - Production	Lea (25)
nRM2012229165	XTO ENERGY, INC	Minor	State	4/17/20	Produced Water	5	BBL	Overflow - Tank, Pit, Etc.	Tank (Any)	Eddy (15)
nRM2012234129	CIMAREX ENERGY CO. OF COLORADO	Minor	State	4/16/20	Produced Water	14	BBL	Human Error	Well	Eddy (15)
nRM2015535581	OXY USA INC	Major	State	4/16/20	Produced Water	27	BBL	Corrosion	Tank (Any)	Eddy (15)
nRM2015552273	OXY USA INC	Major	Federal	4/16/20	Produced Water	375	BBL	Equipment Failure	Dump Valve	Eddy (15)
nRM2012051816	WPX Energy Permian, LLC	Major	Federal	4/15/20	Produced Water	30	BBL	Equipment Failure	Other (Specify)	Eddy (15)
nRM2012166326	BP AMERICA PRODUCTION COMPANY	Minor	Federal	4/14/20	Produced Water	22	BBL	Corrosion	Pipeline (Any)	San Juan (45)
nRM2012232928	COG OPERATING LLC	Minor	State	4/14/20	Produced Water	19	BBL	Corrosion	Flow Line - Production	Lea (25)
nRM2011557540	DUGAN PRODUCTION CORP	Minor	State	4/14/20	Produced Water	19	BBL	Corrosion	Pipeline (Any)	San Juan (45)
nRM2011138650	WPX Energy Permian, LLC	Minor	Federal	4/14/20	Produced Water	10	BBL	Equipment Failure	Tank (Any)	Eddy (15)
nRM2010634337	Spur Energy Partners LLC	Minor	Federal	4/13/20	Produced Water	17	BBL	Other	Other (Specify)	Eddy (15)
nRM2012548982	OXY USA INC	Major	Federal	4/12/20	Produced Water	1500	BBL	Equipment Failure	Gasket	Eddy (15)
nRM2010836658	HILCORP ENERGY COMPANY	Minor	Private	4/10/20	Produced Water	6	BBL	Corrosion	Tank (Any)	San Juan (45)
nRM2011435695	DEVON ENERGY PRODUCTION COMPANY, LP	Minor	State	4/10/20	Produced Water	6	BBL	Equipment Failure	Water Tank	Eddy (15)
nRM2011559899	XTO ENERGY, INC	Minor	Federal	4/10/20	Produced Water	6	BBL	Human Error	Other (Specify)	Eddy (15)

nRM2011535196	XTO ENERGY, INC	Minor	Federal	4/9/20	Produced Water	10	BBL	Other	Fitting	Eddy (15)
nRM2010158449	CIMAREX ENERGY CO. OF COLORADO	Major	Federal	4/8/20	Produced Water	28	BBL	Corrosion	Water Tank	Lea (25)
nRM2011445697	XTO ENERGY, INC	Minor	Federal	4/7/20	Produced Water	10	BBL	Corrosion	Pump	Eddy (15)
nRM2010834974	APACHE CORPORATION	Major	Private	4/7/20	Produced Water	119	BBL	Equipment Failure	Valve	Lea (25)
nRM2010648431	OWL SWD OPERATING, LLC	Major	Federal	4/6/20	Produced Water	1280	BBL	Corrosion	Flow Line - Production	Lea (25)
nRM2010659709	DEVON ENERGY PRODUCTION COMPANY, LP	Major	Federal	4/6/20	Produced Water	110	BBL	Equipment Failure	Pump	Lea (25)
nRM2011140918	COG OPERATING LLC	Minor	State	4/4/20	Produced Water	10	BBL	Corrosion	Tank (Any)	Lea (25)
nRM2010649724	DEVON ENERGY PRODUCTION COMPANY, LP	Major	Federal	4/3/20	Produced Water	89	BBL	Corrosion	Valve	Eddy (15)
nRM2010632321	Spur Energy Partners LLC	Major	Federal	4/3/20	Produced Water	70	BBL	Equipment Failure	Valve	Eddy (15)
nRM2009842331	SOLARIS WATER MIDSTREAM, LLC	Major	Private	4/3/20	Produced Water	69	BBL	Human Error	Pipeline (Any)	Lea (25)
nRM2009840225	BXP Operating, LLC	Minor	State	4/2/20	Produced Water	10	BBL	Corrosion	Pipeline (Any)	Lea (25)
nRM2010853797	XTO ENERGY, INC	Major	Federal	4/2/20	Produced Water	26	BBL	Equipment Failure	Valve	Eddy (15)
nRM2010731078	COG OPERATING LLC	Minor	Federal	3/31/20	Produced Water	15	BBL	Corrosion	Flow Line - Production	Eddy (15)
nRM2009747391	CIMAREX ENERGY CO. OF COLORADO	Major	Federal	3/31/20	Produced Water	55	BBL	Equipment Failure	Tank (Any)	Eddy (15)
nRM2009830410	BXP Operating, LLC	Minor	State	3/30/20	Produced Water	5	BBL	Equipment Failure	Pump	Lea (25)
nRM2010059368	Catena Resources Operating, LLC	Major	State	3/30/20	Produced Water	32	BBL	Human Error	Tank (Any)	Lea (25)
nRM2012539093	OXY USA INC	Major	Federal	3/30/20	Produced Water	31	BBL	Human Error	Frac Tank	Lea (25)
nRM2012859198	ADVANCE ENERGY PARTNERS HAT MESA, LLC	Minor	Private	3/30/20	Produced Water	18	BBL	Equipment Failure	Flow Line - Production	Lea (25)
nRM2010143902	XTO ENERGY, INC	Major	State	3/28/20	Produced Water	40	BBL	Other	Tank (Any)	Eddy (15)
nRM2010150294	XTO ENERGY, INC	Major	State	3/28/20	Produced Water	32	BBL	Corrosion	Other (Specify)	Lea (25)

nRM2009066157	MARATHON OIL PERMIAN LLC	Major	Federal	3/28/20	Produced Water	26	BBL	Other	Flow Line - Production	Lea (25)
nRM2009056532	MARATHON OIL PERMIAN LLC	Minor	State	3/28/20	Produced Water	13	BBL	Corrosion	Water Tank	Eddy (15)
nRM2009059361	MARATHON OIL PERMIAN LLC	Major	State	3/28/20	Produced Water	31	BBL	Equipment Failure	Pump	Eddy (15)
nRM2009054594	Spur Energy Partners LLC	Major	Private	3/27/20	Produced Water	93	BBL	Overflow - Tank, Pit, Etc.	Tank (Any)	Eddy (15)
nRM2009734927	CIMAREX ENERGY CO. OF COLORADO	Minor	Federal	3/27/20	Produced Water	20	BBL	Human Error	Other (Specify)	Lea (25)
nRM2009745985	CIMAREX ENERGY CO. OF COLORADO	Major	Federal	3/26/20	Produced Water	32	BBL	Corrosion	Valve	Eddy (15)
nRM2009256692	CIMAREX ENERGY CO.	Major	Federal	3/26/20	Produced Water	360	BBL	Equipment Failure	Pump	Lea (25)
nRM2009253961	CIMAREX ENERGY CO.	Major	State	3/26/20	Produced Water	41	BBL	Corrosion	Tank (Any)	Eddy (15)
nRM2008733329	DEVON ENERGY PRODUCTION COMPANY, LP	Major	State	3/26/20	Produced Water	72	BBL	Equipment Failure	Other (Specify)	Eddy (15)
nRM2009032079	MATADOR PRODUCTION COMPANY	Minor	Federal	3/25/20	Produced Water	20	BBL	Equipment Failure	Other (Specify)	Eddy (15)
nRM2012547984	OXY USA INC	Major	Private	3/24/20	Produced Water	60	BBL	Equipment Failure	Flow Line - Injection	Lea (25)
nRM2009841041	XTO ENERGY, INC	Major	State	3/23/20	Produced Water	198	BBL	Equipment Failure	Flow Line - Production	Eddy (15)
nRM2009255828	CIMAREX ENERGY CO.	Major	Federal	3/22/20	Produced Water	175	BBL	Other	Other (Specify)	Eddy (15)
nRM2008658076	APACHE CORPORATION	Major	Private	3/22/20	Produced Water	120	BBL	Corrosion	Other (Specify)	Lea (25)
nRM2012543729	OXY USA INC	Major	Private	3/20/20	Produced Water	69	BBL	Corrosion	Other (Specify)	Eddy (15)
nRM2014959813	Fluid Delivery Solutions, LLC	Major	State	3/20/20	Produced Water	133	BBL	Equipment Failure	Gasket	Lea (25)
nRM2008551917	Spur Energy Partners LLC	Minor	Federal	3/18/20	Produced Water	8	BBL	Corrosion	Flow Line - Production	Eddy (15)
nRM2007947298	RIDGEWAY ARIZONA OIL CORP.	Major	Private	3/16/20	Produced Water	80	BBL	Corrosion	Water Tank	Roosevelt (41)
nRM2007952227	CONOCOPHILLIPS CO.	Minor	Federal	3/16/20	Produced Water	7	BBL	Corrosion	Valve	Eddy (15)

nRM2008052559	DEVON ENERGY PRODUCTION COMPANY, LP	Minor	Federal	3/16/20	Produced Water	22	BBL	Corrosion	Pump	Eddy (15)
nRM2008348428	CONOCOPHILLIPS COMPANY	Major	State	3/16/20	Produced Water	135	BBL	Equipment Failure	Flow Line - Production	Lea (25)
nRM2010843574	CHEVRON U S A INC	Minor	Federal	3/16/20	Produced Water	4	BBL	Equipment Failure	Valve	Lea (25)
nRM2008045508	DEVON ENERGY PRODUCTION COMPANY, LP	Major	Federal	3/13/20	Produced Water	58	BBL	Corrosion	Other (Specify)	Lea (25)
nRM2008631179	Franklin Mountain Energy LLC	Major	State	3/13/20	Produced Water	150	BBL	Corrosion	Pipeline (Any)	Lea (25)
nRM2008635903	XTO ENERGY, INC	Minor	State	3/12/20	Produced Water	7	BBL	Corrosion	Tank (Any)	Eddy (15)
nRM2008555443	WPX Energy Permian, LLC	Major	Federal	3/12/20	Produced Water	175	BBL	Human Error	Other (Specify)	Eddy (15)
nRM2008459060	NNOGC EXPLORATION AND PRODUCTION, LLC	Minor	Navajo	3/12/20	Produced Water	7	BBL	Other	Flow Line - Production	San Juan (45)
nRM2008543296	Spur Energy Partners LLC	Minor	Federal	3/11/20	Produced Water	12	BBL	Equipment Failure	Other (Specify)	Eddy (15)
nRM2008641847	COG OPERATING LLC	Major	Federal	3/11/20	Produced Water	210	BBL	Equipment Failure	Pump	Eddy (15)
nRM2008756964	SELECT ENERGY SERVICES, LLC	Major	State	3/11/20	Produced Water	2160	BBL	Human Error	Flow Line - Production	Lea (25)
nRM2007857235	CIMAREX ENERGY CO.	Major	State	3/10/20	Produced Water	323	BBL	Equipment Failure	Valve	Eddy (15)
nRM2008651744	COG OPERATING LLC	Major	Private	3/9/20	Produced Water	30	BBL	Corrosion	Other (Specify)	Lea (25)
nRM2012536459	OXY USA INC	Minor	Federal	3/9/20	Produced Water	8	BBL	Corrosion	Other (Specify)	Eddy (15)
nRM2007957117	BP AMERICA PRODUCTION COMPANY	Major	Federal	3/8/20	Produced Water	120	BBL	Equipment Failure	Pipeline (Any)	San Juan (45)
nRM2007953992	Spur Energy Partners LLC	Major	Federal	3/7/20	Produced Water	30	BBL	Human Error	Tank (Any)	Eddy (15)
nRM2008460163	XTO ENERGY, INC	Minor	Federal	3/5/20	Produced Water	10	BBL	Human Error	Tank (Any)	Eddy (15)
nRM2008461126	XTO ENERGY, INC	Minor	Federal	3/5/20	Produced Water	10	BBL	Human Error	Tank (Any)	Eddy (15)
nRM2007959815	BP AMERICA PRODUCTION COMPANY	Minor	Federal	3/4/20	Produced Water	11	BBL	Corrosion	Other (Specify)	San Juan (45)
nRM2008341796	BP AMERICA PRODUCTION COMPANY	Minor	Federal	3/4/20	Produced Water	11	BBL	Corrosion	Other (Specify)	San Juan (45)
nRM2006560641	HILCORP ENERGY COMPANY	Major	Federal	3/4/20	Produced Water	10	BBL	Freeze	Valve	Rio Arriba (39)

nRM2008344774	BP AMERICA PRODUCTION COMPANY	Minor	Federal	3/3/20	Produced Water	7	BBL	Corrosion	Other (Specify)	San Juan (45)
nRM2009061396	CHEVRON U S A INC	Minor	Federal	3/3/20	Produced Water	6	BBL	Equipment Failure	Pump	Eddy (15)
nRM2007937583	ETC Texas Pipeline, Ltd.	Minor	Federal	3/2/20	Produced Water	3	BBL	Corrosion	Pipeline (Any)	Lea (25)
nRM2006559088	DJR OPERATING, LLC	Major	Indian	3/2/20	Produced Water	35	BBL	Other	Pipeline (Any)	Rio Arriba (39)
nRM2007843906	CIMAREX ENERGY CO.	Major	Federal	3/2/20	Produced Water	30	BBL	Equipment Failure	Pump	Lea (25)
nRM2007849006	CIMAREX ENERGY CO.	Major	Federal	3/1/20	Produced Water	181	BBL	Corrosion	Tank (Any)	Eddy (15)
nRM2007859922	XTO ENERGY, INC	Minor	Federal	3/1/20	Produced Water	7	BBL	Equipment Failure	Other (Specify)	Eddy (15)
nRM2006661276	Wapiti Operating, LLC	Major	Private	3/1/20	Produced Water	192	BBL	Freeze	Flow Line - Production	Colfax (07)
nRM2009062305	CHEVRON U S A INC	Minor	State	3/1/20	Produced Water	9	BBL	Corrosion	Other (Specify)	Eddy (15)
nRM2009064906	CHEVRON U S A INC	Major	Federal	3/1/20	Produced Water	24	BBL	Equipment Failure	Flow Line - Production	Lea (25)
nRM2011949780	CHEVRON U S A INC	Major	State	3/1/20	Produced Water	73	BBL	Equipment Failure	Flow Line - Injection	Lea (25)
nRM2007254419	XTO ENERGY, INC	Minor	State	2/29/20	Produced Water	5	BBL	Equipment Failure	Flow Line - Production	Eddy (15)
nRM2006956859	WPX Energy Permian, LLC	Minor	Federal	2/28/20	Produced Water	13	BBL	Human Error	Other (Specify)	Eddy (15)
nRM2008456960	OXY USA INC	Minor	Federal	2/28/20	Produced Water	20	BBL	Corrosion	Flow Line - Production	Eddy (15)
nRM2006956155	SUNDOWN ENERGY LP	Minor	State	2/27/20	Produced Water	20	BBL	Freeze	Flow Line - Production	Lea (25)
nRM2007037866	CONOCOPHILLIPS COMPANY	Minor	Private	2/27/20	Produced Water	17	BBL	Other	Flow Line - Production	Lea (25)
nRM2005959104	DEVON ENERGY PRODUCTION COMPANY, LP	Major	Federal	2/26/20	Produced Water	40	BBL	Corrosion	Dump Line	Lea (25)
nRM2006341765	MARATHON OIL PERMIAN LLC	Major	Private	2/26/20	Produced Water	60	BBL	Corrosion	Flow Line - Injection	Eddy (15)
nRM2005653696	DEVON ENERGY PRODUCTION COMPANY, LP	Major	Federal	2/24/20	Produced Water	21	BBL	Equipment Failure	Well	Lea (25)

nRM2007031081	DEVON ENERGY PRODUCTION COMPANY, LP	Major	Federal	2/24/20	Produced Water	30	BBL	Other	Well	Eddy (15)
nRM2005941614	APACHE CORPORATION	Major	Private	2/24/20	Produced Water	110	BBL	Equipment Failure	Tank (Any)	Lea (25)
nRM2005560297	SOLARIS WATER MIDSTREAM, LLC	Major	Federal	2/22/20	Produced Water	52	BBL	Human Error	Pump	Eddy (15)
nRM2006457917	XTO ENERGY, INC	Minor	State	2/20/20	Produced Water	16	BBL	Corrosion	Other (Specify)	Eddy (15)
nRM2006453458	CHEVRON U S A INC	Major	Federal	2/19/20	Produced Water	138	BBL	Corrosion	Other (Specify)	Lea (25)
nRM2008458177	OXY USA INC	Minor	Federal	2/19/20	Produced Water	18	BBL	Equipment Failure	Valve	Lea (25)
nRM2005656589	DEVON ENERGY PRODUCTION COMPANY, LP	Major	Federal	2/19/20	Produced Water	40	BBL	Other	Tank (Any)	Eddy (15)
nRM2005838212	MARATHON OIL PERMIAN LLC	Minor	Private	2/18/20	Produced Water	15	BBL	Corrosion	Separator	Eddy (15)
nRM2005549668	CIMAREX ENERGY CO.	Minor	Federal	2/18/20	Produced Water	10	BBL	Equipment Failure	Valve	Eddy (15)
nRM2006432204	XTO ENERGY, INC	Minor	Federal	2/18/20	Produced Water	5	BBL	Human Error	Valve	Eddy (15)
nRM2009935289	OXY USA INC	Major		2/18/20	Produced Water	140	BBL	Equipment Failure	Pump	Lea (25)
nRM2005736272	COG OPERATING LLC	Minor	Federal	2/17/20	Produced Water	8	BBL	Equipment Failure	Gasket	Lea (25)
nRM2006430999	CIMAREX ENERGY CO.	Major	State	2/16/20	Produced Water	30	BBL	Corrosion	Tank (Any)	Lea (25)
nRM2006336502	COG OPERATING LLC	Minor	Federal	2/16/20	Produced Water	10	BBL	Corrosion	Flow Line - Production	Eddy (15)
nRM2005558733	APACHE CORPORATION	Major	State	2/15/20	Produced Water	735	BBL	Equipment Failure	Flow Line - Injection	Lea (25)
nRM2004549559	BTA OIL PRODUCERS, LLC	Major	Federal	2/12/20	Produced Water	21	BBL	Freeze	Valve	Lea (25)
nRM2008455073	OXY USA INC	Minor	Federal	2/12/20	Produced Water	7	BBL	Other	Pump	Eddy (15)
nRM2005230899	Wapiti Operating, LLC	Major	Private	2/11/20	Produced Water	356	BBL	Freeze	Pipeline (Any)	Colfax (07)
nRM2004841653	MARATHON OIL PERMIAN LLC	Minor	Federal	2/10/20	Produced Water	22	BBL	Corrosion	Flow Line - Production	Lea (25)
nRM2004350563	CHEVRON U S A INC	Minor	State	2/10/20	Produced Water	3	BBL	Equipment Failure	Other (Specify)	Eddy (15)
nRM2004557969	Grizzly Operating, LLC	Minor	State	2/9/20	Produced Water	11	BBL	Human Error	Valve	Eddy (15)

nRM2005154141	COG OPERATING LLC	Major	State	2/9/20	Produced Water	89	BBL	Overflow - Tank, Pit, Etc.	Tank (Any)	Lea (25)
nRM2004550944	Grizzly Operating, LLC	Minor		2/8/20	Produced Water	15	BBL	Other	Pump	Eddy (15)
nRM2004436043	MEWBOURNE OIL CO	Minor	State	2/8/20	Produced Water	20	BBL	Other	Other (Specify)	Eddy (15)
nRM2004352168	CIMAREX ENERGY CO. OF COLORADO	Major	Federal	2/7/20	Produced Water	82	BBL	Equipment Failure	Tank (Any)	Eddy (15)
nRM2005259001	HILCORP ENERGY COMPANY	Major	Federal	2/7/20	Produced Water	210	BBL	Equipment Failure	Pump	San Juan (45)
nRM2004537466	APACHE CORPORATION	Minor	State	2/7/20	Produced Water	6	BBL	Freeze	Valve	Lea (25)
nRM2005650487	CIMAREX ENERGY CO.	Major	State	2/7/20	Produced Water	40	BBL	Freeze	Valve	Lea (25)
nRM2004833416	Spur Energy Partners LLC	Minor	Federal	2/6/20	Produced Water	7	BBL	Equipment Failure	Pump	Eddy (15)
nRM2004156228	DJR OPERATING, LLC	Major	Federal	2/6/20	Produced Water	70	BBL	Equipment Failure	Tank (Any)	Sandoval (43)
nRM2004438802	OXY USA INC	Major	Federal	2/4/20	Produced Water	160	BBL	Equipment Failure	Pump	Eddy (15)
nRM2004956954	XTO ENERGY, INC	Major	State	2/3/20	Produced Water	471	BBL	Human Error	Well	Eddy (15)
nRM2004149681	DEVON ENERGY PRODUCTION COMPANY, LP	Minor	Federal	2/3/20	Produced Water	5	BBL	Corrosion	Flow Line - Production	Eddy (15)
nRM2003750457	CIMAREX ENERGY CO.	Major	Federal	2/2/20	Produced Water	40	BBL	Equipment Failure	Other (Specify)	Eddy (15)
nRM2005030364	OXY USA INC	Major	Federal	2/2/20	Produced Water	450	BBL	Other	Other (Specify)	Eddy (15)
nRM2004840589	MARATHON OIL PERMIAN LLC	Major	Private	2/2/20	Produced Water	60	BBL	Corrosion	Tank (Any)	Eddy (15)
nRM2004837732	XTO ENERGY, INC	Minor	State	2/1/20	Produced Water	15	BBL	Human Error	Valve	Eddy (15)
nRM2004834379	EOG RESOURCES INC	Minor	Private	1/31/20	Produced Water	10	BBL	Equipment Failure	Tank (Any)	Eddy (15)
nRM2003745665	ADVANCE ENERGY PARTNERS HAT MESA, LLC	Minor	State	1/31/20	Produced Water	22	BBL	Equipment Failure	Coupling	Lea (25)
nRM2004836746	XTO ENERGY, INC		State	1/30/20	Produced Water	0	BBL	Equipment Failure	Pipeline (Any)	Eddy (15)
nRM2004458711	CONOCOPHILLIPS COMPANY	Minor	Federal	1/29/20	Produced Water	4	BBL	Equipment Failure	Tank (Any)	Lea (25)
nRM2004460443	XTO ENERGY, INC	Minor	Federal	1/29/20	Produced Water	12	BBL	Human Error	Valve	Eddy (15)

nRM2004437525	OXY USA INC	Minor	Federal	1/29/20	Produced Water	4	BBL	Other	Well	Eddy (15)
nRM2004445859	XTO ENERGY, INC	Minor	Federal	1/28/20	Produced Water	11	BBL	Other	Well	Eddy (15)
nRM2004446696	XTO ENERGY, INC	Major	Federal	1/28/20	Produced Water	140	BBL	Equipment Failure	Other (Specify)	Eddy (15)
nRM2004838884	MARATHON OIL PERMIAN LLC	Major	Private	1/27/20	Produced Water	30	BBL	Equipment Failure	Pump	Eddy (15)
nRM2004839548	MARATHON OIL PERMIAN LLC	Minor	Federal	1/27/20	Produced Water	15	BBL	Equipment Failure	Tank (Any)	Eddy (15)
nRM2004351427	CHEVRON U S A INC	Major	State	1/24/20	Produced Water	4	BBL	Other	Other (Specify)	Lea (25)
nRM2003860041	DEVON ENERGY PRODUCTION COMPANY, LP	Major	Federal	1/24/20	Produced Water	48	BBL	Corrosion	Flow Line - Production	Lea (25)
nRM2003757362	MATADOR PRODUCTION COMPANY	Major	State	1/24/20	Produced Water	41	BBL	Human Error	Other (Specify)	Lea (25)
nRM2008758101	MATADOR PRODUCTION COMPANY	Minor	State	1/24/20	Produced Water	17	BBL	Equipment Failure	Flow Line - Production	Eddy (15)
nRM2004353184	DEVON ENERGY PRODUCTION COMPANY, LP	Minor	Federal	1/23/20	Produced Water	18	BBL	Corrosion	Valve	Lea (25)
nCE2003555083	Spur Energy Partners LLC	Minor	State	1/23/20	Produced Water	20	BBL	Equipment Failure	Production Tank	Eddy (15)
nCE2003556136	DEVON ENERGY PRODUCTION COMPANY, LP	Major	Federal	1/23/20	Produced Water	780	BBL	Equipment Failure	Valve	Lea (25)
nVV2003154113	CIMAREX ENERGY CO. OF COLORADO	Minor	Federal	1/23/20	Produced Water	13	BBL	Equipment Failure	Other (Specify)	Lea (25)
nCE2003652970	MATADOR PRODUCTION COMPANY	Major	Private	1/22/20	Produced Water	31	BBL	Equipment Failure	Pump	Eddy (15)
nCE2003552253	CHISHOLM ENERGY OPERATING, LLC	Major	Federal	1/22/20	Produced Water	50	BBL	Equipment Failure	Pipeline (Any)	Eddy (15)
nRM2003759623	KAISER-FRANCIS OIL CO	Minor	Private	1/22/20	Produced Water	24	BBL	Human Error	Pipeline (Any)	Eddy (15)
nRM2003848171	COG OPERATING LLC	Major	Private	1/22/20	Produced Water	10	BBL	Other	Other (Specify)	Lea (25)
nRM2003744725	CONOCOPHILLIPS COMPANY	Minor	Private	1/21/20	Produced Water	8	BBL	Corrosion	Flow Line - Production	Lea (25)
nVV2003433576	WPX Energy Permian, LLC	Major	Private	1/21/20	Produced Water	140	BBL	Equipment Failure	Pump	Eddy (15)

nVV2003029246	WPX Energy Permian, LLC		Private	1/21/20	Produced Water	0	BBL	Equipment Failure	Flow Line - Production	Eddy (15)
nCE2003754052	STEPHENS & JOHNSON OP CO	Minor	Private	1/20/20	Produced Water	15	BBL	Equipment Failure	Pipeline (Any)	Eddy (15)
nVV2003151969	CIMAREX ENERGY CO.	Major	Federal	1/19/20	Produced Water	30	BBL	Equipment Failure	Dump Valve	Eddy (15)
nRM2005137772	SOLARIS WATER MIDSTREAM, LLC	Major	Federal	1/18/20	Produced Water	148	BBL	Equipment Failure	Valve	Eddy (15)
nCE2003749394	MARATHON OIL PERMIAN LLC	Major	Private	1/17/20	Produced Water	60	BBL	Equipment Failure	Pipeline (Any)	Lea (25)
nCE2003651156	HILCORP ENERGY COMPANY	Minor	Private	1/17/20	Produced Water	8	BBL	Freeze	Pipeline (Any)	San Juan (45)
nCE2003757811	HILCORP ENERGY COMPANY	Major	Federal	1/16/20	Produced Water	12	BBL	Freeze	Pipeline (Any)	Rio Arriba (39)
nCE2003739901	MARATHON OIL PERMIAN LLC	Minor	State	1/16/20	Produced Water	7	BBL	Equipment Failure	Separator	Eddy (15)
nRM2004158967	HILCORP ENERGY COMPANY	Minor	Indian	1/16/20	Produced Water	4	BBL	Corrosion	Production Tank	Rio Arriba (39)
nCE2003738053	MARATHON OIL PERMIAN LLC	Minor	Private	1/15/20	Produced Water	10	BBL	Equipment Failure	Pump	Lea (25)
nCE2003739249	MARATHON OIL PERMIAN LLC	Major	Private	1/15/20	Produced Water	29	BBL	Equipment Failure	Well	Lea (25)
nCE2003553560	Spur Energy Partners LLC	Minor	Federal	1/15/20	Produced Water	8	BBL	Equipment Failure	Pipeline (Any)	Eddy (15)
nVV2003149447	CAZA OPERATING, LLC	Major	State	1/14/20	Produced Water	500	BBL	Equipment Failure	Pump	Eddy (15)
nVV2002829022	WPX Energy Permian, LLC	Minor	State	1/14/20	Produced Water	8	BBL	Equipment Failure	Well	Eddy (15)
nRM2008360715	OXY USA INC	Major	Private	1/13/20	Produced Water	56	BBL	Corrosion	Valve	Harding (21)
nRM2004358654	AMEREDEV OPERATING, LLC	Major	Private	1/12/20	Produced Water	146	BBL	Human Error	Flow Line - Production	Lea (25)
nVV2002831233	WPX Energy Permian, LLC	Major	Federal	1/12/20	Produced Water	20	BBL	Equipment Failure	Flow Line - Production	Eddy (15)
nVV2003435771	XTO ENERGY, INC	Major	Federal	1/12/20	Produced Water	777	BBL	Equipment Failure	Flow Line - Injection	Eddy (15)

nCE2003550956	OXY USA INC	Minor	Federal	1/11/20	Produced Water	10	BBL	Overflow - Tank, Pit, Etc.	Tank (Any)	Eddy (15)
nCE2003757295	CIMAREX ENERGY CO.	Minor	Federal	1/10/20	Produced Water	8	BBL	Equipment Failure	Pump	Eddy (15)
nCE2003542701	CONOCOPHILLIPS COMPANY	Major	State	1/10/20	Produced Water	56	BBL	Blow Out	Pipeline (Any)	Lea (25)
nRM2008547914	Spur Energy Partners LLC	Minor	Private	1/10/20	Produced Water	22	BBL	Corrosion	Tank (Any)	Eddy (15)
nVV2003548643	CONOCOPHILLIPS COMPANY	Major	State	1/10/20	Produced Water	56	BBL	Equipment Failure	Flow Line - Injection	Lea (25)
nVV2003550444	OXY USA INC	Minor	Federal	1/10/20	Produced Water	18	BBL	Equipment Failure	Valve	Lea (25)
nVV2003730081	COG OPERATING LLC	Major	State	1/10/20	Produced Water	85	BBL	Equipment Failure	Other (Specify)	Eddy (15)
nVV2003155809	XTO ENERGY, INC	Major	State	1/9/20	Produced Water	45	BBL	Corrosion	Coupling	Eddy (15)
nCE2003540506	ADVANCE ENERGY PARTNERS HAT MESA, LLC	Major	State	1/8/20	Produced Water	52	BBL	Equipment Failure	Pipeline (Any)	Lea (25)
nRM2003552129	ENTERPRISE FIELD SERVICES L.L.C.	Minor	Indian	1/8/20	Produced Water	10	BBL	Other	Pipeline (Any)	San Juan (45)
nRM2008755249	Blue Quail Energy Services, LLC	Major	Private	1/6/20	Produced Water	300	BBL	Equipment Failure	Other (Specify)	Eddy (15)
nRM2014359631	DEVON ENERGY PRODUCTION COMPANY, LP	Minor	Federal	1/6/20	Produced Water	11	BBL	Equipment Failure	Other (Specify)	Lea (25)
nRM2014240786	DEVON ENERGY PRODUCTION COMPANY, LP	Minor	Federal	1/6/20	Produced Water	11	BBL	Equipment Failure	Other (Specify)	Lea (25)
nVV2002439696	WPX Energy Permian, LLC	Major	Federal	1/6/20	Produced Water	25	BBL	Equipment Failure	Well	Eddy (15)
nVV2003542379	XTO ENERGY, INC	Minor	State	1/5/20	Produced Water	1	BBL	Equipment Failure	Other (Specify)	Eddy (15)
nCS2003153919	WPX Energy Permian, LLC	Minor	State	1/3/20	Produced Water	10	BBL	Equipment Failure	Pipeline (Any)	Eddy (15)
nRH2003532478	CONOCOPHILLIPS COMPANY	Major	State	1/2/20	Produced Water	54	BBL	Corrosion	Pipeline (Any)	Lea (25)
nVV2003150585	OXY USA INC	Major	State	1/2/20	Produced Water	3	BBL	Equipment Failure	Gasket	Lea (25)

| nVV2002832621 | XTO ENERGY, INC | Major | State | 1/1/20 | Produced Water | 31 | BBL | Equipment Failure | Valve | Eddy (15) |

WildEarth Guardians Exhibit 10

K. Chamberlain, 'It was Raining on Us': Family Awoken By Produced Water Pipe Burst Near Carlsbad, NM Political Report (Jan. 24, 2020), available at: https://nmpoliticalreport.com/2020/01/24/it-was-raining-on-us-family-awoken-by-produced-water-pipe-burst-near-carlsbad/.

ENVIRONMENTAL PROJECT   January 24, 2020

'It was raining on us': Family awoken by produced water pipe burst near Carlsbad

By **Kendra Chamberlain**

Penny Aucoin

A pipe that transports produced water from an oil pad to a saltwater disposal well burst early Tuesday. This photo, taken by Penny Aucoin, shows the wastewater spewing into the air.

Penny Aucoin and her husband Carl George were awoken in the early hours of Tuesday morning by the sound of a loud pop and gushing water.

"We went out and it was dark at 2:30 in the morning. But when we walked outside we were getting rained on and it smelled like gas — it smelled strongly of gas," Aucoin said as she recounted the events of the night to *NM Political Report*. "I said, 'Honey, where's it coming from?' And he was like, 'I don't know!' So he was using his flashlight on his phone trying to figure out where it was coming from."

The "rain," it turned out, was produced water, a fluid byproduct of oil and gas extraction activities, spewing from a broken pipe across the street. The water pressure was so high in the pipe that the produced water rained down on the family's home, livestock and yard a good 200 yards away.

"It was going all over our yard and all over my animals," Aucoin said, referring to her chickens and goat. "They were spooked, so they were all running everywhere. And I'm trying to shove them all into this little tiny chicken coop, to try to get them out from under

it."

Aucoin said the wastewater poured from the pipe for an hour before the operator that owned the pipeline, WPX Energy, was able to shut it off.

"It was a good forty minutes of spraying over our yard before it petered out and stopped raining on us. It was still coming out, but it wasn't coming all the way across the road anymore," she said.

By that time, the property was drenched in the fluid. The burst left Aucoin's yard, trailers, vehicles and livestock coated in the wastewater.

Emergency responders were able to shine lights in the area to help the family locate the source of the water. WPX Energy employees and representatives of the Oil Conservation Division (OCD), which regulates the oil and gas industry in the state, were also on-site to assess the situation and monitor clean up.

"Nobody light a match around me," Aucoin wrote in a Facebook post in the hours after the ordeal. "It's highly flammable, but no worries it won't explode. Ugh!"

'Icing on the cake'

Aucoin and George live in Otis, New Mexico, a rural community in Eddy County outside Carlsbad. The property has been in George's family since he was nine years old.

"When they first moved out here, they didn't even have water in this neighborhood," Aucoin said. "He's always been here. I've been here ten years."

"The oil and gas arrived about six years ago," she added.

During that time, Aucoin and her husband have witnessed the landscape around them change dramatically as oil and gas activity has steadily ramped up in the area.

"We live next to all these oil rigs and stuff, but we live out in the country. We used to have flares right across from us, but they took those down about a month ago, so now it's dark again. For a while it was like having daylight all the time," Aucoin said. "About a year ago, my husband counted that there were 27 flares within a mile of my home."

Like many that live amidst oil and gas development, Aucoin said her family has been plagued by respiratory issues.

"We have constant headaches, my son gets nosebleeds. It's like having really, really, really, intense allergies that never quit," she said. "My daughter is on meds for allergies and asthma. I've had to take breathing treatments. It's horrible."

Aucoin has been a vocal advocate (https://www.santafenewmexican.com/opinion/my_view/proposed-epa-rollback-threatens-new-mexicans-health/article_94ea5d26-ab1d-515d-ae15-e054e218f03b.html) for families living near oil and gas development who she says are exposed to elevated levels of methane. Aucoin traveled to Dallas, Texas, last year to speak at a public hearing held by the U.S. EPA on its proposal to roll back methane regulations from oil and gas activity.

"It's frustrating. And having this happen, it's like icing on the cake," she said. "How much worse can it get?"

Cleaning up the wastewater

Produced water has become a hot button issue for New Mexicans as the state's oil and gas production reached record-setting levels over the past three years. Every barrel of oil produces four to seven barrels of produced water. In 2019, the state produced an estimated 300 million barrels of oil, and 1.2 billion barrels of produced water.

That spike in production has led to a spike in spills, too. In 2018, OCD reported 656 spills containing produced water (https://westernpriorities.org/2018-new-mexico-oil-and-gas-toxic-release-tracker/), representing nearly 4 million gallons. Most of those spills occurred in the counties of Eddy and Lea.

Produced water typically contains formation water — water that has been trapped in underground geologic formations for millions of years — with naturally occurring minerals, heavy metals and rare earth elements, as well as drilling constituents and hydrocarbons, but the exact chemical composition in produced water varies from operator to operator. Researchers are now attempting to devise methods for determining the constituents and toxicity of produced water, which will help state regulators better understand how to treat the wastewater.

RELATED: *Characterizing fracking fluids: More details on the state's plans for produced water* (https://nmpoliticalreport.com/2019/12/03/characterizing-fracking-fluids-more-details-on-the-states-plans-for-produced-water/)

The WPX pipe that burst is a part of a short, 1-mile long pipeline that carries produced water from a producing well to a saltwater disposal well, according to Kelly Swan, director of communications and community relations at WPX Energy.

Swan said the company hasn't yet determined the cause of the burst, but said officials are investigating the situation and will have that portion of the pipe replaced.

"You're going to take that section of line out of service, and then you're going to study it. While all that's happening, you're also repairing the line and putting in a new section," Swan said. "Once all that is complete, the line will go back in service. We expect all that to happen by this weekend."

OCD confirmed with *NM Political Report* that the department had been notified of the burst.

"At about 2:30 in the morning on Tuesday a resident of Carlsbad called emergency services when they heard a pop and noticed a gas smell in their backyard. WPX, the company who owns and operates the well pad, was notified of a leak in the flowline and began taking appropriate clean-up measures immediately," Adrienne Sandoval, OCD director, said in a statement. "An environmental consultant is on the site location, and the Oil Conservation Division was notified about the incident. The OCD is in frequent communication with WPX and is ensuring that all clean-up measures are taken."

WPX employees worked well into the next day cleaning up the produced water on the property.

"We power-washed their vehicles, their fencing and their residence," Swan said. The company sent out an environmental contractor to apply Micro-blaze (http://www.micro-blaze.com/site/home/), a proprietary bacteria-based product developed by Verde Environmental that uses microbes to breakdown and remove hydrocarbons, to Aucoin's yard.

"It's something you can put on a surface that can basically eat up any traces of hydrocarbons. It's something that we use in the oilfield, and it's proven pretty effective," Swan said.

WPX employees hand-washed several of Aucoin's chickens. The company has also offered to replace Aucoin's chicken coop.

WPX employees hand-washed Penny Aucoin's chickens which were exposed to the produced water. Source: Penny Aucoin, Facebook

"The homeowners have been great to work with. Obviously, this has been a great inconvenience for them," Swan said. "We've had several people on our operations staff in contact with them and walking them through everything we're doing."

While she's happy everyone is safe, Aucoin said she's concerned about whether produced water constituents may still present a threat to her family and livestock.

"They said it's still not safe for my animals to go into the yard. They said four or five days until we can go into the yard. The more I read about this Micro-blaze, I'm still not sure it's going to be safe for them, even after [the five days]," she said. "I think it takes the [hydrocarbons] out of it, it doesn't help with the salts and heavy metals. I'm not sure that's going to make it ok for my grazing animals. The chickens scratch and peck, and the goat chews everything down to the root."

WPX offered to pay for one load of topsoil, but Aucoin refused the offer because she didn't think one load would be enough to cover her one-acre property. Instead, the company has taken soil samples to be analyzed, Aucoin said.

"It's maddening," Audcoin said later in an email. "They offered me buckets to feed my chickens in and a new chicken coop for them to feel more comfortable in after their ordeal. I'm just furious that they think that is enough to make my animals safe."

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July 6, 2020
In "News"

(https://nmpoliticalreport.com/2019/04/05/oil-and-gas-had-little-to-fear-during-legislative-session/)

Oil and gas had little to fear during legislative session (https://nmpoliticalreport.com/2019/04/05/oil-and-gas-had-little-to-fear-during-legislative-session/)
April 5, 2019
In "News"

WildEarth Guardians Exhibit 11

EPA, Exemption of Oil and Gas Exploration and Production Wastes from Federal Hazardous Waste Regulations (Oct. 2002), available at: https://yosemite.epa.gov/oa/eab_web_docket.nsf/Attachments%20By%20ParentFilingId/945EF425FA4A9B4F85257E2800480C65/$FILE/28%20-%20RCRA%20E%26P%20Exemption.pdf

Exhibit 28

U.S. Envtl. Prot. Agency, Office of Solid Waste, EPA530-K-01-004, *Exemption of Oil and Gas Exploration and Production Wastes from Federal Hazardous Waste Regulations* (2002)

Exemption of Oil and Gas Exploration and Production Wastes from Federal Hazardous Waste Regulations

Introduction

This publication provides an understanding of the exemption of certain oil and gas exploration and production (E&P) wastes from regulation as hazardous wastes under Subtitle C of the Resource Conservation and Recovery Act (RCRA).

The information contained in this booklet is intended to furnish the reader with:

- A basic background on the E&P exemption.
- Basic rules for determining the exempt or non-exempt status of wastes.
- Examples of exempt and non-exempt wastes.
- Status of E&P waste mixtures.
- Clarifications of several misunderstandings about the exemption.

- Answers to frequently asked questions.
- Recommendations for sensible waste management.
- Additional sources of information.

The American Petroleum Institute (API) estimated that 149 million barrels of drilling wastes, 17.9 billion barrels of produced water and 20.6 million barrels of other associated wastes were generated in 1995 from exploration and production (E&P) operations.

Once generated, managing these wastes in a manner that protects human health and the environment is essential for limiting operators' legal and financial liabilities and also makes good business sense. Operators must also determine if the waste is subject to hazardous waste regulations. At times this determination is misunderstood and can lead to improper waste management decisions.

Drilling waste volumes are directly related to the level of drilling activity. API data show that the total footage drilled for all oil and gas wells dropped from 315.4 million feet in 1985 to 118 million feet in 1995, a decrease of 60 percent. A corresponding drop in the volume of drilling waste, from 361 million barrels in 1985, to 149 million barrels in 1995, was estimated.

On the other hand, as hydrocarbons from producing wells deplete, produced water volumes typically increase. API has estimated that the average volume of produced water increased from 6 barrels of water per barrel of oil in 1985, to 7.5 barrels of water per barrel of oil in 1995.

Prudent waste management decisions, even for nonhazardous wastes, should be based on the inherent nature of the waste. Not all waste management options are appropriate for every waste. Operators also should be familiar with state and federal regulations governing the management of hazardous and nonhazardous wastes.

The preferred option for preventing pollution is to avoid generating wastes whenever possible (source reduction). Examples include process modifications to reduce waste volumes and materials substitution to reduce toxicity.

Understanding the procedures for determining the exempt or nonexempt status of a waste is a valuable tool, especially for operators who choose to develop voluntary waste management plans. When these procedures are used in conjunction with a knowledge of the nature of the waste, the operator will be better prepared to develop site-specific waste management plans and to manage E&P wastes in a manner that protects human health and the environment.

Scope of the Exemption

In December 1978, EPA proposed hazardous waste management standards that included reduced requirements for several types of large volume wastes. Generally, EPA believed these large volume "special wastes" are lower in toxicity than other wastes being regulated as hazardous waste under RCRA. Subsequently, Congress exempted these wastes from the RCRA Subtitle C hazardous waste regulations pending a study and regulatory determination by EPA. In 1988, EPA issued a regulatory determination stating that control of E&P wastes under RCRA Subtitle C regulations is not warranted. Hence, E&P wastes have remained exempt from Subtitle C regulations. The RCRA Subtitle C exemption, however, did not preclude these wastes from control under state regulations, under the less stringent RCRA Subtitle D solid waste regulations, or under other federal regulations. In addition, although they are relieved from regulation as hazardous wastes, the exemption does not mean these wastes could not present a hazard to human health and the environment if improperly managed.

Among the wastes covered by the 1978 proposal were "gas and oil drilling muds and oil production brines." The oil and gas exemption was expanded in the 1980 legislative amendments to RCRA to include "drilling fluids, produced water, and other wastes associated with the exploration, development, or production of crude oil or natural gas. . . ." (Geothermal energy wastes were also exempted but are not addressed by this publication.)

According to the legislative history, the term "other wastes associated" specifically includes waste materials intrinsically derived from primary field operations associated with the exploration, development, or production of crude oil and natural gas. The phrase "intrinsically derived from the primary field operations" is intended to distinguish exploration, development, and production operations from transportation and manufacturing operations.

With respect to crude oil, primary field operations include activities occurring at or near the wellhead and before the point where the oil is transferred from an individual field facility or a centrally located facility to a carrier for transport to a refinery or a refiner.

With respect to natural gas, primary field operations are those activities occurring at or near the wellhead or at the gas plant, but before the point where the gas is transferred from an individual field facility, a centrally located facility, or a gas plant to a carrier for transport to market. Examples of carriers include trucks, interstate pipelines, and some intrastate pipelines.

Primary field operations include exploration, development, and the primary, secondary, and tertiary production of oil or gas. Crude oil processing, such as water separation, de-emulsifying, degassing, and storage at tank batteries associated with a specific well or wells, are examples of primary field operations. Furthermore, because natural gas often requires processing to remove water and other impurities prior to entering the sales line, gas plants are considered to be part of production operations regardless of their location with respect to the wellhead.

In general, the exempt status of an E&P waste depends on how the material was used or generated as waste, not necessarily whether the material is hazardous or toxic. For example, some exempt E&P wastes might be harmful to human health and the environment, and many non-exempt wastes might not be as harmful. The following simple rule of thumb can be used to determine if an E&P waste is exempt or non-exempt from RCRA Subtitle C regulations:

◆ Has the waste come from down-hole, i.e., was it brought to the surface during oil and gas E&P operations?

◆ Has the waste otherwise been generated by contact with the oil and gas production stream during the removal of produced water or other contaminants from the product?

If the answer to either question is yes, then the waste is likely considered exempt from RCRA Subtitle C regulations. It is important to remember that *all* E&P wastes require proper management to ensure protection of human health and the environment.

Exempt and Non-Exempt Wastes

In its 1988 regulatory determination, EPA published the following lists of wastes that were determined to be either exempt or non-exempt. These lists are provided as examples of wastes regarded as exempt and non-exempt and should not be considered to be comprehensive. The exempt waste list applies only to those wastes generated by E&P operations. Similar wastes generated by activities other than E&P operations are not covered by the exemption.

Exempt E&P Wastes

- Produced water

- Drilling fluids

- Drill cuttings

- Rigwash

- Drilling fluids and cuttings from offshore operations disposed of onshore

- Geothermal production fluids

- Hydrogen sulfide abatement wastes from geothermal energy production

- Well completion, treatment, and stimulation fluids

- Basic sediment, water, and other tank bottoms from storage facilities that hold product and exempt waste

- Accumulated materials such as hydrocarbons, solids, sands, and emulsion from production separators, fluid treating vessels, and production impoundments

- Pit sludges and contaminated bottoms from storage or disposal of exempt wastes

- Gas plant dehydration wastes, including glycol-based compounds, glycol filters, and filter media, backwash, and molecular sieves

- Workover wastes

- Cooling tower blowdown

- Gas plant sweetening wastes for sulfur removal, including amines, amine filters, amine filter media, backwash, precipitated amine sludge, iron sponge, and hydrogen sulfide scrubber liquid and sludge

- Spent filters, filter media, and backwash (assuming the filter itself is not hazardous and the residue in it is from an exempt waste stream)

- Pipe scale, hydrocarbon solids, hydrates, and other deposits removed from piping and equipment prior to transportation

- Produced sand

- Packing fluids

- Hydrocarbon-bearing soil

- Pigging wastes from gathering lines

- Wastes from subsurface gas storage and retrieval, except for the non-exempt wastes listed on page 11

- Constituents removed from produced water before it is injected or otherwise disposed of

- Liquid hydrocarbons removed from the production stream but not from oil refining

- Gases from the production stream, such as hydrogen sulfide and carbon dioxide, and volatilized hydrocarbons

- Materials ejected from a producing well during blowdown

- Waste crude oil from primary field operations

- Light organics volatilized from exempt wastes in reserve pits, impoundments, or production equipment

Non-Exempt Wastes

- Unused fracturing fluids or acids

- Gas plant cooling tower cleaning wastes

- Painting wastes

- Waste solvents

- Oil and gas service company wastes such as empty drums, drum rinsate, sandblast media, painting wastes, spent solvents, spilled chemicals, and waste acids

- Vacuum truck and drum rinsate from trucks and drums transporting or containing non-exempt waste

- Refinery wastes

- Liquid and solid wastes generated by crude oil and tank bottom reclaimers [1]

- Used equipment lubricating oils

- Waste compressor oil, filters, and blowdown

- Used hydraulic fluids

- Waste in transportation pipeline related pits

- Caustic or acid cleaners

- Boiler cleaning wastes

- Boiler refractory bricks

- Boiler scrubber fluids, sludges, and ash

- Incinerator ash

- Laboratory wastes

- Sanitary wastes

- Pesticide wastes

- Radioactive tracer wastes

- Drums, insulation, and miscellaneous solids

[1] Although non-E&P wastes generated from crude oil and tank bottom reclamation operations (e.g., waste equipment cleaning solvent) are non-exempt, residuals derived from exempt wastes (e.g., produced water separated from tank bottoms) are exempt. For a further discussion, see the Federal Register notice, Clarification of the Regulatory Determination for Waste from the Exploration, Development, and Production of Crude Oil, Natural Gas and Geothermal Energy, March 22, 1993, Federal Register Volume 58, Pages 15284 to 15287.

Exempt/Non-Exempt Wastes
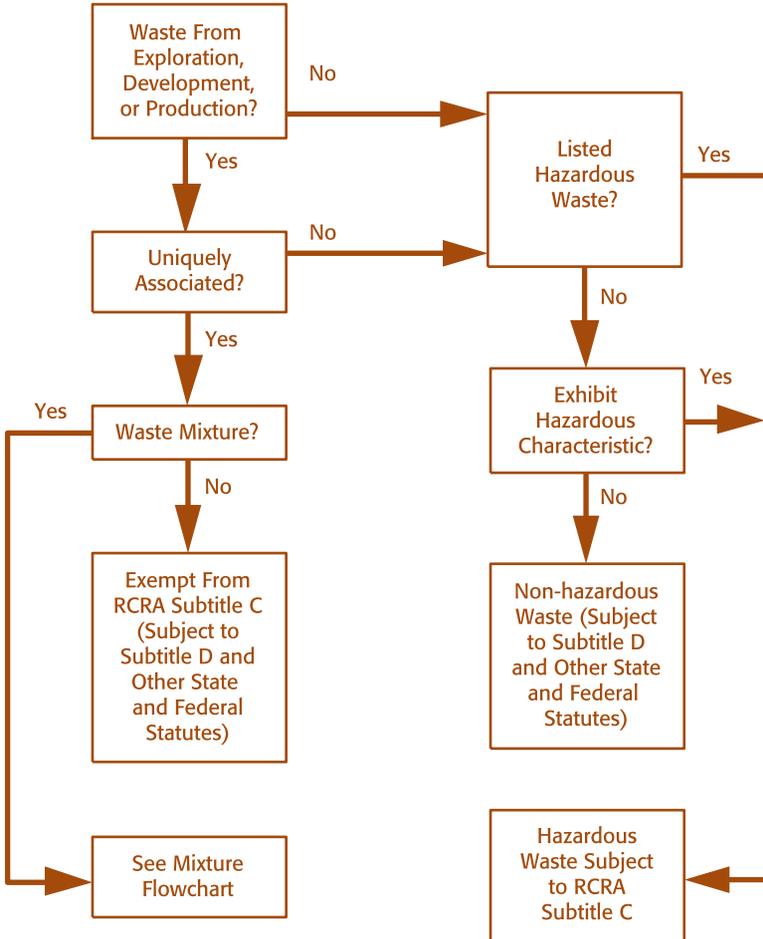
Mixing Wastes

Mixing wastes, particularly exempt and non-exempt wastes, creates additional considerations. Determining whether a mixture is an exempt or non-exempt waste requires an understanding of the nature of the wastes prior to mixing and, in some instances, might require a chemical analysis of the mixture. Whenever possible, avoid mixing non-exempt wastes with exempt wastes. If the non-exempt waste is a listed or characteristic hazardous waste, the resulting mixture might become a non-exempt waste and require management under RCRA Subtitle C regulation. Furthermore, mixing a characteristic hazardous waste with a non-hazardous or exempt waste for the purpose of rendering the hazardous waste non-hazardous or less hazardous might be considered a treatment process subject to appropriate RCRA Subtitle C hazardous waste regulation and permitting requirements.

NOTE: In a policy letter dated September 25, 1997, EPA clarified that a mixture is exempt if it contains exempt oil and gas exploration and production (E&P) waste mixed with non-hazardous, non-exempt waste. Mixing exempt E&P waste with non-exempt characteristic hazardous waste, however, for the purpose of rendering the mixture non-hazardous or less hazardous, could be considered hazardous waste treatment or impermissible dilution.

Below are some basic guidelines for determining if a mixture is an exempt or non-exempt waste under the present mixture rule.

◆ **A mixture of an exempt waste with another exempt waste remains exempt.**

   Example: A mixture of stimulation fluid that returns from a well with produced water results in an exempt waste.

◆ **Mixing a non-hazardous waste (exempt or non-exempt) with an exempt waste results in a mixture that is also exempt.**

   Example: If non-hazardous wash water from rinsing road dirt off equipment or vehicles is mixed with the contents of a reserve pit containing only exempt drilling waste, the wastes in the pit remain exempt regardless of the characteristics of the waste mixture in the pit.

◆ **If, after mixing a non-exempt characteristic hazardous waste with an exempt waste, the resulting mixture exhibits any of the same hazardous characteristics as the hazardous waste (ignitability, corrosivity, reactivity, or toxicity), the mixture is a non-exempt hazardous waste.**

   Example: If, after mixing non-exempt caustic soda (NaOH) that exhibits the hazardous characteristic of corrosivity in a pit containing exempt waste, the mixture also exhibits the hazardous characteristic of corrosivity as determined from pH or steel corrosion tests, then the entire mixture becomes a non-exempt hazardous waste.

   Example: If, after mixing a non-exempt solvent containing benzene with an exempt waste also containing benzene,

the mixture exhibits the hazardous characteristic for benzene, then the entire mixture becomes a non-exempt hazardous waste.

◆ **If, after mixing a non-exempt characteristic hazardous waste with an exempt waste, the resulting mixture does not exhibit any of the same characteristics as the hazardous waste, the mixture is exempt. Even if the mixture exhibits some other characteristic of a hazardous waste, it is still exempt.**

Example: If, after mixing non-exempt hydrochloric acid (HCl) that only exhibits the corrosive characteristic with an exempt waste, the mixture does not exhibit the hazardous characteristic of corrosivity but does exhibit some other hazardous characteristic such as toxicity, then the mixture is exempt.

Example: If, after mixing a non-exempt waste exhibiting the hazardous characteristic for lead with an exempt waste exhibiting the characteristic for benzene, the mixture exhibits the characteristic for benzene but not for lead, then the mixture is exempt.

◆ **Generally, if a listed hazardous waste[2] is mixed with an exempt waste, regardless of the proportions, the mixture is a non-exempt hazardous waste.**

Example: If any amount of leaded tank bottoms from the petroleum refining industry (listed as waste code K052) is mixed with an exempt tank bottom waste, the mixture is considered a hazardous waste and is therefore non-exempt.

---

[2] Listed hazardous wastes are those wastes listed as hazardous in the Code of Federal Regulations under Subpart D of 40 CFR Part 261.

It is also important to emphasize that a mixture of an exempt waste with a listed hazardous waste generally becomes a non-exempt hazardous waste regardless of the relative volumes or concentrations of the wastes. However, if the listed hazardous waste was listed solely for one or more of the characteristics of ignitability, corrosivity, or reactivity, then a mixture of this waste with an exempt waste would only become non-exempt if the mixture exhibits the characteristic for which the hazardous waste was listed (i.e., if the mixture is ignitable, corrosive, or reactive).

Similarly, if a mixture of an exempt waste with a non-exempt characteristic hazardous waste exhibits any of the same hazardous waste characteristics as the hazardous waste, or if it exhibits a characteristic that would not have been exhibited by the exempt waste alone, the mixture becomes a non-exempt hazardous waste regardless of the relative volumes or concentrations of the wastes. In other words, for any of these scenarios, the wastes could become non-exempt even if only one barrel of hazardous waste were mixed with 10,000 barrels of exempt waste.

NOTE: The act of mixing a hazardous waste with an exempt waste may be subject to RCRA regulations affecting hazardous waste treatment, including the need for a permit (unless the unit or process is otherwise exempt). Moreover, the waste may still be subject to the 40 CFR 268 Land Disposal Restrictions (LDR) regulations (as applicable), including the prohibition of dilution as a substitute for adequate treatment.

Possible Waste Mixtures and Their Exempt and Non-Exempt Status

Exempt Waste

Exempt Waste

→ Exempt Waste ←

Non-hazardous Waste

Exempt Waste

No → Exempt Waste (See Note on Previous Page)

Exempt Waste

Non-exempt Characteristic Hazardous Waste

→ Does Mixture Exhibit Any Hazardous Characteristic Exhibited by Non-exempt Waste?

Yes → Non-exempt Characteristic Hazardous Waste

Exempt Waste

Listed Hazardous Waste

→ Listed Hazardous Waste
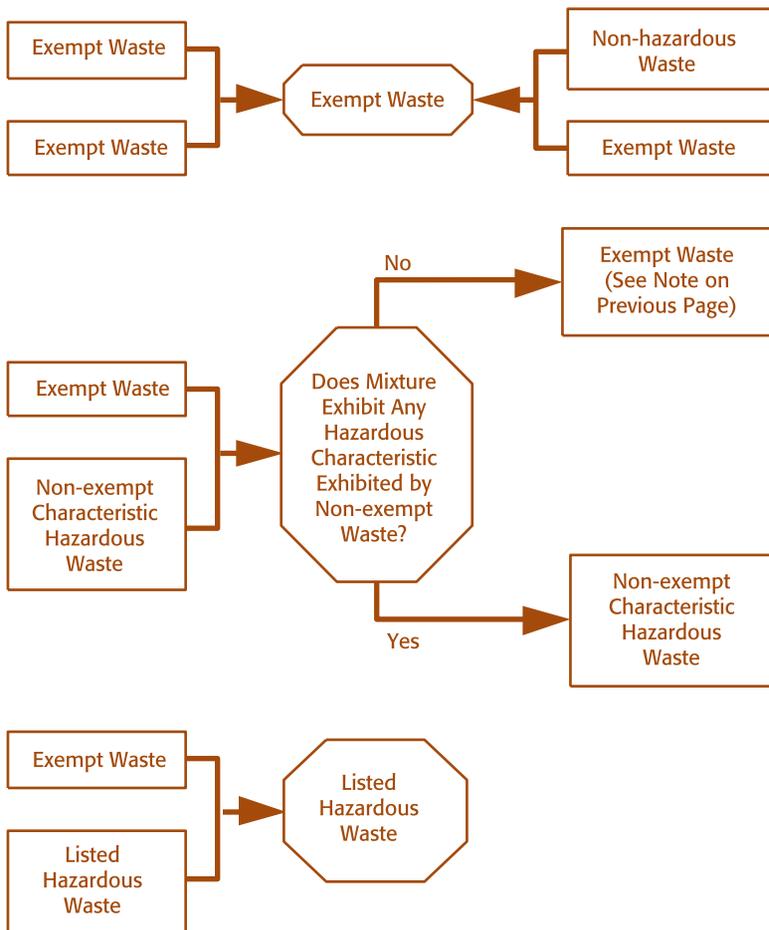
Common Misunderstandings

An incomplete understanding of the hazardous waste regulations can result in misinterpretations of the regulatory status of various wastes. The following are common misunderstandings that arise with the RCRA Subtitle C exemption and hazardous waste determinations.

Misunderstanding: All wastes located at E&P sites are exempt.

Fact: All wastes located at E&P sites are not necessarily exempt. To be considered an exempt waste, the waste must have been generated from a material or process uniquely associated with the exploration, development, and production of crude oil and natural gas. For example, a solvent used to clean surface equipment or machinery is not exempt because it is not uniquely associated with exploration, development, or production operations. Conversely, if the same solvent were used in a well, it would be exempt because it was generated through a procedure that is uniquely associated with production operations.

◆ ◆ ◆

Misunderstanding: All service company wastes are exempt.

Fact: Not all service company wastes are exempt. As with all oilfield wastes, only those wastes generated from a material or process uniquely associated with the exploration and pro-

duction of oil and gas are considered exempt. The previous example of solvents used for cleaning equipment and machinery would also apply in this case—the solvent is not an exempt waste.

◆ ◆ ◆

Misunderstanding: Unused products are exempt.

Fact: Unused products, if disposed of, are not exempt, regardless of their intended use, because they have not been used and therefore are not uniquely associated with the exploration or production of oil and gas. When unused products become waste (e.g., they are disposed of), they are subject to RCRA Subtitle C hazardous waste regulations if they are listed or exhibit a hazardous characteristic.

◆ ◆ ◆

Misunderstanding: All exempt wastes are harmless to human health and the environment.

Fact: Certain exempt wastes, while excluded from RCRA Subtitle C hazardous wastes control, might still be harmful to human health and the environment if not properly managed. The exemption relieves wastes that are uniquely associated with the exploration and production of oil and gas from regulation as hazardous wastes under RCRA Subtitle C but does not indicate the hazard potential of the exempt waste. Additionally, some of these wastes might still be subject to state hazardous or non-hazardous waste regulations or other federal regulations (e.g., hazardous materials transportation regulations and National Pollutants Discharge Elimination System (NPDES) or state discharge regulations) unless specifically excluded from regulation under those laws.

Misunderstanding: Any mixture of a non-exempt hazardous waste with an exempt waste becomes an exempt waste.

Fact: Not all mixtures of a non-exempt hazardous waste with an exempt waste become exempt wastes. Generally, a mixture of a listed hazardous waste with an exempt waste becomes a non-exempt hazardous waste.

Also, a mixture of a hazardous waste that exhibits one of the characteristics of a hazardous waste (ignitability, corrosivity, reactivity, or toxicity) with an exempt waste, becomes a non-exempt characteristic hazardous waste if the mixture exhibits one of the same hazardous characteristics as the original hazardous waste. Conversely, if the mixture does not exhibit one of the same hazardous characteristics of the hazardous waste, the mixture becomes a non-hazardous exempt waste. Remember, mixing a non-exempt hazardous waste with an exempt waste for the purpose of rendering the hazardous waste non-hazardous or less hazardous may be considered a treatment process and must be conducted in accordance with applicable RCRA Subtitle C regulations.

◆ ◆ ◆

Misunderstanding: A waste exempt from RCRA Subtitle C regulation is also exempt from state and other federal waste management regulations.

Fact: The exemption applies only to the federal requirements of RCRA Subtitle C. A waste that is exempt from RCRA Subtitle C regulation might be subject to more stringent or broader state hazardous and non-hazardous waste regulations and other state and federal program regulations. For example, oil and gas exploration and production wastes are subject to regulation under the Clean Air Act (CAA), Clean Water Act (CWA), Safe Drinking Water Act (SDWA), and Oil Pollution Act of 1990 (OPA).

Frequently Asked Questions

EPA receives calls on a regular basis requesting answers to questions related to the E&P exemption. The most common questions and answers are listed below.

Q: **Are RCRA-exempt wastes also exempt under other federal laws?**

A: Not necessarily. Unless specifically excluded from regulation under other federal laws, RCRA-exempt wastes might still be subject to regulation under authorities other than RCRA.

◆ ◆ ◆

Q: **What is the benefit of the RCRA exemption if the operator is still liable for cleanups under RCRA?**

A: Although the operator might still be liable for cleanup actions under RCRA for wastes that pose an imminent and substantial endangerment to human health and the environment, the RCRA exemption does allow the operator to choose a waste management and disposal option that is less stringent and possibly less costly than those required under RCRA Subtitle C. The operator,

however, should make every effort to choose the proper management and disposal procedures for a particular waste to avoid the need for later cleanup action.

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Q: **When is a waste considered "uniquely associated with" exploration and production operations?**

A: A waste is "uniquely associated with" exploration and production operations if it is generated from a material or procedure that is necessary to locate and produce crude oil or natural gas. Also, a waste is "uniquely associated with" exploration and production operations if it is generated from a material or procedure that only occurs during the exploration and production of crude oil or natural gas. A simple rule of thumb for identifying "uniquely associated wastes" is whether the waste came from downhole or otherwise was generated in contact with the oil or gas production stream for the purpose of removing water or other contaminants from the well or the product.

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Q: **Are wastes generated from a transportation pipeline considered exempt wastes under RCRA Subtitle C?**

A: No. The RCRA Subtitle C exemption only applies to wastes generated from the exploration, development, and production (i.e., primary field operations) of crude oil or natural gas. Hence, wastes generated from the transportation of crude oil or natural gas are not RCRA-exempt.

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Q: **Do exempt wastes lose their exempt status if they undergo custody transfer and are transported offsite for disposal?**

A: No. Custody transfer is used to define the endpoint of production operations for crude oil and applies only to the change in ownership of the product (e.g., crude oil). Exempt wastes maintain their exempt status even if they undergo custody transfer and are transported off-site for disposal or treatment.

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Q: **Are all wastes generated at facilities that treat or reclaim exempt wastes also exempt?**

A: No. The exemption applies only to those wastes derived from exempt wastes, not to additional wastes generated by the treatment or reclamation of exempt wastes. For example, if a treatment facility uses an acid in the treatment of an exempt waste, any waste derived from the exempt waste being treated is also exempt but the spent acid is not.

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Q: **When does transportation begin?**

A: For crude oil, transportation begins at the point of custody transfer of the oil or, in the absence of custody transfer, after the endpoint of production separation and dehydration. Storage of crude oil in stock tanks at production facilities is considered part of the production separation process, not transportation, and is

included in the exemption. For natural gas, transportation begins at the point where the gas leaves the facility after production separation and dehydration at the gas plant. Natural gas pipelines between the gas well and the gas plant are considered to be part of the production process, rather than transportation, and wastes that are uniquely associated with production that are generated along such a pipeline are exempt.

EPA periodically issues interpretive letters regarding the oil and gas exemption. One such letter was in response to a request for clarification of the exempt or non-exempt status of wastes generated at natural gas compressor stations. In some regions, such as the Appalachian states, natural gas might not require sweetening or extensive dehydration. Therefore, the gas generally does not go to a gas plant but is carried from the wellhead to a main transmission line and, in some cases, directly to the customer. Compressor stations are located as needed along the pipelines that run between the wellhead and the main transmission line or the customer to maintain pressure in the lines. The Agency has taken the position that these compressor stations (in the absence of gas plants, and handling only local production) should be treated the same as gas plants, and that wastes generated by these compressor stations are exempt. On the other hand, compressor stations located along main gas transmission lines are considered to be part of the transportation process, and any wastes generated by these compressor stations are non-exempt.

Sensible Waste Management

Sensible waste management begins with "good housekeeping." Prudent operators design E&P facilities and processes to minimize potential environmental threats and legal liabilities. EPA promotes sensible waste management practices through a number of joint efforts with organizations such as API, individual states, and the Interstate Oil and Gas Compact Commission (IOGCC). The following waste management suggestions have been compiled from publications produced by these organizations as well as from literature available from industry trade associations, trade journals, and EPA.

Suggested E&P Waste Management Practices

- Size reserve pits properly to avoid overflows.

- Use closed loop mud systems when practical, particularly with oil-based muds.

- Review material safety data sheets (MSDSs) of materials used, and select less toxic alternatives when possible.

- Minimize waste generation, such as by designing systems with the smallest volumes possible (e.g., drilling mud systems).

- Reduce the amount of excess fluids entering reserve and production pits.

- Keep non-exempt wastes out of reserve or production pits.

- Design the drilling pad to contain stormwater and rig-wash.

- Recycle and reuse oil-based muds and high density brines when practical.

- Perform routine equipment inspections and maintenance to prevent leaks or emissions.

- Reclaim oily debris and tank bottoms when practical.

- Minimize the volume of materials stored at facilities.

- Construct adequate berms around materials and waste storage areas to contain spills.

- Perform routine inspections of materials and waste storage areas to locate damaged or leaking containers.

- Train personnel to use sensible waste management practices.
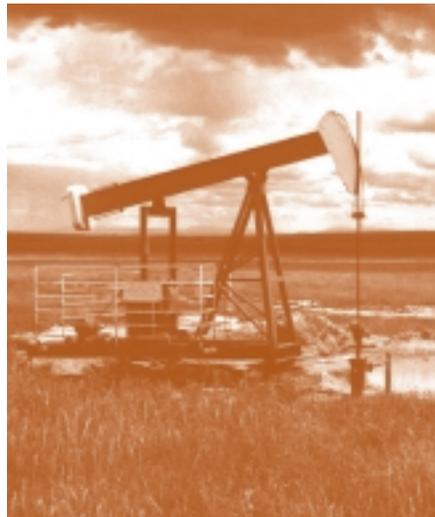
Sources of Information

Resource Conservation and Recovery Act (RCRA)

RCRA regulates hazardous waste generators, hazardous waste transporters, and hazardous waste treatment, storage, and disposal facilities (TSDFs). RCRA encourages environmentally sound methods for managing commercial and industrial waste, as well as household and municipal waste.

RCRA Resources:

- 40 CFR Parts 260 to 279
- RCRA Call Center: 800 424-9346 or Washington, DC Area Local 703 412-9810 or TDD 800 553-7672 or TDD Washington, DC Area Local 703 412-3323 Fax: 703 308-8686
- Internet access: <www.epa.gov/epaoswer/other/oil/index.htm>

Clean Water Act (CWA)

The Water Pollution Control Act, commonly known as the Clean Water Act (CWA), is the Federal program designed to restore and maintain the integrity of the nation's surface waters. CWA controls direct discharges to surface waters (e.g., through a pipe) from industrial processes or stormwater systems associated with an industrial activity. It also regulates indirect discharges, or discharges to publicly owned treatment works (POTWs) through a public sewer system, by requiring industrial facilities to pretreat their waste before discharging to a public sewer.

CWA Resources:

- 40 CFR Parts 100-129 and 400-503
- EPA Office of Water: 202 260-5700
- State water authority, regional EPA office, and local POTW
- Internet access: <www.epa.gov/ow/>

Oil Pollution Prevention (Spill Prevention, Control and Countermeasures Regulations)

Spill prevention, control and countermeasures (SPCC) regulations promulgated pursuant to the CWA are designed to protect our nation's waters from oil pollution caused by oil spills that could reach the navigable waters of the United States or adjoining shorelines. The regulations apply to non-transportation-related facilities with a specific aboveground or underground oil storage capacity that, due to its location, can be reasonably expected to discharge oil into the navigable waters of the United States.

SPCC Regulations Resources:

- 40 CFR Part 112
- RCRA Call Center: 800 424-9346
- Internet Access: <www.epa.gov/oilspill/index.htm>

Discharge of Oil

The section of the CWA regulations commonly known as the "sheen rule" provides the framework for determining whether a facility or vessel responsible for an oil spill must report the spill to the federal government. These rules require oil spills that may be "harmful to the public health or welfare" to be reported to the National Response Center. Usually, oil spills that cause a sheen or discoloration on the surface of a body of water, violate applicable water quality standards, and cause a sludge or emulsion to be deposited beneath the surface of the water or on adjoining shorelines, must be reported.

Discharge of Oil Regulations Resources:

- 40 CFR Part 110
- RCRA Call Center: 800 424-9346
- Internet Access: <www.epa.gov/oilspill/index.htm>
- Reporting discharges to the National Response Center: 800 424-8802.

Oil Pollution Act (OPA)

OPA of 1990 amended the CWA, and provided new requirements for contingency planning by government and industry under the National Oil and

Hazardous Substances Pollution Contingency Plan. OPA also increased penalties for regulatory noncompliance, broadened the response and enforcement authorities of the federal government, and preserved state authority to establish laws governing oil spill prevention and response.

OPA Resources:

- ■ Internet Access: <www.epa.gov/oilspill/index.htm>

Safe Drinking Water Act (SDWA)

SDWA mandates that EPA establish regulations to protect human health from contaminants present in drinking water. Under the authority of the SDWA, EPA developed national drinking water standards and created a joint federal/state system to ensure compliance with these standards. EPA also regulates underground injection of liquid wastes through the Underground Injection Control (UIC) program under the SDWA. The UIC program regulates five classes of injection wells to protect underground sources of drinking water.

SDWA Resources:

- ■ 40 CFR Parts 141-143 (SDWA); 40 CFR Parts 144-148 (UIC)
- ■ SDWA Hotline: 800 426-4791
- ■ State oil and gas regulatory authority.
- ■ Internet Access: <www.epa.gov/ogwdw>

Clean Air Act (CAA)

CAA regulates air pollution. It includes national emission standards for new stationary sources within particular industrial categories. It also includes the National Emission Standards for Hazardous Air Pollutants (NESHAPs), which are designated to control the emissions of particular hazardous air pollutants (HAPS). NESHAPs specific to oil and gas production were promulgated in 1999.

The CAA includes a Risk Management Program. This program requires stationary sources with more than a threshold quantity of a regulated substance (designated in the regulations) to develop and implement a risk management program (RMP). The RMP must include a hazard assessment, a prevention program, and an emergency response program.

CAA Resources:

- 40 CFR Parts 50-99
- Control Technology Center, Office of Air Quality, Planning and Standards (OAQPS), EPA, General Information: 919 541-0800; Publications: 919 541-2777
- RCRA Call Center (CAA §112(r) questions): 800 424-9346
- Internet Access: <www.epa.gov/oar/oaq_caa.html>
- Oil and Gas Production NESHAPs Rule: <www.epa.gov/ttn/uatw/oilgas/oilgaspg.html>

The Emergency Planning and Community Right-to-Know Act (EPCRA)

EPCRA was designed to improve community access to information about potential chemical hazards and to facilitate the development of chemical emergency response plans by State and local governments. EPCRA regulations establish four types of reporting obligations for facilities that store or manage certain chemicals above specified quantities.

EPCRA Resources:

- 40 CFR Parts 350-372
- RCRA Call Center: 800 424-9346
- Internet Access: <www.epa.gov/opptintr/tri/> and <www.epa.gov/swercepp>

Comprehensive Environmental Response Compensation, and Liability Act (CERCLA or Superfund)

Superfund authorizes EPA to respond to releases, or threatened releases, of hazardous substances that might endanger public health, welfare, or the environment. It also grants EPA the authority to force parties responsible for environmental contamination to clean it up or to reimburse response costs incurred by EPA. CERCLA also contains hazardous substance release reporting regulations that require facilities to report to the National Response Center (NRC) any release of a hazardous substance that exceeds the specified quantity for that substance.

CERCLA Resources:

- 40 CFR Parts 300-399
- RCRA Call Center: 800 424-9346

- Internet Access: <www.epa.gov/superfund>

Toxic Substances Control Act (TSCA)

TSCA allows EPA to collect data on chemicals to evaluate, assess, mitigate, and control risks that might be posed by their manufacture, processing, and use. Facilities are required to report information as necessary to allow EPA to develop and maintain this inventory.

TSCA Resources:

- 40 CFR Parts 702-799
- TSCA Hotline: 202 554-1404
- Internet Access: <www.epa.gov/internet/opptsfrs/home/opptsim.htm>

Other EPA Information Resources

Office of Solid Waste
Industrial and Extractive Wastes Branch
1200 Pennsylvania Avenue, NW.
Mail Code 5306W
Washington, DC 20460

RCRA Call Center: 800 424-9346 or
Washington, DC Area Local 703 412-9810 or
TDD 800 553-7672 or TDD Washington, DC
Area Local 703 412-3323 Fax: 703 308-8686
Internet access: <www.epa.gov/epaoswer/hotline>

The RCRA Call Center is a publicly accessible service that provides up-to-date information on several EPA programs. Please note that the Center cannot provide regulatory interpretations. It also processes requests for relevant publications and information resources.

Office of Emergency and Remedial Response, Oil Spill Program
1200 Pennsylvania Avenue, NW.
Washington, DC 20460
Oil Spill Program Information Line: 800 424-9346
Internet access: <www.epa.gov/oilspill/>

The Office of Emergency and Remedial Response (OERR) manages the Superfund and Oil Spill programs.

National Response Team

c/o U.S. EPA
1200 Pennsylvania Avenue, NW.
Washington, DC 20460
Telephone: 800 424-8802
Fax: 202 260-0154
Internet access: <www.nrt.org>

The National Response Team and the Regional Response Teams are the federal component of the National Response System (NRS), the federal government's coordinated mechanism for emergency response to discharges of oil and releases of chemicals. The NRT is chaired by the U.S. EPA with the United States Coast Guard serving as Vice Chair. The National Response Center (800 424-8802) is the sole federal point of contact for reporting oil and chemical spills.

Other Federal Agencies

U.S. Department of Interior

U.S. Bureau of Land Management
Fluid Minerals Group
1849 C Street, Room 406-LS
Washington, DC 20240
Telephone: 202 452-5125
Fax: 202 452-5124
Internet access: <www.blm.gov/nhp/300/wo310/>

The Bureau of Land Management's (BLM's) management of fluid minerals includes overseeing the production and conservation of oil and gas, geothermal energy, and helium. BLM is responsible for leasing oil and gas resources on all federally owned lands, including those lands managed by other federal agencies. This includes about 564 million acres of federal minerals estate, or about 28 percent of all lands within the United States. Additionally, BLM is responsible for the review and approval of all permits and licenses to explore, develop, and produce oil and gas and geothermal resources on both Federal and Indian lands.

U.S. Fish and Wildlife Service
Division of Environmental Quality
4401 North Fairfax Drive, Suite 322
Arlington, VA 22203
Telephone: 703 358-2148
Internet access: <contaminants.fws.gov>

The U.S. Fish and Wildlife Service is the main federal agency dedicated to protecting wildlife and their habitat from pollution's harmful effects. Specialists in the Environmental Contaminants Program focus on detecting toxic chemicals; addressing their effects; preventing harm to fish, wildlife and their habitats; and removing toxic chemicals and restoring habitat when prevention is not possible. These specialists are experts on oil and chemical spills, pesticides, water quality, hazardous materials disposal and other aspects of pollution biology.

U.S. Department of Energy

Office of Natural Gas & Petroleum Technology,
Office of Fossil Energy
1000 Independence Ave. SW. - Forrestal Building
Washington, DC 20585
Telephone: 202 586-6503
Fax: 202 586-5145
Internet access: <www.fe.doe.gov/programs_oilgas.html>

The Department of Energy's (DOE's) Office of Natural Gas and Petroleum Technology is responsible for the gas and oil exploration and production program, natural gas storage and delivery, downstream petroleum processing, and environmental and regulatory analysis programs for oil and natural gas operations, and natural gas import/export authorizations.

Other Information Resources

American Petroleum Institute

1220 L Street, NW.
Washington, DC 20005
Telephone: 202 682-8000
Internet access: <www.api.org>

The American Petroleum Institute (API) is the national trade association representing over 400 companies involved in oil and gas exploration, production, transportation, refining, and marketing. API represents its members in addressing public policy and regulatory issues. API also sponsors research, collects statistics, conducts workshops, and develops standards and recommended practices for industry equipment and operations.

Interstate Oil and Gas Compact Commission

P.O. Box 53127
Oklahoma City, OK 73152-3127
Telephone: 405 525-3556
Fax: 405 525-3592
E-mail: iogcc@iogcc.state.ok.us
Internet access: <www.iogcc.state.ok.us>

Founded by six states in 1935, the Interstate Oil and Gas Compact Commission (IOGCC) was established to control unregulated petroleum overproduction and resulting waste. "Since that time, states have established effective regulation of the oil and natural gas industry through a variety of IOGCC programs designed to gather and share information, technologies and regulatory methods."

Ground Water Protection Council

13208 N. MacArthur
Oklahoma City, OK 73142
Telephone: 405 516-4972
Fax: 405 516-4973
Internet access: <www.gwpc.org>

The Ground Water Protection Council is an organization whose members consist of state and federal ground water agencies, industry representatives, environmentalists, and concerned citizens. Since it includes state Underground Injection Control (UIC) program directors, it is the best source of data on Class II well injection issues.

National Governors' Association

Emergency Management and Oil Spill Prevention and
    Response Project
Hall of States
444 North Capitol Street, NW.
Washington, DC 20001-1512
Telephone: 202 624-5300
Internet access: <www.nga.org>

The National Governors' Association's project on oil spill prevention, preparedness, and response offers states an opportunity to share their experiences and coordinate with the federal agencies involved in oil spill prevention and response. This program facilitates the exchange of information on successful state programs among state and federal emergency managers. NGA works with U.S. EPA to coordinate and promote state oil spill prevention programs by holding workshops, summarizing successful state oil programs, and establishing ongoing workgroups to discuss oil spill topics.

Publications

Title: "Report to Congress: Management of Wastes from the Exploration, Development, and Production of Crude Oil, Natural Gas, and Geothermal Energy," U.S. EPA, December 1987, NTIS Publication No. PB 88-146212.
Available from: National Technical Information Service, 5285 Port Royal Road, Springfield, VA 22161, 703 487-4650.

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Title: "Regulatory Determination for Oil and Gas and Geothermal Exploration, Development, and Production Wastes," July 6, 1988, Federal Register Volume 53, Pages 25446 to 25459.
Available from: RCRA Call Center, Washington, DC, 800 424-9346
Internet access: <www.epa.gov/epaoswer/other/oil/index.htm>

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Title: "Clarification of the Regulatory Determination for Wastes from the Exploration, Development, and Production of Crude Oil, Natural Gas and Geothermal Energy," March 22, 1993, Federal Register Volume 58, Pages 15284 to 15287.

Available from: RCRA Call Center, Washington, DC, 800 424-9346

Internet access: <www.epa.gov/epaoswer/other/oil/index.htm>

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Title: Associated Wastes Reports: "Crude Oil Tank Bottoms and Oily Debris," "Completion and Workover Wastes," "Dehydration and Sweetening Wastes."

Available from: EPA Office of Solid Waste

Internet access: <www.epa.gov/epaoswer/other/oil/execrep.htm>

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Title: "Profile of the Oil and Gas Extraction Industry"

Available from: EPA Office of Enforcement and Compliance Assurance

Internet access: <es.epa.gov/oeca/sector/index.html#oilgasex>

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Title: "Environmental Guidance Document: Waste Management in Exploration and Production Operations," API Bulletin E5, Second Edition, February 1997.

Available from: American Petroleum Institute, c/o Global Engineering Documents, 15 Inverness Way E., Englewood, CO 80112, 800 854-7179

Internet access: <www.api.org/cat>

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Title: "Guidelines for Commercial Exploration and Production Waste Management Facilities," (Order Number G0004), March 2001.

Available from: American Petroleum Institute, c/o Global Engineering Documents, 15 Inverness Way E., Englewood, CO 80112, 800 854-7179

Internet access: <www.api.org/ehs/CommFac>

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Title: "Environmental Engineering for Exploration and Production Activities," Monograph Volume 18.

Available from: Society of Petroleum Engineers, P.O. Box 833836, Richardson, TX 75083-3836, 972 952-9393

E-mail: books@spe.org

Internet access: <www.spe.org>

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Title: "Suggested Procedure for Development of Spill Prevention Control and Countermeasure Plans," API Bulletin D16, Second Edition, August 1, 1989.

Available from: American Petroleum Institute, c/o Global Engineering Documents, 15 Inverness Way E., Englewood, CO 80112, 800 854-7179

Internet access: <www.api.org/cat>

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Title: "Onshore Oil and Gas Production Practices for Protection of the Environment," API Recommended Practice 51, Third Edition, February 2001.

Available from: American Petroleum Institute, c/o Global Engineering Documents, 15 Inverness Way E., Englewood, CO 80112, 800 854-7179

Internet access: <www.api.org/cat>

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Title: "Revised Guidelines for Waste Minimization in Oil and Gas Exploration and Production."

Available from: Interstate Oil and Gas Compact Commission, P.O. Box 53127, Oklahoma City, OK 73152-3127, 405 525-3556

Internet access: <www.iogcc.state.ok.us>

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