HEI energy

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A Health Effects Institute Affiliate

Potential Human Exposures to Produced Water from Onshore Oil and Gas Production

This Research Brief is part of a series of periodic updates on the literature about potential human exposures and health effects associated with unconventional oil and natural gas development (UOGD) in the United States

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Trusted Science, Clean Environment, Better Health

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TRUSTED SCIENCE, CLEAN ENVIRONMENT, BETTER HEALTH

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About HEI Energy

The Health Effects Institute (HEI) Energy is a national research program formed to identify and conduct high-priority research on potential population exposures and health effects from development of oil and natural gas from shale and other unconventional resources across the United States. HEI Energy supports community exposure research in multiple regions. To enable exposure research planning, HEI Energy conducts periodic reviews of the relevant scientific literature. Once initial research is completed, HEI Energy will assess the results to identify additional exposure research priorities and, where feasible and appropriate, health research needs for funding in subsequent years.

The scientific review and research provided by HEI Energy will contribute high-quality and credible science that supports decisions about how best to protect public health. To achieve this goal, HEI Energy has put into place a governance structure that mirrors the one successfully employed for nearly forty years by its parent organization, the Health Effects Institute, with several critical features:

- HEI Energy receives joint funding from the U.S. Environmental Protection Agency under a contract that funds HEI Energy exclusively and from the oil and natural gas industry;
- HEI Energy's independent Board of Directors consists of leaders in science and policy who are committed to fostering the public–private partnership that is central to the organization;
- HEI Energy's research program is governed independently by individuals having no direct ties to, or interests in, sponsor organizations;
- HEI Energy's Research Committee consists of members who are internationally recognized experts in one or more subject areas relevant to the Committee's work, have demonstrated their ability to conduct and review scientific research impartially, and have been vetted to avoid conflicts of interest;
- All research undergoes rigorous peer review by HEI Energy's Review Committee;
- HEI Energy staff and committees engage in open and extensive stakeholder engagement before, during, and after research, and communicate all results in the context of other relevant research;
- HEI Energy makes publicly available all literature reviews and original research that it funds and provides summaries written for a general audience; and
- Without advocating policy positions, HEI Energy provides impartial science, targeted to make better-informed decisions.

HEI Energy is a separately funded affiliate of the Health Effects Institute (*www.healtheffects.org*).

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Purpose of this Research Brief

People living near oil and natural gas development (OGD) can be exposed to chemicals released into air or water, noise emitted by operations, land use changes, and other impacts to their environment. This Research Brief summarizes peer-reviewed literature that contributes to understanding how people in the United States might be exposed to produced water from OGD following its release to the environment. This Research Brief is the fifth in a series summarizing literature about potential exposure and human health effects associated with OGD.

Overview of Produced Water

Produced water is a combination of naturally occurring, highly saline water (also known as formation water) that is present in the geologic formations where oil and gas originate as well as water and chemicals injected into the well during its development and to maintain production (Engle et al. 2014; American Geosciences Institute 2016). Flowback period is the phase when fluid introduced to a well begins to return to the surface after hydraulic fracturing or refracturing (40 CFR § 60.5430a). Flowback water can generally be defined as produced water generated during the first days and weeks following hydraulic fracturing (Engle et al. 2014).[1] Produced water can flow from a completed well for months to years (Butkovskyi et al. 2017). For the purposes of this research brief, we define produced water as any liquid surfaced from an OGD well (Bean et al. 2018, Engle et al., 2014).

Under certain exposure conditions, produced water, and some of its components, can adversely affect water quality, ecological health, and human health (Abualfaraj et al. 2018; Balise et al. 2019; Boulé et al. 2018; Danforth et al. 2020; Elliott et al. 2016, 2017; Farag et al. 2022; Folkerts et al. 2017; Geeza et al. 2018; Hu et al. 2022; Hull et al. 2018; McLimans et al. 2022; Nagel et al. 2020; Patnode et al. 2015; Webb et al. 2014; Xu et al. 2019).

Whether and how exposure occurs depends on if produced water enters the environment where people can come into contact with it. This depends on how produced water is managed from the time it leaves a well to its eventual disposal or reuse. Management of produced water can include its collection, storage, transport, disposal, spill or leak mitigation, treatment, and various reuses within and outside the oil and gas fields. These practices vary over time and across regions due to variations in climate and hydrology, heterogeneity in produced water composition and quantity, and differences in regulation and industry practices.

Produced water management is subject to local, state, and regional regulations as well as operational standards set by individual treatment and disposal facilities (U.S. EPA 2018, 2020). The need for location-specific and timely information on produced water to guide appropriate operational and regulatory changes has also prompted the creation of produced water research consortiums in Texas, New Mexico, and most recently Colorado (Groundwater Protection Council 2023), each of which explore how or if produced water use outside of the oilfield can be expanded. Potential uses include agricultural irrigation; rangeland restoration; subsurface discharge for groundwater aquifer storage and recovery and hydrologic control; and municipal reuses, including potable uses and non-potable uses such as park irrigation, firefighting, dust suppression on roads, and construction (State of New Mexico and U.S. EPA 2018; U.S. EPA 2020).

Summary of the Review

We used the literature search phrases employed in the HEI Energy Research Committee's 2020 survey of the unconventional OGD (UOGD) exposure literature (HEI Energy Research Committee 2020) to search for peer-

[11] Flowback primarily contains injected treatment fluid, and consequently a higher proportion of hydraulic fracturing fluid and lower proportion of formation water than the produced water that returns to the surface after well completion during the production phase (Abualfaraj et al. 2014).

reviewed articles published between January 1, 2000, and December 20, 2023, that contribute to understanding potential human exposures to produced water. We excluded reports and data that were not published in the peer-reviewed literature, meaning those that were not included in scholarly journals subject to review and evaluation by independent experts. We also excluded topics not directly related to understanding the potential for people living in U.S. communities near OGD sites to be exposed to produced water, such as studies that exclusively described analytical methods or model development, or treatment technology. We did not include coalbed methane produced water.

The search phrases returned 327 publications. Two papers were added manually as they were known to be relevant to produced water characterization and road spreading but were not returned by the search phrases (Graber et al. 2017; Nell and Helbling 2019). The inclusion and exclusion criteria for the publications that met HEI's literature search criteria are summarized in Figure 1. These publications reported measurement or modeling of chemicals in produced water, potential contamination of surface water, groundwater, air, surface sediment, and soil by produced water, exposure and human health risk assessments, and socioeconomic characteristics of potentially exposed human populations. We entered all literature returned by this search into HEI Energy's publicly available online literature database and organized the collection under the "Produced water" tag.

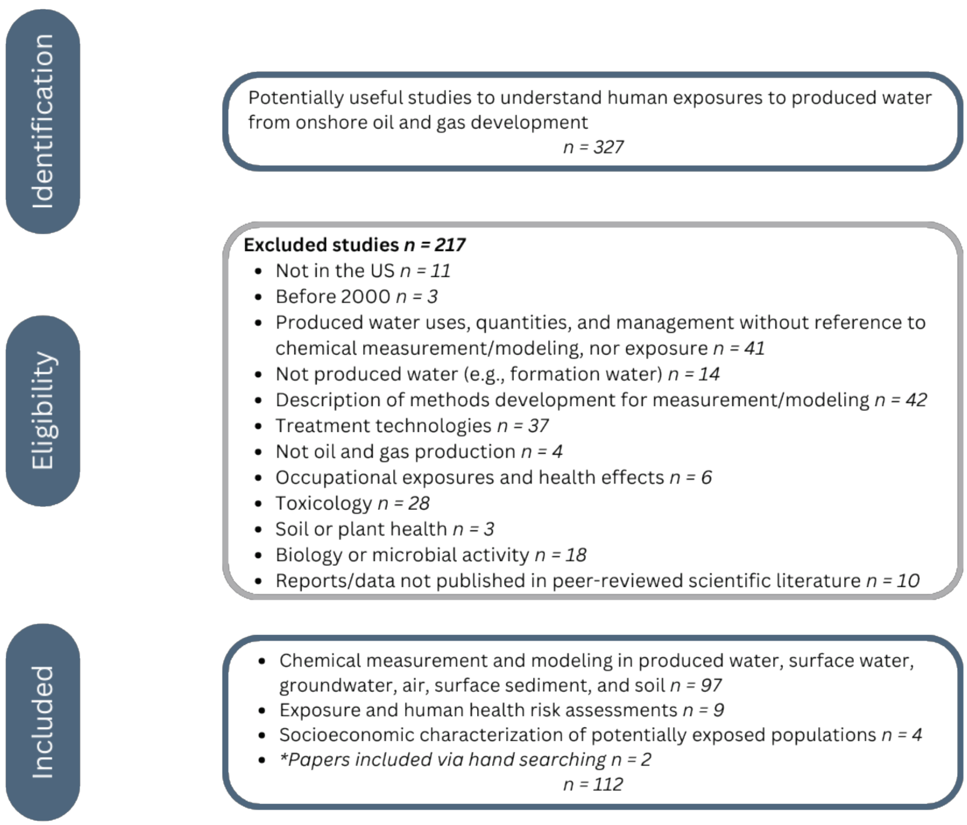

Figure 1. Study types included in this brief are screened from results of the search phrases, which initially returned a total of 327 studies. The 112 studies summarized in this brief conducted chemical measurement and modeling of produced water and environmental media (surface water, groundwater, air, surface sediment, and soil) potentially contaminated by produced water, exposure and human health risk assessments, and socioeconomic characterization of potentially exposed populations.

In this Research Brief, we summarize a total of 112 papers. Of these, 43 publications characterized produced water composition (Table 1) and 69 publications examined produced water releases to the environment and associated potential exposure pathways (Table 2).

The discussion of this literature is organized in accordance with a conceptual model of potential exposure pathways assessed in the literature (Figure 2). Because the model is limited to what was assessed in the literature, it might not depict all possible produced water exposure pathways.

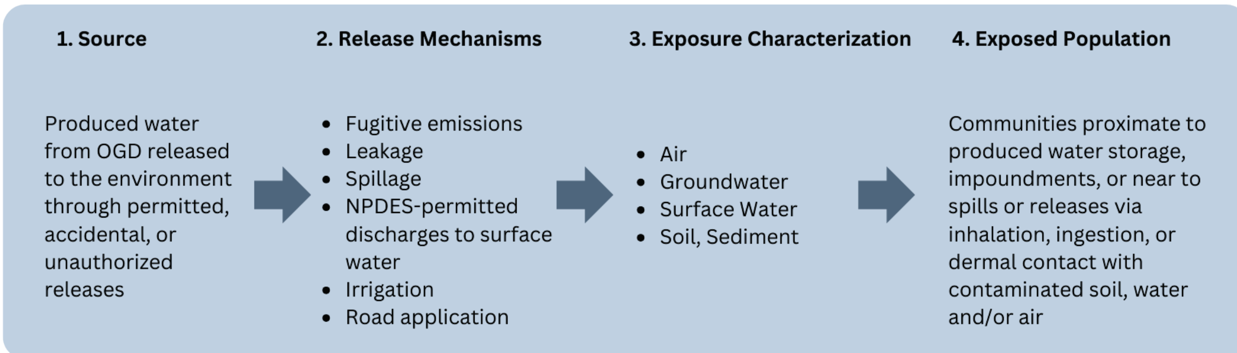

Figure 2. Potential pathways of exposure to produced water from onshore oil and gas development in the United States. The pathways reflect the literature summarized in this brief and do not necessarily include all possible exposure pathways.

Source of Potential Exposure: Produced Water Composition

The composition and quantity of produced water varies depending on the location, the type of drilling used to complete the well, well maintenance operations, the age of the well, the composition and volume of hydraulic fracturing fluid (HFF) injected in the well, and the composition of the formation water and hydrocarbons naturally existing in the specific geologic formation (U.S. EPA 2018, 2020). Onshore, untreated produced water in the United States contains varying levels of salinity, often indicated by total dissolved solids (TDS), and can be ten times more saline than sea water in some locations like the Bakken and Marcellus Formations (Blondes et al. 2019; American Geosciences Institute 2016). Produced water may also contain varying concentrations of total suspended solids (TSS), inorganic compounds, metals, metalloids such as arsenic, volatile and semi-volatile organic compounds (VOCs and SVOCs) including BTEX (benzene, toluene, ethylbenzene, and xylene) and polycyclic aromatic hydrocarbons (PAHs), naturally occurring radioactive material (NORM), ammonia, and HFF chemical additives such as surfactants, biocides, and per-and polyfluoroalkyl substances (PFAS) for well development, treatment, and maintenance (Akob et al. 2015a; Gallegos et al. 2021; Jiang et al. 2022; Liden et al. 2022; Maguire-Boyle and Barron 2014; Nell and Helbling 2019; Rosenblum et al. 2017a; Schreiber and Cozzarelli 2021; U.S. EPA 2020).

Reviews of Produced Water Composition

Seven studies conducted national and multi-region analyses of produced water characteristics or reviewed papers that conducted chemical measurements and analysis of composition (Al-Ghouti et al. 2019a; Bern et al. 2021; Luek and Gonsior 2017; McDevitt et al. 2022; Orem et al. 2014; Schreiber and Cozzarelli 2021; Sitterley et al. 2018). Analyses summarizing the main constituents in produced water reported that benzene is found in higher concentrations than the rest of the BTEX compounds, and that sodium is the dominant cation contributing to salinity in produced waters from both conventional oil and gas development (COGD) and UOGD (Al-Ghouti et al. 2019b).

Collectively, three studies summarized trends of organic compounds found in UOGD produced water in the Marcellus, Utica, New Albany, Burkett, Barnett, Fayetteville, and Eagle Ford Shales and the Permian, Denver-

Julesburg, Tongue River, and Williston Basins (Luek and Gonsior 2017; Maguire-Boyle and Barron 2014; Orem et al. 2014). Luek and Gonsior (2017) reported that VOCs and SVOCs, particularly BTEX compounds, and acetate and acetone are the most frequently analyzed and detected in produced water. Research utilizing non-targeted analyses of organic compounds exhibited an extensive array of constituents, which suggests developing new methods and standards to characterize produced water more broadly (Luek and Gonsior 2017). From a temporal perspective, Orem et al. (2014) noted that hydraulic fracturing chemicals and total organic carbon (TOC) levels decrease in produced water dramatically after 20 days of produced water recovery from a well but can persist up to 250 days after hydraulic fracturing. Furthermore, a research group studying produced water in the Denver-Julesburg Basin identified hydraulic fracturing compounds in samples taken at least 405 days post-fracturing, as discussed below. Maguire-Boyle and Barron (2014) identified several organic compounds to inform fit-for-purpose treatment methods for various reuses in produced water samples specifically from the Marcellus, Eagle Ford, and Barnett Shales. They reported halogen containing compounds in each of the samples and, due to the addition of chlorine containing oxidants to remove bacteria, recommended non-chemical treatment of produced water to mitigate the formation of chlorocarbons and organobromides.

Sitterley et al. (2018) looked at 20 samples of UOGD produced water in the western United States to identify specific compounds from the injected HFF. The investigators identified glycols, amines, and carboxylates (surfactant chemicals), which they observed were not explicitly listed in FracFocus[2] reports, but categorized as a larger blend of surfactants. They added that further information on specific compounds would support understanding of produced water chemistry, treatment, and possible toxicities.

Schreiber and Cozzarelli (2021) reviewed trends of arsenic in various regions of the United States to summarize how it can be released to the environment from hydrocarbon production, storage, transportation, use and waste management. Nationally, based on the U.S. Geological Survey (USGS) Produced Water Geochemical Database, which contains 114,943 samples of produced water sampled nationally from different types of production and 284 samples from OGD, indicated the highest concentration of arsenic (7 mg/L) was measured in produced water from COGD wells (Blondes et al. 2019). They noted that UOGD produced waters can be particularly rich in arsenic because arsenic is abundant in the shale itself. Arsenic often goes undetected because of the large amount of dilution required for analysis given the high salinity of produced water, which can lead to some higher detection limits that limit data availability. Bern et al. (2021) compared trace element concentrations between COGD and two types of UOGD produced waters (tight oil and shale gas) using the USGS Produced Water Geochemical Database and samples collected from the Marcellus Shale and the Bakken, Barnett, and Niobrara Formations. They reported similar patterns of high lithium, strontium, and barium concentrations in produced water across the three types of OGD, and larger variation in measurements of arsenic, lead, and nickel. They noted that the number of samples and number of chemicals measured varied between basins and formations, which can make comparison of composition difficult given the methodological differences of the studies.

Chen et al. (2023) and McDevitt et al. (2022) evaluated produced water composition specifically in terms of disposal and reuse. Chen et al. (2023) reported that high TDS levels (a median concentration of 95,724 mg/L) in produced water from the Permian Basin made it difficult to reuse outside of OGD, whereas produced water from the Raton and San Juan Basins had lower TDS (median concentrations of 1,940 mg/L and 11,573 mg/L, respectively) that is conducive for reuse in irrigation and livestock watering once sufficiently treated. Analyzing 18 samples of produced water from six UOGD formations across the United States, McDevitt et al. (2022) observed that DOM levels in produced water may impede treatment targeting NORM and salinity removal. Capturing data on the structural components of DOM at finer resolutions can give insights into microbial activity and petroleum thermal maturity of produced water, to help identify the specific ways DOM impedes treatment targeting these constituents.

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[2] FracFocus is a public national registry for reporting the chemicals used in hydraulic fracturing fluid (http://fracfocs.org/)

Marcellus and the Utica/Point Pleasant Shale

Abualfaraj et al. (2014) created a database with 35,000 entries of flowback water and produced water sampling data from the Marcellus between 2008 to 2010 sourced from the U.S. Environmental Protection Agency (EPA), Gas Technology Institute, Pennsylvania Department of Environmental Protection (PA DEP), Bureau of Oil and Gas Management, and New York Department of Environmental Conservation. They reported high concentrations of disinfectants, dissolved metals, organic compounds, radionuclides, TDS, and chlorinated solvents. They also observed statistically significant differences in mean concentrations between the four databases for 60% of the constituents. In another study of thirteen produced water samples from gas-liquid separator tanks from different well sites, Akob et al. (2015) also observed intraregional variability, specifically of organic chemical levels and microbial activity.

Abualfaraj et al. (2014) reported several constituents of concern, including 1,2-dichloroethane, antimony, barium, benzene, benzo(a)pyrene, chloride, dibromochloromethane, gross alpha, iron, manganese, pentachlorophenol, radium, thallium, and vinyl chloride. Ziemkiewicz and He (2015) reported iron, aluminum, manganese, lead, selenium, radium isotopes, benzene, and toluene in their analysis of the chemical evolution of flowback water in UOGD wells in the Marcellus. Additionally, they identified ethylbenzene, oil and grease, methane, ethane, and propane. They measured higher concentrations of most of these constituents in flowback water than in the injected fluid, which the investigators suggested could be from the formation water already in the shale or from interactions between chemicals in the injected fluid and minerals and organic compounds naturally existing in the shale. In an investigation of time series samples of flowback water and produced water, Luek et al. (2018) reported measuring concentrations of iodinated organic compounds that increased and stayed elevated up to 10 months after well production began. Iodinated organic compounds were nearly undetectable in HFF samples prior to injection, which led the investigators to conclude that such compounds formed in the subsurface through biotic and abiotic reactions, catalyzed by HFF, to form reactive halogen species.

Analyzing samples of injected water and produced water from 19 UOGD wells in the Marcellus, Engle and Rowan (2014) suggested two processes that shape chemical evolution in produced water during the first 90 days of production: 1) mixing of injected fluids and formation water, and 2) using injection fluids with a high concentration of sulfate, which can stimulate microbially mediated sulfate reduction. They observed that variations in sulfate and alkalinity ratios influenced barium and strontium concentrations. The study reported a greater proportion of strontium in bicarbonate-poor environments, and a greater proportion of barium in sulfate-poor environments. Chapman et al. (2012) and Capo et al. (2014) investigated strontium concentrations in UOGD wells in various parts of the Marcellus in Pennsylvania. Capo et al. (2015) reported that strontium concentrations rose steadily and plateaued within the first year of production and were potentially sourced from mixing high-TDS formation water with injected fluids. Both studies reported basin-wide uniformity of strontium isotopic ratios, and Chapman et al. (2013) suggested that strontium isotopic ratios can be used to distinguish Marcellus produced water from other sources of dissolved solids in the region.

Barbot et al. (2013) and Haluszczak et al. (2013) evaluated trends of Marcellus produced water constituents over time. When Barbot et al. (2013) analyzed 160 samples of flowback water from three well sites in southwest Pennsylvania, they reported correlations between chloride and select cation concentrations (calcium, magnesium, and strontium) and observed that barium concentrations differed based on geographic location. Haluszczak et al. (2013) reported that radium activity and concentrations of TDS, chloride, barium, iron, manganese, and major cation concentrations increased over time in flowback water samples from various datasets, including from the PA DEP and the Bureau of Oil and Gas Management. They reported that these waters contain concentrations of barium and activities of radium that often exceed EPA MCLs. Radium activity in the flowback samples exceeded the MCL of 5 pCi/L by 13 to 1,300 times. The MCL for barium is 2 mg/L and was detected up to 13,600 mg/L.

Rowan et al. (2015) collected 3 time-series and 13 grab samples of produced water from UOGD wells in the Marcellus and reported rapid increases in salinity in the first 1–2 weeks of production that eventually plateaued within a year. Tasker et al. (2020) analyzed produced water from 26 UOGD wells producing within the Utica/Point Pleasant Formation and reported higher radium activity than measured in Marcellus Shale produced water samples from the USGS Produced Water Chemical Database. The investigators suggested that radium isotopes may be the most effective way to distinguish between regional water samples as they otherwise share similar chemistries.

Oetjen and Thomas (2016) looked at patterns of diesel range organic (DRO) and gasoline range organic (GRO) compounds from both COGD and UOGD wells using flowback water data from the Shale Network, a database about water resources that may be affected by UOGD in the Northeast of the U.S. (Brantley 2011). DRO concentrations decreased in produced water sampled from COGD wells after the completion of the flowback phase but increased in produced water in UOGD wells over time. The difference in DRO concentrations between COGD and UOGD wells may suggest that the method of well completion may affect DRO concentrations. GRO concentrations did not appear to be affected by any differences in well production methods (Oetjen and Thomas 2016). Welch et al. (2021) observed that TDS and major ions (sodium, calcium, and chloride) decreased over time after natural gas well completion in two UOGD wells in the Utica/Point Pleasant Shale and one UOGD well in the Marcellus (Welch et al. 2021). The Marcellus samples had the highest concentrations of barium sourced from the shale, whereas the Utica/Point Pleasant samples had elevated strontium due to strontium-rich produced water recycled for hydraulic fracturing in the region (Welch et al. 2021). In a follow-up study analyzing produced water samples from two well pads in the Utica/Point Pleasant Shale, the investigators observed sulfate ion concentration variations in the injected fluid that could have shaped differences in barium concentrations and radium activity in flowback water between the two well pads (Welch et al. 2022). They suggested that elevated sulfate ions in the injected fluid may have the potential to sequester barium and radium within the rock formation as insoluble barite before flowback water returns to the surface.

Nell and Helbling (2019) specifically sought to quantify concentrations of HFF chemicals in 14 samples of flowback and produced water collected from two UOGD wells in West Virginia. The study also presented a generalizable approach to identify HFF chemicals in produced water to inform future toxicity and exposure assessments. Using analytical chemistry methods, the investigators reported concentrations of glutaraldehyde, used as a biocide, and compounds used as surfactants including 2-butoxyethanol, benzalkonium chloride, polyethylene glycols, and polypropylene glycols in flowback and produced waters.

Permian Basin and the Eagle Ford and Fayetteville Shales

Jiang et al. (2022) characterized produced water in the Permian region using samples collected from the wellhead, separator, storage tanks or ponds, and the back end of the disposal tank battery system at UOGD sites. Produced water samples had TDS levels ranging from 100,800 to 201,500 mg/L and varying concentrations of salts, metals, hydrocarbons, organic compounds, radionuclides, PFAS, ammonia, and HFF chemicals. Thakur et al. (2022) collected seven samples of UOGD flowback water and produced water and three samples of waste proppant sand from storage tanks in New Mexico and Texas to understand uranium and thorium occurrences in the Permian. Radium, dissolved salts, and TDS were present at elevated activities or concentrations compared to background groundwaters in the region, which the authors concluded represented a major source of radium entering the environment (Thakur et al. 2022).

Texas. Three studies analyzed produced water composition in the Texas portion of the Permian Basin (Khan et al. 2016; Liden et al. 2022; Ogbuji et al. 2022). Based on COGD and UOGD produced water geochemical data sets from 115,000 samples reported by the USGS and 45 oil and gas operations, Ogbuji et al. (2022) reported sodium, calcium, and chloride to be the dominant ions, and observed no differences in concentration trends between COGD and UOGD. They suggested that calcium-sulfate and sodium-chloride ratios could be predicted from TDS concentrations, which could help fill data gaps on constituent concentrations (Ogbuji et al. 2022). Liden et al. (2022) collected 24 samples of produced water from a variety of onsite storage, production, disposal, and treatment sites from both COGD and UOGD in the Eagle Ford Shale and Permian regions of Texas to assess the potential for direct reuse within the OGD industry. Observing inter- and intraregional variability in TOC, nitrogen, TDS, TSS, and other inorganic constituents, the investigators concluded that reuse of produced water from these regions for well development would not be feasible without multiple treatment mechanisms.

Khan et al. (2016) collected produced water samples from eight wells in the Wolfcamp Formation of the Permian. They identified alkanes, cyclohexanes, cyclopentanes, alkyl benzenes, propyl-benzenes, naphthalenes, BTEX, and heteroatomic compounds containing nitrogen, oxygen, and sulfur. They observed that salinity (represented by TDS levels) increased with depth and ranged from 105 to 162 g/L (105,000 to 162,000 mg/L). Based on the composition they measured, the investigators suggested that treatment for TSS and organics would support onsite reuses and water use for bio-energy production.

New Mexico. Two studies analyzed produced water data specifically from the New Mexico portion of the Permian Basin. Using data from the USGS Produced Water Geochemical Database and the New Mexico Water and Infrastructure Data System to gauge spatial variability of produced water quality, Chaudhary et al. (2019) reported that mean salinity of produced water was higher in shallow and younger formations in the Permian. They reported no significant association between mean TDS and depth within a given formation. Jiang et al. (2021) applied machine learning techniques based on historical produced water quality and quantity data to understand trends in composition. They reported that COGD was the main contributor to TDS levels. The Delaware Formation had the highest TDS levels (194,535 mg/L) and Artesia Formation having the lowest average (100,035 mg/L) among the basins analyzed (Jiang et al. 2021).

Arkansas. Hoelzer et al. (2016) characterized organic compounds in six samples of produced water and flowback in the Fayetteville Shale to identify transformation products that were geogenic (from the formation itself) and any chemical additives disclosed by the operators. They observed geogenic compounds (e.g., hydrocarbons) typical to the region, hydraulic fracturing additives (e.g., phthalates), and identified halogenated methanes and acetones that could be unintended byproducts of the hydraulic fracturing process. They also observed non-geogenic compounds such as chloromethyl alkanoates, which the investigators hypothesized could be intended byproducts because the compounds could be used to react to the subsurface in specific ways.

Denver-Julesburg Basin

Five studies analyzed the composition of produced water in Colorado in the Denver-Julesburg Basin (Kim et al. 2019, 2016, 2020; Lester et al. 2015; Oetjen et al. 2018b; Rosenblum et al. 2017a).

Oetjen et al. (2018) collected samples directly from a hydraulically fractured well in the Wattenberg Field in the Denver-Julesburg Basin throughout the flowback period. The investigators identified the temporal patterns of HFF additives and formation water compounds in flowback water and identified three key periods that marked changes in composition: 1) the first 1–2 days of the flowback water stage where the concentrations of surfactants and biocides from the HFF are at their highest; 2) the transition stage from flowback water to production at days 6 to 21 characterized by increases in PAHs, TOC, and dissolved organic carbon (DOC) levels; and 3) the produced water stage from days 21 to 87 that exhibited the highest levels of TDS and other ions.

Kim et al. (2016, 2019) analyzed produced water from wells that used different types of fracturing fluid over a 200-day and 63-day period, respectively. Kim et al. (2016) reported concentrations of chloride, calcium, and sodium that increased similarly to TDS levels in both wells in their study, indicating similar effects from the two HFF types used. They noted an exception for barium and magnesium levels, which differed between samples from the two wells, potentially due to differing pH levels of the two HFF types. In 2019, Kim et al. reported that produced water samples from wells that were hydraulically fractured with gel and hybrid fluids had higher TOC levels than wells fractured with slickwater fluid, likely due to organics used in the gel fluids.

Rosenblum et al. (2017a) assessed wastewater quality, volume, elemental composition and NORM activities in nine flowback water and produced water samples from a storage tank of a single UOGD well in the Denver-

Julesburg Basin in Colorado over 220 days of operation. NORM activities decreased over time, whereas TDS concentrations increased over time from 14,200 mg/L to roughly 19,000 mg/L. The investigators highlight that these TDS levels are relatively low compared to other shale basins such as the Marcellus and Bakken, but similar to levels found in other samples collected in the Denver-Julesburg Basin and the Fayetteville Shale. Rosenblum et al. (2017b) conducted a 405-day long-term field study of one UOGD well in Weld County, Colorado, to characterize concentrations of organic compounds over time. They reported that DOC concentrations decreased from 1,500 mg/L in initial flowback water to 200 mg/L in produced water toward the end of sampling. Individual BTEX compound concentrations ranged from 0.1 to 11 mg/L throughout the study. The investigators also observed non-volatile organic compounds such as polyethylene and polypropylene glycols in all samples, which may indicate they can be used as organic tracers of UOGD produced water in the region.

To assess the best treatment options for reuse, Lester et al. (2015) analyzed concentrations of DOM and trace organic and inorganic constituents of a sample of flowback water taken by an operator. The sample was delivered under a non-disclosure agreement about the sampling period, specific well location, and composition of the injected fracturing fluid. The sample contained 22,500 mg/L of TDS, 81.4 mg/L of iron, 590 mg carbon/L DOM, and fracturing fluid additives such as surfactants and acetic acid. The investigators concluded that treatment for iron, bacteria, and suspended solids would be sufficient to recycle flowback water for future OGD operations, and further treatment for DOM and salinity may allow reuse for non-OGD purposes such as crop irrigation.

Williston Basin

Gallegos et al. (2021) analyzed produced water samples collected at the wellhead[3] from 17 UOGD wells in Montana and North Dakota to help distinguish between flowback water and formation water and between produced waters from different formations. The investigators saw that produced-to-injected water ratios were reliable proxies for distinguishing flowback water from formation water, especially if there were higher concentrations of glycol ethers indicating the presence of HFF (as is typical during the flowback phase). They reported that radium activity ratios were helpful signatures in distinguishing between water produced from the Bakken Shale and the Three Forks Formations (Gallegos et al. 2021). Varonka et al. (2020) added to the knowledge on organic composition of produced water in the same region. They measured DOC (33–190 mg/L), acetate (16–40 mg/L), and cyclic ketones (<1 to 400 µg/L) concentrations in twelve produced water samples from twelve wells and observed that DOC in the Bakken samples were greater than in the Three Forks samples (Varonka et al. 2020a).

California

Chittick & Srebotnjak et al. (2017) conducted one-time analyses of produced water samples from 630 hydraulically stimulated wells in California. They found that 95% of wells contained measurable concentrations of BTEX and polycyclic aromatic hydrocarbon (PAH) compounds that, at times, exceeded EPA Maximum Contaminant Levels (MCLs). Nearly 500 wells contained lead, uranium, and other metals. Stringfellow and Camarillo (2019) analyzed data from state-mandated reporting for all well simulations, which include produced water and injected fluids sampling and characterization. They reported a "first-flush" phenomena specific to UOGD wells from diatomite and sandstone formations, where salts and metal concentrations were initially high in flowback water and decreased in concentration over time.

Accidental or Unauthorized Releases of Produced Water

Produced water can be released to the environment through evaporation, spillage or leakage from well equipment such as onsite storage tanks, or through accidental or unauthorized discharges to surface water (Akob et al. 2016; Bean et al. 2018; Drollette et al. 2015; Groundwater Protection Council 2023; Maloney et al. 2017). Produced

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[3] The wellhead is infrastructure around a production or drilling well that provides pressure control (Schlumberger 2015).

water enters the environment through these various release mechanisms and can impact different media such as air, soil, sediment, surface water and groundwater, which can include potable water sources.

Fugitive Emissions

Five studies modeled or monitored air emissions from produced water evaporation (Allen et al. 2013; Bean et al. 2018; Johnson et al. 2022; Lyman et al. 2018; Mansfield et al. 2018).

To model airborne emissions from produced water evaporation, Bean et al. (2018) collected 12 samples of flowback water from separator tanks and open-top storage tanks in the Wolfcamp Formation of the Permian Basin. Using environmental chamber experiments, the investigators reported that evaporation of flowback water could increase the contribution of ambient particulate matter (PM) in Texas from the oil and gas industry. The concentration of total volatile carbon (as determined by hydrocarbons evaporating at room temperature), averaged 29 mg carbon attributed to each liter of produced water, and photochemical oxidation processes showed 24 µg of organic PM formation attributed to each milliliter of evaporated wastewater, which the authors noted was comparable to the estimated emissions from diesel engines used in oil rigs. Allen et al. (2013) conducted a similar analysis at the national scale using direct measurements of methane emissions from various well equipment on 190 natural gas sites. The average methane emissions for the 27 well completion flowback water events monitored as a part of this study were 1.7 megagrams, which is lower than the average of 81 megagrams reported in the 2011 EPA national greenhouse gas emission inventory. The authors attributed this difference to several factors including tighter regulatory requirements since 2011, improved operating practices with more effective emission control equipment, and inherently lower emissions from wells that had uncontrolled emission releases. Johnson et al. (2022) characterized methane and other emissions from produced water and condensate[4] storage tanks from 15 natural gas production sites in West Virginia. An initial independent inspection for visible emission sources conducted by site operator personnel yielded 224 emission sources from the 15 sites, all of which went under optical gas imaging (OGI) surveillance and were subsequently analyzed to quantify emission rates. In the context of all site emissions, the investigators reported that produced water and condensate storage tanks contributed 25% of total emissions at 14.3 kg/hour. All liquid storage tanks were equipped with enclosed combustion devices (ECD) to limit emissions, and the investigators reported their emission capture efficiencies to range from 63 to 92%.

Mansfield et al. (2018) and Lyman et al. (2018) conducted companion analyses based on a 3-year measurement campaign and inventory of emissions from produced water surface impoundments in the Uinta and Upper Green River Basin in Utah and Wyoming, respectively. They reported that the impoundments accounted for 1% of methane, 13% of aromatics, 58% of alcohols (mainly methanol, constituting 91% of total VOCs), and 4 to 14% of total organic compound emissions from the basin. They acknowledged substantial uncertainties due to fluctuations in OGD processes and changes in composition of produced water over time due to evaporation and other chemical changes from exposure to the atmosphere.

Leakage

Two papers examined leakage into surface water (Akob et al. 2016; Orem et al. 2017), three examined leakages into groundwater (DiGiulio et al. 2021; Tisherman et al. 2023; Wang et al. 2021), and five evaluated impacts of leakage on various potable water sources (DiGiulio and Jackson 2016; Llewellyn et al. 2015; McMahon et al. 2017, 2019; Warner et al. 2013b).

[4] Condensate is a low-density mixture of hydrocarbon liquids typically separated out of the natural gas stream (McKinsey&Company).

Surface Water

Akob et al. (2016) and Orem et al. (2017) examined samples of surface water and streambed sediment around Underground Injection Control disposal facilities in West Virginia and Pennsylvania to study potential impacts to headwaters in the Wolf Creek watershed. Akob et al. (2016) reported that inorganic constituents such as sodium, barium, and strontium ions, known to be associated with regional UOGD produced water, were elevated in samples downstream from the disposal facility, compared to background locations, suggesting contamination from leaked wastes. Orem et al. (2017) measured chemical additives of HFF and several hydrocarbons in surface water and sediment in two sites downstream at the same disposal facility that were consistent with Marcellus UOGD produced water composition. The investigators followed up with a toxicological analysis and concluded that any human exposures to the UOGD constituents in stream sediment and water were minimal due to low contamination that was limited to sites immediately downstream of the disposal facility.

Groundwater

Using produced water data between 2007 and 2016 in the Southeast New Mexico portion of the Permian, Wang explored the potential relationships between shale oil production and constituents found in produced water (Wang 2021). Wang reported that oil well density in shale plays positively correlated with TDS, chloride, and sodium levels in produced water samples. Wang also reported that the shift in production from primarily COGD to UOGD drove substantial increases of TDS, chloride, sodium, and calcium levels in produced water. This increase in produced water constituent concentrations may pose an increased risk to groundwater in shallow aquifers due to hydrologic connections to deep formations, and Wang urged continued monitoring of produced water to protect proximal groundwater reservoirs.

In the San Joaquin Valley in California, DiGiulio et al. (2021) and Tisherman et al. (2023) evaluated risks to groundwater resources near unlined produced water disposal ponds. DiGiulio et al. (2021) used geospatial data of the disposal ponds from California's WellSTAR statewide tracking and reporting system as well as produced water composition data discharged to disposal ponds to conclude that electrical conductivity, chloride, and boron ion concentrations in the ponds were elevated. Where public groundwater monitoring data were available, the maximum levels of electrical conductivity and constituents associated with produced water (mainly TDS, chloride, boron, and BTEX compounds) were periodically observed in specified groundwater bodies in concentrations above the effluent limitations for the area. Tisherman et al. (2023) used groundwater monitoring well data proximate to two ponds to examine uranium contamination and reported that groundwater wells installed within two kilometers of the ponds contained median uranium concentrations at or above the EPA MCLs.

Potable Water Sources

Two studies attributed groundwater contamination to produced water chemicals migrating through the subsurface and into potable water sources due to historical disposal into unlined pits (DiGiulio and Jackson 2016) and less strict well construction practices (Llewellyn et al. 2015). DiGiulio & Jackson (2016) measured organic compounds and major ion concentrations in drinking water monitoring wells installed by the EPA in Pavilion Field, Wyoming, at the same depths where hydraulic fracturing and other drilling activities occur. They detected DRO and other compounds in domestic wells less than 600 meters from unlined pits that were used prior to the mid-1990s to dispose of diesel-fuel based drilling mud and production fluids (DiGiulio and Jackson 2016).

In samples from a potable groundwater aquifer used by several households, Llewellyn et al. (2015) reported organic compounds with similar geochemical signatures to Marcellus flowback water. No constituents in the samples were above regulatory drinking water levels, but they observed natural gas in the water at concentrations exceeding regulatory recommended action limits.[5] The investigators also detected 2-butoxyethanol, which may indicate UOGD contamination because of its use in hydraulic fracturing. However, they were unable to fingerprint specific contamination sources due to lack of drilling, pit, and HFF samples and recommended documentation of such details. The investigators suggested stricter well construction practices including intermediate casing strings, proper cementation, and mitigating over-pressured gas well annuli[6] (Llewellyn et al. 2015).

McMahon et al. (2019) sampled 50 domestic groundwater wells in upland areas of the Marcellus Shale regions in Pennsylvania and New York to investigate potential impacts of UOGD. Uplands are defined as areas more than 325 meters in elevation and more than 300 meters away from rivers. Some of the detected hydrocarbons, such as thermogenic methane, were detected in the samples that could indicate minor leakage from gas wells or underground storage tanks. The investigators also observed concentrations of chemicals known to be in HFF used in the region, but ruled out produced water spillage at the surface as a source based on modeled groundwater-age distributions (McMahon et al. 2019).

Two studies evaluated the potential contamination of potable groundwater resources that were overlying OGD in the Eagle Ford, Fayetteville, and Haynesville Shale production areas (McMahon et al. 2017; Warner et al. 2013b). Looking specifically at the Fayetteville Shale, Warner et al. (2013b) compared the geochemistry of major ions, trace metals, methane, and NORM in 127 drinking water wells with flowback water samples from the Fayetteville Shale. Based on an analysis of the composition of flowback water and produced water in the Fayetteville Shale, the authors reported that flowback water did not contaminate the sampled drinking water wells as the chemical and isotopic compositions of this groundwater were different, indicating no association between the groundwater and the location of nearby shale gas wells (Warner et al. 2013b).

McMahon et al. (2017) sampled 116 groundwater wells overlying the Eagle Ford, Fayetteville, and Haynesville Shale UOGD areas to investigate sources of methane and benzene (McMahon et al. 2017). The detected methane compositions indicated that most of the methane in the wells was biogenic and not from thermogenic shale gas. Eight out of nine samples where benzene was detected at low concentrations had groundwater that was more than 2,500 years old, which could indicate subsurface sources such as natural hydrocarbon migration or leaking hydrocarbon wells, and only one sample contained benzene that could be attributed to a surface release of produced water from OGD due to its age of around ten years and proximity to oil and gas wells. Overall, the investigators concluded that UOGD did not significantly contribute to methane or benzene levels in the sampled drinking water wells, but suggested that older groundwater may have been affected by subsurface or surface releases of OGD hydrocarbons even before the shale boom (McMahon et al. 2017).

Spillage

Six studies examined the impact of spillage on surface water and sediment (Cozzarelli et al. 2017, 2021; Lauer et al. 2016; Maloney et al. 2017; Oetjen et al. 2018a; Rossi et al. 2022), eight examined the impact on groundwater (Gross et al. 2013; Kanno and McCray 2021; Preston et al. 2014, 2019; Scanlon et al. 2021; Shores et al. 2017; Shores and Laituri 2018; Soriano et al. 2022), four specifically evaluated potable water sources (Abraham et al. 2023; Drollette et al. 2015; Reilly et al. 2015; Wright et al. 2019), and four looked at impacts at the watershed scale more broadly (Bonetti et al. 2021; Harkness et al. 2017; Johnson et al. 2015; Pelak and Sharma 2014).

[5] Regulatory recommended action limits are less stringent than drinking water guidelines but still call for remedial action.
[6] Annuli are the spaces between different layers of the well where fluid can flow, such as those between the wellbore, casing, and tubing (Schlumberger 2015).

Surface Water and Sediment

In January 2015, 11.4 million liters of OGD wastewater leaked from a pipeline and spilled into Blacktail Creek, a tributary of the Little Muddy River, in the Williston Basin in North Dakota. Two studies by the USGS examined this spill event to ascertain environmental signatures and effects of produced water constituents on the ecosystem at different time periods (Cozzarelli et al. 2017, 2021). Both papers referenced surface water data from upstream, background conditions to compare with samples of surface water and sediment downstream from where the spill occurred. Cozzarelli et al. (2017) reported elevated barium and strontium concentrations and radium activity in the downstream sediment six months after the spill in concentrations fifteen times the reference condition upstream. The investigators also documented the partitioning of select constituents from the aqueous phase into sediment. Cozzarelli et al. (2021) reported the sediment could become a long-term reservoir for constituents both in the creek where the spill occurred and the surrounding flood plain and could provide insight on potential exposure outside the assigned source-remediation zone. They found that barium, strontium, radium, and ammonium persisted in sediment 7.2 kilometers downstream from the spill even after 2.5 years. The team concluded that the effect of produced water constituents on the environment is still poorly understood and is highly variable depending on hydrological conditions and groundwater-surface water interactions.

Maloney et al. (2017) analyzed state databases on spill records in four states (Colorado, New Mexico, North Dakota, and Pennsylvania) from 2005 to 2014 to track volume, frequency, spill rate, and content of spillage. They summarized risks to drinking water using the U.S. Forest Service's Forest to Faucets data set to identify watersheds where spillage had occurred with the highest relative importance to drinking water. The investigators also gauged environmental risks of spillage by distance from surface water bodies. They found 6,662 reported spills, identified 21,300 UOGD wells, and reported that spill rates increased for all states except for Pennsylvania, which began to decrease in 2009. Wastewater, crude oil, drilling wastes, and HFFs were spilled the most often, and volumes ranged from 10,000 to 100,000 liters. Spillage in Pennsylvania occurred in watersheds that have the highest relative importance to drinking water compared with the other three states in the study. However, along with well-development rates, the authors note that differences in reporting requirements by the states (e.g., volumetric threshold to be considered a spill) may account for higher or lower spill rates among the states that collect these data.

Focusing on California with a similar analysis, Rossi et al. (2022) reviewed the California Governor's Office of Emergency Services (CalOES)'s HazMat database to identify trends in produced water spill incident data from 2006–2020. Using the keyword "produced water," they saw 1,029 reported incidents of produced water spillage, with the majority (65%) occurring in Kern County, which generates 71% of oil and 57% of produced water in the state. The number of spill incidents and their frequency decreased between 2006 to 2020, and 16% of the reported incidences of produced water spillage had documented effects on waterways, and no known impact on drinking water from 2016, which is when drinking water was first included in monitoring. They noted that it was unclear from the database whether groundwater monitoring was conducted following spill events and proposed restructuring the HazMat database for accessibility and clarity of data. They also recommended requiring operators to submit spill volumes in standardized measurements, as their analysis found that spillage was underreported in initial reports anywhere from 35 to 2,750% in the years 2018 to 2020.

In North Dakota, Lauer et al. (2016) collected Bakken Shale produced water, surface water, and sediment samples from locations where there was reported spillage to gauge impact on surface water quality. Compared to the background conditions of local surface water, they reported that there were elevated concentrations of dissolved salts, lead, and ammonia in surface water and elevated Ra-228 and Ra-226 activities in soil and sediment at spill sites, some of which persisted up to four years after the spill events occurred. Given the relatively long half-life of Ra-226 of about 1,600 years, Ra-226 contamination at spill sites can last thousands of years. They analyzed spill sources and volume statewide and reported that spill volumes generally ranged from 200 to 10,000 liters. Pipeline leakage was responsible for 47% of the volume but only 18% of spill events, followed by leakage from valve to piping connections and tank leakage and overflows. The investigators urged future research to focus on evaluating additional spill sites, analyzing organic contamination, and assessing downstream impacts of spillage, such as potential risks to drinking water sources and long-term ecological and possible human health impacts.

Using produced water from a hydraulically fractured well in the Denver-Julesburg Basin in Colorado, Oetjen et al. (2018) simulated a spill into agricultural soil to evaluate the transport of surfactants and metals through soil. They reported measuring no surfactants in the soil samples but measured environmentally relevant concentrations of copper, lead, and iron. They also observed a substantial decrease in the water infiltration rate of the soil; it was ten times slower than control conditions, due to the increased salinity of produced water, which could have potential impacts on crop production.

Groundwater

Through a combination of modeling and machine learning, Soriano et al. (2022) simulated groundwater contamination risk from UOGD surface spillage or shallow subsurface leakage in Pennsylvania, Ohio, and West Virginia. The machine learning models accounted for proximity to UOGD wells, hydrological position, and topography, while data on domestic groundwater uses identified populations potentially consuming contaminated groundwater. Using the 152-meter setback distance[7] as a benchmark, the investigators analyzed three scenarios: 1) no retardation (no slowing down of constituent transport in the water), 2) weakly adsorbing, and 3) strongly adsorbing. They reported that 86–90% of the pathways exceeded the setback distance in the model for constituents with no retardation, 20–43% of pathways exceeded the setback distance for weakly adsorbing contaminants, and 0% of pathways exceeded the setback distance for strongly adsorbing contaminants. Based on the percentage of constituents that passed the 152-meter mark, the researchers concluded that 21,000 to 30,000 individuals out of the population served by domestic groundwater wells were potentially vulnerable to UOGD contamination (Soriano et al. 2022).

The Prairie Pothole Region in central North America is an energy development-dense region in which the historical handling of produced water has led to the salinization of surface water and groundwater in several sites (Preston et al. 2014). In 2013, Preston et al. (2014) set out to validate a GIS-based vulnerability assessment of produced water contamination of aquatic resources conducted by the USGS. Twenty surface water and groundwater samples were collected from different areas to assess vulnerability of aquatic resources based on a Contamination Index defined as the ratio of chloride concentration to specific conductance in a water sample developed by the Montana Bureau of Mines and Geology. They reported that 19 of the 40 water samples had Contaminant Index values that indicated contamination (Preston et al. 2014). Using surface water quality monitoring data from 1988 to 2018 at Goose Lake in Montana, Preston et al. (2019) calculated subsurface chloride migration from OGD to estimate the time required for chloride levels to naturally decrease in groundwater resources. They reported that all the sites downgradient from OGD were still contaminated in 2018, but the number of extremely contaminated sites were reduced from 13 to 2 in the 30-year time frame. However, the benchmark for "extremely contaminated" sites at the time was chloride levels greater than 10,000 mg/L, which is 11.6 times greater than the EPA acute toxicity threshold for chloride. Preston et al. (2019) predicted that water-quality targets would likely only be reached in 2045 (for outwash sediment) and 2113 (for till sediment) based on EPA's acute toxicity benchmark.

Using spill reports from the Colorado Energy and Carbon Management Commission (ECMC, formerly the Oil and Gas Conservation Commission), Shores et al. (2017), Kanno and McCray (2021), and Gross et al. (2013) analyzed the fate and transport of BTEX and naphthalene in groundwater potentially contaminated by surface

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[7] The setback distance is a regulatory tool that requires OGD wells to be sited a certain distance away from existing infrastructure (Richardson et al. 2013). The 152 meter-setback is the distance set by the state of Pennsylvania between UOGD wells and groundwater wells (Soriano et al. 2022)

spillage of produced water from storage and production equipment on active well sites in the Denver-Julesburg Basin. Shores et al. (2017) observed that benzene and toluene concentrations may reach groundwater faster through coarse textured soil due to lower partition between water and sediment accumulation. Since a large fraction of produced water spillage occurs at well pads, the study specifically suggested that OGD siting be cautionary or exclusive of areas with shallow aquifers and coarsely textured soils to prevent contaminant transport over longer distances away from the well pad.

Kanno and McCray (2021) modeled benzene transport from surface spillage into the South Platte Alluvial Aquifer. The investigators reported low risk of benzene contamination of groundwater. Their analysis demonstrated increased risk with increased spill size and with storm incidences that could transport benzene from the surface into the aquifer.

In Weld County, Colorado, Gross et al. (2013) reported that BTEX concentrations exceeded the national drinking water MCLs in 90% of the samples for benzene, 30% for toluene, 12% for ethylbenzene, and 8% for xylene. However, at least 84% of the 77 reported surface spills between July 2010 to July 2011 successfully reduced BTEX levels after the remediation process determined by the ECMC Rule 900 series was implemented by operators. Using the same database, Shores and Laituri (2018) conducted a broader assessment of groundwater contamination from spillage in the county. They saw that the likelihood of contamination decreased with increased depth and that conducting fewer large-scale operations may decrease the overall volume of produced water and, by extension, potential spill volumes. The investigators gave several recommendations to operators, which include 1) choosing OGD sites carefully, taking into consideration factors such as the depth of nearby groundwater reserves, 2) conducting comprehensive chemical risk analyses and environmental sampling plans as relevant to the hydraulic fracturing processes, 3) using alternative chemicals or enhanced safety measures after identifying hazardous chemicals, and 4) actively engaging with local communities to effectively communicate information on the social, health, and environmental implications of local OGD.

Scanlon et al. (2021) evaluated water impacts of OGD in the Texas portion of the Permian Basin, including potential surface water and groundwater contamination from surface spillage and leakage from underground disposal. They gathered data from several sources including the Texas Water Development Board database, other state monitoring networks, the USGS Groundwater Toolbox, and the National Water Information System. They reported potential groundwater contamination from produced water leakage from around 70,000 abandoned oil wells. However, they were unable to confirm evidence for contamination as the state monitoring system was not designed to assess leakage from abandoned wells.

Potable Water Sources

Four studies evaluated potential contamination of potable water sources or private residential groundwater wells either by flowback water spillage or leakage of produced water stored in containment pits (Abraham et al. 2023; Drollette et al. 2015; Reilly et al. 2015; Wright et al. 2019).

Abraham et al. (2023) analyzed for the potential of 69 regulated and priority unregulated disinfection byproducts (DBPs) being formed in drinking water in Texas by spiking drinking water with COGD produced water to simulate a spill scenario. After the spiked drinking water sample was treated by chlorination and chloramination processes to disinfect it, the investigators reported it had 1.3–5x higher levels of total disinfection by-products (DBPs) compared to uncontaminated surface water treated with the same processes. In particular, chlorinated waters had the highest levels of individual DBPs that exceeded the EPA regulatory limit of 80 ug/L (the EPA regulatory limit at the time of the study's publication) in their modeling analysis, and chloraminated waters had more iodinated DBPs that had the highest levels of haloacetamides (23 ug/L). The investigators concluded that even after treatment, COGD produced water could adversely affect downstream drinking water supplies due to such DBP formation.

To assess potential contamination, Wright et al. (2019) analyzed chemical, isotopic, dissolved gas, and age-dating tracers in produced water from oilfield wells in California and in drinking water from a public supply aquifer. The study reported lower TDS levels in the aquifer than in the sampled produced water. While there were trace thermogenic methane concentrations in three of the drinking water samples, and a low concentration of petroleum hydrocarbons, the samples did not have dissolved inorganic or isotopic indicators typically associated with produced water, which suggested that stray gases and anthropogenic VOCs could have migrated from subsurface or surface sources. The investigators concluded that oilfield produced water did not contaminate the public supply aquifer potentially due to the relatively rapid flushing of the aquifer system by recharge from the Kern River.

Using several different statistical methods, Reilly et al. (2015) compared major and trace ion water chemistry of 21 residential drinking water wells in Pennsylvania with historical groundwater data, Marcellus flowback water, and other potential sources of groundwater contamination (e.g., agricultural and septic waste and road salt). The investigators reported that Marcellus flowback water did not contaminate the groundwater wells due to differences in water chemistry, but that animal waste, septic effluent, and road salt may have contaminated these wells. Similarly, Drollette et al. (2015) used inorganic chemical fingerprinting of groundwater, residence time approximations, characteristic noble gas isotopes, and spatial relationships between active shale gas extraction wells and wells with disclosed environmental health and safety violations to evaluate groundwater aquifer contamination in Pennsylvania. The study showed trace concentrations of DRO compounds and relatively lower GRO compounds in groundwater wells within one kilometer of active shale gas wells and wells with disclosed environmental health and safety violations. They did not find evidence of direct communication with deeper formations or injected fracturing fluids.

Surface Water at the Watershed Scale

Four studies assessed impacts of produced water releases in the Marcellus Shale region at the watershed and regional level in New York, Maryland, Pennsylvania, Ohio, West Virginia, and Virginia (Bonetti et al. 2021; Harkness et al. 2017; Johnson et al. 2015; Pelak and Sharma 2014).

Bonetti et al. (2021) conducted a national-level analysis to examine whether temporal and spatial well variation was associated with salt concentrations in different watersheds due to produced water spillage, surface water discharges after insufficient treatment, or leakage of HFFs. Focusing their analysis on barium, chloride, strontium, and bromide ions to serve as indicators for UOGD in a watershed, they combined a geocoded database of 46,479 UOGD wells from 25 shales with 60,783 surface water measurements taken from 2006 to 2016 across 408 watersheds. The investigators reported that small increases in barium, chloride, and strontium ion concentrations were associated with increases in new UOGD wells, but no such association existed with bromide ions. However, all ions showed small increases in concentration in sampled surface waters after the first well drilling stages began. This association was particularly strong with wells that returned larger volumes of produced water, were located over high-salinity oil and gas formations, or were closer and likely upstream of where surface waters were sampled (Bonetti et al. 2021).

Given naturally occurring methane and salinity in groundwater in many sedimentary basins, Harkness et al. (2017) analyzed geochemical variations in surface water and groundwater quality, before, during, and after hydraulic fracturing in the West Virginia part of Marcellus to delineate anthropogenic sources of contamination. However, eight samples of surface water taken near documented spill and leak sites mimicked the composition of Marcellus flowback water, which served as direct evidence of the impact of such environmental releases. Of the 105 drinking-water groundwater wells sampled, 33 wells were sampled before and after the installation of UOGD wells less than one kilometer away. The researchers found that 37% of the groundwater samples had methane concentrations above 1 ccSTP/L (cubic centimeters at standard temperature and pressure per liter) and 79% had elevated salinity with chloride levels above 50 mg/L attributed to naturally occurring upward migration of formation water.

In the Marcellus region, Pelak and Sharma (2014) collected surface water samples from 50 streams to distinguish the sources of salinity between coal mining and UOGD. They reported that some streams were impacted by mine drainage, but none demonstrated contamination by formation water or UOGD produced water. However, they acknowledged data limitations of their analysis being based on one-time samples from a few sampling stations and did not account for changes in water chemistry over time. Johnson et al. (2015) also conducted a source appropriation analysis where they set out to identify and quantify regional formation water, road salt, and produced water contributions to watersheds in the Susquehanna River Basin. They analyzed the geochemical composition of 300 stream samples collected from ten sites in four watersheds over differing seasonal flow conditions. They reported that the barium and strontium to magnesium ratio may be the geochemical signature most likely to indicate Marcellus produced water, and to distinguish between regional brine and road salt sources.

In Garfield County, Colorado, a drilling-dense region, Kassotis et al. (2020) measured endocrine bioactivities, geochemical tracers of UOGD produced water, and related organic constituents in surface water. They also analyzed reported spillage and nearby UOGD well count. They reported that elevated endocrine bioactivities of estrogen, androgen, progesterone, and glucocorticoid receptors were observed in surface water and were associated with nearby shale gas well counts and density. However, their geochemical signatures were not associated with nearby reported spillage of produced water and were dissimilar to UOGD produced water composition in the region. The investigators proposed an alternative explanation where low-saline HFFs or chemicals from well activity other than produced water were incrementally released to the environment leading to the measured endocrine activities.

Permitted Releases of Produced Water

In certain situations, produced water may be permitted for discharge to surface water. In the eastern United States, indirect discharge through off-site, commercial wastewater treatment facilities (CWTs) or publicly owned wastewater treatment works (POTWs, for conventional produced water only), is allowed (U.S. EPA 2018, 2020). In the western United States, produced water that "has a use in agriculture or wildlife propagation when discharged into navigable waters" and is "of good enough quality to be used for wildlife or livestock watering or other agricultural uses," may be discharged to surface water if it meets the effluent limitation of 35 mg/L oil and grease (40 CFR Part 435 Subpart E).

Discharge to Surface Water East of the 98th Meridian

East of the 98th meridian, which is the line of longitude in the United States that approximately defines where the climate shifts to become more humid, discharges of produced water directly to surface water are prohibited (U.S. EPA 2020). In Pennsylvania, seven studies analyzed samples of effluent and indirect discharges to surface water from POTWs (sometimes referred to as a wastewater treatment plants or WWTPs) and CWTs to evaluate whether treatment was sufficient for safe discharge of produced water (Ferrar et al. 2013; Hladik et al. 2014; Huang et al. 2018; Landis et al. 2016; Van Sice et al. 2018; Weaver et al. 2015; Wilson and Van Briesen 2013; Wilson and VanBriesen 2012).

Wilson and VanBriesen (2012) used publicly available data from the PA DEP on produced water quality, quantity, and management to evaluate whether discharges to surface water from CWTs and POTWs would negatively impact drinking water sources. Based on salt load estimates associated with produced water in their model, they reported that between 2008 to 2009, more than 50% of the TDS, including bromide, in produced water were released to surface water systems even after treatment. They observed that these discharges could negatively impact drinking water by reaching drinking water treatment plants, especially during low flow conditions. This is because increased concentrations of bromide in surface water can lead to the formation of brominated DBPs during the drinking water disinfection process. After the PA DEP requested drilling companies to voluntarily stop disposing of and treating UOGD wastewater through CWTs and POTWs in 2011, the model demonstrated that decreasing such discharges to surface water reduced TDS and bromide concentrations in surface water going to downstream drinking water treatment plants. In 2013, they reported similar results through a three-year field study in the Monongahela River sampling influent for six drinking water treatment plants. While they reported increases in bromide and chloride concentrations during low flow conditions in the summer of 2010, they observed decreases in the bromide-chloride ratios after the PA DEP's request to recycle rather than treat UOGD wastewater through CWTs and POTWs in 2011–2012, consistent with the modeling analysis in Wilson and VanBriesen (2012).

Ferrar et al. (2013) analyzed samples of surface water discharges from three WWTPs in the Marcellus region before and after it implemented the PA DEP's request in 2011 to stop treating produced water. The investigators reported that concentrations of constituents including barium, strontium, bromide, chloride, benzene, and TDS in effluent discharged from WWTPs statistically decreased in most of the samples after they implemented the PA DEP's request (Ferrar et al. 2013).

Weaver et al. (2015) modeled bromide concentrations in CWT discharges to surface water in the Allegheny River and Blacklick Creek to evaluate potential impacts on drinking water quality. The investigators used voluntarily submitted data on CWT discharges, river flow data from western Pennsylvania, and Marcellus produced water composition data to construct scenarios where produced water with different bromide concentrations were included in CWT influent. All scenarios showed elevated downstream bromide concentrations. However, the investigators specified that the actual impact on drinking water depended on the composition, volume, and discharge rate of CWT effluents, flow rate of receiving surface water body, and distance from wastewater discharge. Other factors included the TOC concentrations of the influent and the type of disinfection process which would impact the subsequent formation of brominated DBPs in drinking water. The investigators also pointed out uncertainty of bromide concentrations in the watershed coming from sources other than from oil and gas wastewater, such as from coal mine drainage and coal-fired electric plant effluent.

Huang et al. (2018) explored potential impacts of produced water management on receiving waters by spiking surface water with synthetic produced water and then chlorinating it to model DBP formation. Spiking the surface water at various percentages, they investigated the effects of both bromide and non-bromide constituents on the production of DBPs. They reported that as the percentage of spiked produced water increased, the concentration of chlorinated DBPs increased as well. Magnesium, calcium, and barium ions in produced water contributed to the increase in chlorinated DBPs, in that order. The investigators highlighted that discharges of treated produced water that contained elevated sulfate could also increase the formation of DBPs.

Hladik et al. (2014) sampled surface water from four sites along a river to ascertain if wastewater treatment plants that accepted produced water discharged effluent with greater concentrations of brominated DBPs. The four sites included one upstream to serve as a background condition, one downstream of a POTW that did not accept produced water, one downstream of an oil and gas CWT facility, and another downstream of both treatment plants. The investigators observed that the site downstream of the POTW that did not accept produced water had the highest number of DBPs. Downstream of the oil and gas CWT plant, investigators reported relatively high concentrations of two DBPs and elevated bromide concentrations that could lead to higher concentrations of brominated DBPs in drinking water.

Similarly, Landis et al. (2016) quantified the impact of a CWT facility that solely treated OGD wastes on DBP formation in the upper Allegheny River that had public drinking water plants downstream. The investigators took automated daily samples in 2012 at six sites during three seasonal two-week sampling campaigns. Taking into consideration variable river discharge rates, the investigators reported that the CWT facility discharges led to significant increases in bromide ions compared to upstream baseline concentrations, which led to small, modeled increases in total trihalomethanes, a type of chlorinated DBP. Specifically on the days where the CWT facility was actively discharging, bromide ion concentrations increased by 39 parts per billion under low river discharge conditions, and 7 parts per billion under high river discharge conditions.

Along the Allegheny River, States et al. (2013) investigated potential sources of bromide in the environment to explain the significant increase in brominated DBP concentrations in river water used as drinking water. They reported associations between elevated bromide concentrations in the river water and elevated DBP concentrations in the drinking water. A survey of the river system suggested that produced water treatment plants were contributors of bromide to the raw river water. The investigators also concluded that the Pittsburgh Water and Sewer Authority's 2010 conventional treatment process was ineffective in removing bromide from the produced water.

Five studies conducted soil and sediment monitoring and modeling analyses to assess water quality impacts of surface water disposal of treated produced water in Pennsylvania (Burgos et al. 2017; Lauer et al. 2018; Skalak et al. 2013; Van Sice et al. 2018; Warner et al. 2013a). In response to PA DEP's request in 2011 to stop surface discharge of treated UOGD produced water, Lauer et al. (2018) and Van Sice et al. (2018) conducted stream sediment monitoring around wastewater disposal sites and CWTs that processed COGD produced water to specifically analyze changes in radium activity. Van Sice et al. (2018) sampled sediments at five CWTs processing COGD produced water from 2011 to 2017 and reported that despite reduced discharges of UOGD treated produced water, radium activities in sediments downstream of the CWTs were elevated at levels often hundreds of times higher than the background upstream of these facilities. Lauer et al. (2018) collected stream sediment around three disposal sites receiving treated COGD produced water between 2014 and 2017 and similarly observed elevated concentrations of Ra-228 and Ra-226 compared to upstream, background sediments.

Warner et al. (2013a) and Burgos et al. (2017) analyzed effluents, stream water, and sediment to evaluate the impact of discharges from a treatment facility treating produced water. In the effluent, Warner et al. (2013a) reported elevated chloride, bromide, strontium, radium, and oxygen levels typical of Marcellus produced water composition. They observed that such discharges increased downstream concentrations of chloride and bromide above background conditions measured upstream of the facility. Concentrations of Ra-226 in downstream stream sediments (544–8759 Bq/kg) were around 200 times greater than upstream background sediments (22–44 Bq/kg). Burgos et al. (2017) reported similar results from their analysis of sediment cores and regulatory compliance data of surface water constituents. They reported that a surface water reservoir 10 and 19 kilometers downstream of two CWT plants had constituent concentrations that matched OGD activity from years earlier. They were able to identify this by sectioning sediment cores and analyzing which layers corresponded to the years of maximum OGD produced water disposal and whether those sediment layers had higher concentrations of salts, alkaline earth metals, organic chemicals, and radioactive radium and strontium activity that can be attributed to Marcellus Shale produced waters.

Discharge to Surface Water West of the 98th Meridian

To understand downstream impacts of National Pollutant Discharge Elimination System (NPDES)-authorized produced water discharges to surface waters of the United States west of the 98th meridian, which are permissible if they are of "good enough quality" for agriculture, livestock, or wildlife propagation, four studies analyzed constituents of minimally treated produced water discharged to surface water in different rural areas of Wyoming (McDevitt et al. 2020, 2021a; McLaughlin et al. 2020, 2021; 40 CFR Part 435 Subpart E, 2003).

McLaughlin et al. (2020b) analyzed effluent and stream samples in Wyoming where a NPDES-authorized discharge of treated produced water was occurring. The investigators observed that most anthropogenic chemical constituents were removed from the stream's water within fifteen kilometers of discharge due to volatilization, biodegradation, and sorption to sediment. They reported that inorganic constituents such as strontium, barium, and radium detected were within regulatory effluent limits at discharge and decreased in concentration downstream. Other constituents like sodium, sulfate, and boron increased in concentration due to water evaporation, as supported by the chloride-normalized metal ratios measured in the analysis in McDevitt et al. (2020).

Using surface water and sediment samples, McDevitt et al. (2021) and McLaughlin et al. (2021) evaluated the potential for naturally occurring wetlands and constructed wetlands to remove potentially harmful constituents in treated produced water discharged for beneficial use. Wetland systems, also referred to as produced water retention ponds in the study, are natural treatment systems that employ vegetation and soil to attenuate constituents via processes like sorption and biodegradation. McDevitt et al. (2021) reported that while produced water retention ponds did not decrease inorganic constituent concentrations, measurements showed that they can sequester radionuclides from produced water under oxygenic conditions. McLaughlin et al. (2021) also observed that aside from three surfactants and one biocide, more than 94% of OGD organic chemical additives were removed after sequentially passing through two constructed wetlands systems. McDevitt et al. (2020) recommended using a multi-isotope approach to accurately characterize treated produced water composition and inform best management practices.

Road Application

Tasker et al. (2018) reviewed potential environmental and human health impacts of produced water used for deicing or dust suppression using Pennsylvania and Ohio as demonstrative case studies and analyzed relevant regulations in all 50 states. They summarized that produced water spread on roads has high concentrations of salt, radioactivity, metals, and organic compounds that may leach from the road after rain events and accumulate in nearby sediment, infiltrate nearby groundwater, and run off into surface water bodies.

In the Marcellus region, Skalak et al. (2014) analyzed changes in radium, barium, calcium, and strontium levels in surface water potentially attributed to treated OGD produced water discharges from POTWs and CWTs. Across their five study sites, the investigators did not report any statistical increases in concentration of Ra-226, barium, calcium, sodium, or strontium but instead saw that road spreading of COGD produced water for de-icing led to the accumulation of these constituents in soil and sediment close to roads. Farnan et al. (2023) specifically measured the chemical composition of seventeen road applicants, inclusive of COGD produced water used for road spreading in some states, to understand potential human and environmental risks. They reported that the radium activity of calcium chloride palliatives was similar to that of produced water and could be a source of radium entering the environment. In North Dakota in between the Bakken and Three Forks Formations, Graber et al. (2017) used passive dust collectors to evaluate the efficacy of produced water as a dust suppressant on unpaved roads. Eighty-four days post-road application of produced water, they reported that produced water did not significantly reduce dust compared to sites where no produced water was applied. They also observed changes in dust composition with noted differences in molybdenum, manganese, iron, arsenic, gold, and mercury potentially attributed to produced water.

Potential Human Exposures

Nine studies assessed exposure and risk to human health (Abualfaraj et al. 2018; Bain et al. 2021; Ma et al. 2019, 2022; Redmon et al. 2021; Rish and Pfau 2018; Torres et al. 2017a, 2018; Zhang et al. 2015). Here we summarize potential human exposure described in those studies.

Potable Water Sources Contaminated by Produced Water Spillage

Abualfaraj et al. (2018) calculated the potential exposure to a surface water reservoir theoretically contaminated by a spill of flowback water, based on an analysis of flowback samples collected in the Marcellus. The investigators examined two potential scenarios: 1) dermal exposure to or ingestion and inhalation of contaminated residential tap water, and 2) swimming in a pond contaminated by the spill. The team reported that the most realistic predicted risk to human health (in order) was from radionuclides 1) inhaled, 2) ingested, or 3) through dermal exposure in residential drinking water. Additionally, barium and thallium exceeded regulatory limits for non-carcinogenic effects in their modeling analysis.

Rish and Pfau (2018) estimated health risk from ingestion of drinking water contaminated by a simulated spill of 10,000 gallons of flowback water onto soil, which is the volume of the largest recorded spill onto land in Pennsylvania between 2008 and 2011. They identified chemicals of potential concern by screening 260 chemicals in flowback water samples from 19 shale gas wells collected in 2009. The investigators reported that chloride and sodium levels would be higher than EPA guidance levels. They advised developing toxicity factors for several constituents in the samples that are lacking any health-based guidance values.

In North Dakota, Torres et al. (2017a, 2018) modeled human exposure to the radionuclides Lead-210 (Pb-210) and Radium-226 (Ra-226) from produced water spillage into surface water bodies (Torres et al. 2017a, 2018). The team assessed Pb-210 in produced water entering surface water through three potential scenarios: 1) storage tank overflow, 2) equipment leakage, and 3) spillage related to trucks transporting produced water (2017a). Due to limited data on Pb-210, the investigators used Ra-226 (a parent radionuclide of Pb-210) data from Lauer et al. (2016) to simulate lead concentrations. Across the scenarios, the probability of lead in produced water reaching surface water was low.

Additionally, Torres et al. (2018) examined three potential scenarios of human exposure: 1) ingestion of treated water from a lake contaminated by produced water, 2) consumption of potatoes irrigated with the contaminated lake water, and 3) consumption of fish caught in the contaminated lake. The investigators calculated the effective dose of Ra-226 based on three produced water samples from the Bakken Shale in North Dakota. Due to limited availability of data on Ra-226 concentrations in produced water from the Bakken Shale, the investigators simulated Ra-226 levels based on correlations with strontium, barium, and calcium levels in produced water. They predicted potentially elevated concentrations of Ra-226 activity in fish, potatoes, and drinking water, depending on the volume and composition of the produced water spill, if produced water is treated insufficiently or mishandled.

Produced Water Chemicals in Soil and Air

In the Marcellus, Zhang et al. (2015) analyzed the fate and transport of radium in three flowback water impoundments in southwestern Pennsylvania over a 2.5-year period. They summarized that Ra-226 concentrations increased over time in impoundments storing flowback water that had been reused multiple times for hydraulic fracturing and had more “impoundment sludge” developed at the bottom. Impoundment sludge can be broadly defined as the solid deposition of produced water constituents that collect over time at the bottom of an impoundment. The investigators recommended careful management such as transporting impoundment sludge to low-level radioactive waste landfills, hazardous waste landfills, or municipal and industrial solid waste landfills to avoid environmental and health risks from improper releases.

In the Marcellus region, Ma et al. (2019) modeled potential exposures from groundwater, soil, or air contaminated by produced water leakage or spillage from storage tanks. They reported that almost all organic compounds included in the study (BTEX, acetophenone, phenol, and PAHs) were adsorbed to soil within the first 100 days of the spill. In the same region, Ma et al. (2022) simulated contamination of soil and air over 10,000 days from a hypothetical produced water leak from a storage reservoir in the Marcellus. Based on modeled contaminant transport pathways, the team concluded there is a potential for inhalation exposure to BTEX, 1,2,4-trimethylbenene and 1,3,5-trimethylbenzene, with exposure through ingestion of or dermal contact with soil being less likely.

Reuses of Produced Water

Redmon et al. (2021) evaluated exposure to trace metals in California food crops irrigated with treated produced water. Using data from California’s published soil survey database, publicly available monitoring data from the Central Valley Regional Water Quality Board, and field samples of soil, edible crops, and treated produced water, they reported that irrigation with produced water was unlikely to be associated with metal concentrations of concern for health in soil or food.

In the Marcellus region inclusive of Ohio and West Virginia, Bain et al. (2021) analyzed exposure to produced water brines used for de-icing or dust suppression in residential areas such as on roads, sidewalks, or driveways through a model based on different exposure time scenarios. Using the maximum range of near-road soil radium activity observed in the region to model residential scenario, Bain et al. (2021) estimated that residents could be exposed to 296 millirems per year (depending on exposure time), which exceeds the predicted exposures from state regulatory assessments of 0.4 to 0.6 millirems per year. The investigators urged further investigation to understand exposures under scenarios involving different exposure times.

Characterizing Potentially Exposed Human Populations

Four studies characterized populations who may have been exposed to produced water (Bain et al. 2021; Johnston et al. 2016; Reilly et al. 2015; Silva et al. 2018). In the Eagle Ford area of Texas, Johnston et al. (2016) analyzed the racial composition of residents living less than 5 kilometers from an OGD disposal well. They reported that disposal wells are more often located in high-poverty areas or blocks of 80% or more people of color, and when adjusting for both rurality and poverty, the proportion of people of color living in the vicinity of a disposal well was 1.3 times higher than for non-Hispanic Whites (Johnston et al. 2016). Silva et al. (2018) conducted a similar analysis focusing on sociodemographic predictors of the locations of disposal injection wells between census block groups in Ohio. They summarized that the locations of injection wells were inversely associated with median income by block group after adjusting for other variables (Silva et al. 2018). In Cleveland, Ohio, Bain et al. (2021) also used socioeconomic data from the 2010 Census to demonstrate how areas within 40 miles of a major commuter route where produced water was applied to roads have a median household income of $27,6348, which is lower than the county median household income of $43,603 (Bain et al. 2021). In Pennsylvania, Reilly et al. (2015) characterized the area in which private residential groundwater wells were potentially contaminated with flowback water as “rural” based on land use and population density. Based on data from USGS Land Cover Data, Pennsylvania Department of Transportation, and the 2011 U.S. Census, the investigators described the area to be 61% forest, 17% agricultural, 10% water, 7% fields, and only 5% urban, with around 22 people populating every square kilometer (Reilly et al. 2015).

Knowledge Gaps Identified in the Reviewed Literature

Investigators recommended more comprehensive and accessible data reporting to be able to trace specific contaminants in produced water from sources through different media (Drollette et al. 2015; Ferrar et al. 2013; Llewellyn et al. 2015; U.S. EPA 2018; Wilson and VanBriesen 2012). Specifically, more location-specific and time-dependent measurements of chemicals in produced water can help guide suitable treatment for various reuses (Danforth et al. 2019; Scanlon et al. 2021; Sun et al. 2019). More comprehensive data on surface water quality near locations of produced water treatment or disposal facilities might help to further gauge the potential for contamination with produced water (Drollette et al. 2015; Landis et al. 2016).

Several investigators recommended more standardized and comprehensive record-keeping for spills to help identify the source of a produced water spill and how its constituents migrate in the environment (Drollette et al. 2015; Gross et al. 2013; Maloney et al. 2017; Rossi et al. 2022; Torres et al. 2017). Ferrar et al. (2013) further recommended a transparent tracking system for produced water at every step of its management.

Chen et al. (2023), Chittick and Srebotnjak (2017), and McLaughlin et al. (2020b) reported mismatches between regulated chemicals and the chemicals measured in produced water with greatest relevance to health. McLaughlin et al. (2020b) reported more than 50 geogenic and anthropogenic organic chemicals in a surface water body receiving NPDES-permitted discharges, none of which were specified in effluent limit guidelines. They noted the absence of regulatory thresholds for produced water discharges that protect people and livestock, and recommended further investigation to understand the long-term fate of produced water constituents in sediments or groundwater (McLaughlin et al. 2020). Torres et al. (2017a, 2017b) recommended research to understand public perception of risk associated with produced water and how this perception might contribute to cumulative effects on potentially exposed populations.

Summary and Next Steps

This Research Brief summarizes a growing body of peer-reviewed literature that contributes to understanding potential human exposures to produced water from oil and gas development and production. Investigators have reported multiple pathways by which people might be exposed to produced water, but assessing their significance for public health remains challenging due to the variability in produced water composition, toxicity, and environmental mobility under different meteorological, hydrological, and other local conditions, which dictates whether and to what extent exposures occur.

Future research to improve understanding of produced water releases and associated human exposures would benefit from an assessment of the evolving landscape of produced water management, including literature outside of peer-reviewed journals, and gauging the information needed for effective evaluation of exposures and health risks that can support health-protective policy. Research should include characterization of exposed populations and how exposures vary among various subpopulations, including historically marginalized communities. To assess HEI Energy's potential role in supporting such research, we will host a Research Planning Workshop in 2024. Participants will include HEI Energy's Research Committee and other experts from government, industry, community groups, NGOs, and academia. Discussion at the workshop will be informed by this Research Brief, an expanded review of the scientific peer-reviewed literature, and a review of the gray literature.

Tables

Table 1. Summary table of produced water composition studies referenced in this brief organized by location, type of water, data used for analysis, and the type of oil and gas production. (N = 43)

Study	State	Shale, Basin, or Formation	Type of water	Data	UOGD or COGD
(Abualfaraj et al. 2014)	PA, NY	Marcellus	Flowback, produced water	Database of 35,000 entries of flowback water and produced water sampling data from the EPA, Gas Technology Institute, PA DEP, Bureau of Oil and Gas Management, and the New York Department of Environmental Conservation	N/A
(Akob et al. 2015b p. 201)	PA	Devonian, Marcellus, Burket	Produced water	13 samples of produced water from gas-liquid separator tanks	N/A
(Al-Ghouti et al. 2019b)	National	N/A	Produced water	Review of various studies	N/A
(Barbot et al. 2013)	PA	Marcellus	Produced water	160 samples of flowback water and produced water	UOGD
(Bern et al. 2021)	NY, ND, TX, CO	National, Marcellus, Bakken, Barnett, Niobara	Produced water	USGS Produced Water Geochemical Database, samples of produced water from specified shales and states	Both
(Capo et al. 2014)	PA	Marcellus	Produced water	Samples of flowback water and produced water from five wells	UOGD
(Chapman et al. 2012)	PA	Marcellus	Produced water	Samples of produced water collected from wellheads and impoundments	UOGD
(Chaudhary et al. 2019)	NM	Permian	Produced water	USGS Produced Water Geochemical Database and data from the Mew Mexico Water and Infrastructure Data System	UOGD
(Chen et al. 2023)	AZ, CO, MT, NM, UT, WY	Anadarko, Permian, Raton, San Juan, Uinta, Williston	Produced water	Review of various studies	N/A
(Chittick and Srebotnjak 2017)	CA	N/A	Produced water	Data compiled from individual well reports submitted by operators	UOGD
(Engle and Rowan 2014)	PA, WV	Marcellus	Produced water	Samples of injected water and produced water from 19 UOGD wells	UOGD
(Gallegos et al. 2021)	ND, MT	Williston	Produced water	Samples of flowback water and produced water	UOGD
(Haluszczak et al. 2013)	PA	Marcellus	Flowback	22 samples of flowback water collected by the PA DEP and Bureau of Oil and Gas Management, samples of flowback water from two wells, and data from 40 COGD wells sampled in 1985	Both
(Hoelzer et al. 2016)	AK	Fayetteville	Flowback, produced water	Five samples of flowback and one sample of produced water	UOGD

Study	State	Shale, Basin, or Formation	Type of water	Data	UOGD or COGD
(Jiang et al. 2021)	NM	Permian	Produced water	USGS Produced Water Geochemical Database and data on produced water quantity from the New Mexico Oil Conservation Division	Both
(Jiang et al. 2022)	NM, TX	Permian	Produced water, surface water	Samples of produced water collected from the wellhead, separator, storage tanks or ponds, and the back end of the disposal tank battery system	UOGD
(Khan et al. 2016)	TX	Permian	Produced water	Samples of produced water from 8 wells in the Wolfcamp Formation	UOGD
(Kim et al. 2019)	CO	Denver-Julesburg	Produced water	Samples of produced water from wells hydraulically fractured with different types of fracturing fluid	UOGD
(Kim et al. 2016)	CO	Denver-Julesburg	Flowback, produced water	Samples of flowback water and produced water collected from two wells	UOGD
(Lester et al. 2015)	CO	Denver-Julesburg	Flowback	One sample of flowback water taken by an operator	UOGD
(Liden et al. 2022)	TX	Permian, Eagle Ford	Produced water	24 samples of produced water from different well equipment on various well pads	UOGD
(Luek et al. 2018)	WV	Marcellus	Produced water, Flowback, Hydraulic fracturing fluid	Time series samples of produced water, flowback water, and hydraulic fracturing fluid from two adjacent wells	UOGD
(Luek and Gonsior 2017)	PA, CO, WV, TX, AR, OH, NM, IN, KY (National)	Marcellus, Denver-Julesburg, Burkett, Fayetteville, Permian, Utica, Barnett, New Albany	Hydraulic fracturing fluid, flowback water, produced water	Review of various studies	UOGD
(Maguire-Boyle and Barron 2014)	PA, NM, TX	Marcellus, Eagle Ford, Barnett	Flowback, produced water	Samples of produced water from the three shales	UOGD
(McDevitt et al. 2022)	National	Bakken, Denver-Julesburg, Eagle Ford, Marcellus, Permian, Williston	Produced water	Review of various studies	UOGD
(Nell and Helbling 2019)	WV	Marcellus	Flowback, produced water	Fourteen samples of flowback and produced water, FracFocus for information on hydraulic fracturing chemicals	UOGD
(Oetjen and Thomas 2016)	PA, WV	Marcellus	Flowback	Flowback data from the Shale Network	Both

Study	State	Shale, Basin, or Formation	Type of water	Data	UOGD or COGD
(Oetjen et al. 2018b)	CO	Denver-Julesburg	Flowback, produced water	Flowback and produced water samples from one well over time	UOGD
(Ogbuji et al. 2022)	TX	Permian	Produced water	USGS produced water datasets and geochemical data sets from 45 oil and gas operations	UOGD
(Orem et al. 2014)	PA, IL, IN, AL, WY, MT, ND (National)	Marcellus, New Albany, Tongue River, Williston	Produced water, formation water	Review of various studies	UOGD
(Rosenblum et al. 2017a)	CO	Denver-Julesburg	Flowback, produced water	Nine samples of flowback water and produced water from a storage tank of one well taken over time	UOGD
(Rosenblum et al. 2017b)	CO	Denver-Julesburg	Flowback, produced water, hydraulic fracturing fluid	Nine samples of produced water and flowback, and samples of the injected fluids from one well measured over 405 days	UOGD
(Rowan et al. 2015)	PA	Marcellus	Produced water	Three time-series and 13 grab samples of produced water	Both
(Schreiber and Cozzarelli 2021)	National	Marcellus, Eagle Ford, Bakken, Antrim, New Albany	Produced water	Review of various studies	Both
(Sitterley et al. 2018)	CO, OK, ND, TX, WY	N/A	Flowback, produced water	20 samples of flowback and produced water collected from various shale deposits in the US	UOGD
(Stringfellow and Camarillo 2019)	CA	N/A	Produced water	Data from mandatory reporting of characterization of produced water and injected fluids from well simulation	UOGD
(Tasker et al. 2020)	PA, WV, OH	Utica/Point Pleasant	Produced water	Samples of produced water from 26 wells	UOGD
(Thakur et al. 2022)	NM, TX	Permian	Flowback, produced water, waste proppant sand	Seven samples of flowback water and produced water and three samples of waste proppant sand from storage tanks	UOGD
(Varonka et al. 2020b)	ND	Bakken, Three Forks, Williston	Produced water	12 samples of produced water from 12 wells	UOGD

Study	State	Shale, Basin, or Formation	Type of water	Data	UOGD or COGD
(Warner et al. 2014)	AK, PA, WV	Bakken, Marcellus	Produced water, flowback water, hydraulic fracturing fluid, groundwater, wastewater treatment facility effluent	39 samples of produced water from both COGD and UOGD, one sample of hydraulic fracturing fluid, 15 samples of flowback water from two wells in the Marcellus and six wells in the Fayetteville Formation, samples of shallow groundwater from a salt spring overlying the Marcellus, samples of effluent of treated OGD wastewater discharged to surface water, one sample of surface water collected at an accidental spill site	Both
(Welch et al. 2021)	OH, WV	Utica/Point Pleasant, Marcellus	Flowback, produced water	Samples of flowback water and produced water from two wells in the Utica/ Point Pleasant shale and one in the Marcellus	UOGD
(Welch et al. 2022)	OH	Utica Shale/Point Pleasant	Flowback, produced water	Samples of flowback water and produced water from five wells on two well pads	UOGD
(Ziemkiewicz and He 2015)	WV	Marcellus	Hydraulic fracturing fluid, flowback water, produced water	Samples of flowback water, hydraulic fracturing fluid, and produced water from four wells taken over time	UOGD

Table 2. Summary table of produced water studies referenced in this brief organized by location, study type, exposure medium, data used for analysis, and the type of oil and gas. *Studies on produced water composition are in Table 1.* (N = 69)

Study	State	Shale, Basin or Formation	Study Type	Exposure Medium	Data	UOGD or COGD
(Abraham et al. 2023)	TX	N/A	Water modeling	Drinking water	Samples of produced water and surface water used for drinking water	N/A
(Abualfaraj et al. 2018)	PA, WV, NY	Marcellus	Human health risk assessment	Drinking water	Samples from a freshwater reservoir into which flowback water was known to be spilled	UOGD
(Akob et al. 2016)	WV	Appalachian, Marcellus	Water monitoring	Surface water	Samples of surface water near an Underground Injection Control disposal facility	Both
(Allen et al. 2013)	National	Appalachian, Gulf Coast, Midcontinent, Rocky Mountain	Air monitoring	Air	Methane measurements from different well equipment at several development and production stages	Both
(Bain et al. 2021)	WV, OH, PA	Appalachian	Exposure assessment using water modeling	Road treatment	Samples of produced water treated for use as a deicer and dust suppressor on roads in a residential area	COGD

Study	State	Shale, Basin or Formation	Study Type	Exposure Medium	Data	UOGD or COGD
(Bean et al. 2018)	TX	Permian	Water modeling	Air	Airborne emissions measured from flowback water stored at a well site in the Wolfcamp Formation	UOGD
(Bonetti et al. 2021)	National	N/A	Water monitoring	Surface water	Samples of surface water and geocoded data on OGD well density	UOGD
(Burgos et al. 2017)	PA	Marcellus	Water monitoring, Soil monitoring	Groundwater, sediment	Samples of groundwater and sediment potentially contaminated by insufficiently treated produced water	UOGD
(Cozzarelli et al. 2021)	ND	Williston	Water monitoring	Surface water	Samples of surface water and sediments known to be contaminated by a wastewater spill	UOGD
(Cozzarelli et al. 2017)	ND	Williston	Water monitoring	Surface water	Samples of surface water and sediments known to be contaminated by a wastewater spill	UOGD
(DiGiulio and Jackson 2016b)	WY	Wind River	Water monitoring	Drinking water	Samples of domestic drinking water wells and produced water	UOGD
(DiGiulio et al. 2021)	CA	Tulare	Water monitoring	Groundwater	Samples of groundwater in the vicinity of produced water ponds	COGD
(Drollette et al. 2015)	PA	Marcellus	Water monitoring	Groundwater	Samples from private groundwater residential wells hypothesized to be contaminated by produced water and flowback water stored in containment pits	UOGD
(Farnan et al. 2023)	PA	N/A	Water monitoring	Surface water (that may be used as drinking water) and sediment	Samples of produced water treated for use as road treatment	N/A
(Ferrar et al. 2013)	PA	Marcellus	Water monitoring	Treated produced water discharged to surface water	Samples of effluent discharged from three wastewater treatment plants that processed OG wastewater	UOGD
(Graber et al. 2017)	ND	Bakken, Three Forks	Air monitoring	Air	Samples of dust from passive dust collectors positioned at various distances from a road applied with produced water	N/A
(Gross et al. 2013)	CO	Denver-Julesburg	Water monitoring	Groundwater	Samples of groundwater potentially contaminated from surface spillage of produced water from active well sites	N/A

Study	State	Shale, Basin or Formation	Study Type	Exposure Medium	Data	UOGD or COGD
(Harkness et al. 2017)	WV	Marcellus	Water monitoring	Groundwater, surface water	Samples of groundwater and surface water collected before, during, and after hydraulic fracturing in a shale gas development area.	UOGD
(Hladik et al. 2014)	PA, VA, MD, CO	N/A	Water monitoring	Treated produced water discharged to surface water	Samples of surface water collected around wastewater treatment and disposal facilities	COGD
(Huang et al. 2018)	PA	Marcellus	Water modeling	Surface water	Samples of surface water injected with OGD wastewater	UOGD
(Johnson et al. 2022)	WV	N/A	Air monitoring	Air	Emissions measured from evaporated produce water in onsite storage tanks	N/A
(Johnson et al. 2015)	NY, PA	Marcellus	Water monitoring	Groundwater, surface water	Samples of groundwater and surface water in an OGD-dense region	N/A
(Johnston et al. 2016)	TX	Eagle Ford	Socio-economic	N/A	Locations of OGD wastewater disposal wells and socioeconomic data	N/A
(Kanno and McCray 2021)	CO	Denver-Julesburg Basin	Water modeling	Groundwater	ECMC (formerly COGCC) data on reported spillage of produced water	UOGD
(Kassotis et al. 2020)	CO	N/A	Water monitoring	Groundwater, surface water	Measurements of endocrine bioactivities and UOGD geochemical tracers of wastewater in groundwater and surface water samples	UOGD
(Landis et al. 2016)	PA	Marcellus	Water monitoring	Surface water	Samples of surface water potentially contaminated by insufficiently treated OGD wastewater	Both
(Lauer et al. 2016)	ND	Bakken, Williston	Water monitoring, Soil monitoring	Surface water, soil	Samples of surface water, produced water, and soil	UOGD
(Lauer et al. 2018)	PA	Marcellus	Soil monitoring	Sediment in surface water near wastewater disposal sites	Samples of surface water sediment	COGD
(Llewellyn et al. 2015)	PA	Marcellus	Water monitoring	Drinking water	Samples of aquifer groundwater hypothesized to be contaminated with flowback water	UOGD
(Lyman et al. 2018)	UT, WY	Uintah, Upper Green River	Air monitoring	Air	Emission measurements from produced water impoundments taken over a 3-year period	N/A

Study	State	Shale, Basin or Formation	Study Type	Exposure Medium	Data	UOGD or COGD
(Ma et al. 2019)	PA, WV	Marcellus	Exposure assessment using water modeling	Groundwater, soil, air	Estimated volume of produced water and potential chemical pathways of constituents	UOGD
(Ma et al. 2022)	PA, WV	Marcellus	Human health risk assessment	Groundwater, soil, air	Return water from several horizontal wells	UOGD
(Maloney et al. 2017)	CO, ND, NM, PA	N/A	Water monitoring	Groundwater, soil, air	Samples of return water from several horizontal wells	UOGD
(Mansfield et al. 2018)	UT, WY	Uinta, Upper Green River	Air monitoring	Air	Emission measurements from produced water impoundments taken over a 3-year period	N/A
(McDevitt et al. 2020)	WY	N/A	Water monitoring	Surface water	Samples of treated produced water discharged to surface water intended for irrigation	Both
(McDevitt et al. 2021b)	WY	N/A	Water monitoring, sediment monitoring	Surface water	Samples from 3 NPDES discharge facilities and 5 wetlands	N/A
(McLaughlin et al. 2020)	WY	N/A	Water monitoring	N/A	Samples of surface water collected downstream of discharge location of produced water treated for irrigation	N/A
(McLaughlin et al. 2021)	WY	N/A	Water monitoring	Surface water	Samples of produced water undergoing passive treatment in constructed wetlands	N/A
(McMahon et al. 2019)	NY, PA	Marcellus	Water monitoring	Groundwater	Samples of groundwater in 50 domestic wells in upland areas of the Marcellus region	UOGD
(McMahon et al. 2017 p. 201)	TX	Eagle Ford, Fayetteville, Haynesville	Water monitoring	Groundwater	Samples of groundwater from 116 wells in an UOGD-dense region	UOGD
(Oetjen et al. 2018a p. 201)	CO	Denver-Julesburg	Soil modeling	Soil, food (crop)	Simulated produced water spill onto agricultural soil	UOGD
(Orem et al. 2017)	PA	Marcellus	Water monitoring, sediment monitoring	Surface water	Samples of surface water and sediment next to an underground injection disposal facility handling UOGD wastewater	UOGD
(Pelak and Sharma 2014)	PA	Marcellus	Water monitoring	Surface water	Samples of surface water from 50 streams in a UOGD-dense region	UOGD
(Preston et al. 2014)	MT	Williston	Water monitoring and modeling	Groundwater and surface water potentially contaminated by produced water	Samples of groundwater and surface water in an energy development-dense region	N/A

Study	State	Shale, Basin or Formation	Study Type	Exposure Medium	Data	UOGD or COGD
(Preston et al. 2019)	MT	Williston	Water monitoring	Groundwater and surface water potentially contaminate by produced water	Samples of groundwater and surface water in an energy development-dense region	N/A
(Redmon et al. 2021)	CA	N/A	Human health risk assessment	Food (crop)	Samples of produced water treated for irrigation	COGD
(Reilly et al. 2015)	PA	Marcellus	Water monitoring	Drinking water	Samples of flowback water and drinking water from 21 residential water wells	N/A
(Rish and Pfau 2018)	PA, WV	Marcellus	Human health risk assessment	Drinking water	Samples of flowback water from 19 shale gas wells	N/A
(Rossi et al. 2022)	CA	N/A	Water monitoring	N/A	Produced water spill records	Both
(Scanlon et al. 2021)	TX	Permian	Water monitoring	Groundwater, surface water	Samples of groundwater and surface water contaminated by produced water spillage	UOGD
(Shores and Laituri 2018)	CO	Denver-Julesburg	Water monitoring	Groundwater	Publicly available produced water production and spill data from the ECMC (formerly COGCC) database	N/A
(Shores et al. 2017)	CO	Denver-Julesburg	Water modeling	Groundwater	Produced water spill records	UOGD
(Silva et al. 2018)	OH	N/A	Socio-economic	N/A	Locations of Class II underground injection wells	N/A
(Skalak et al. 2014)	PA	Marcellus	Soil monitoring and modeling	Sediment potentially contaminated by treated produced water from wastewater treatment plants	Samples of sediment surrounding wastewater treatment plants	Both
(Soriano et al. 2022)	National	Appalachian	Exposure assessment using water modeling	Groundwater	No samples taken; Modeling groundwater flow and contaminant transport	UOGD
(States et al. 2013)	PA	Marcellus	Water monitoring	Drinking water, surface water	Samples of surface water and drinking water	N/A
(Tasker et al. 2018)	National	N/A	Water monitoring and modeling	Surface water and sediment	Samples of produced water used for road treatment from PA	Both
(Tisherman et al. 2023)	CA	San Joaquin Valley	Water monitoring	Groundwater	Samples of produced water from produced water storage ponds and samples of groundwater in their vicinity	N/A

Study	State	Shale, Basin or Formation	Study Type	Exposure Medium	Data	UOGD or COGD
(Torres et al. 2018)	ND	Bakken	Exposure assessment using water modeling	Food (fish, crop) consumption, Drinking water	Simulated Ra-226 levels in produced water based on correlations with Sr, Ba, Ca- ions	UOGD
(Torres et al. 2017a p. 201)	ND	Bakken Shale	Exposure assessment using water modeling	Surface water, drinking water	Modelled pathways of lead isotope Pb-210 reaching drinking water through produced water spillage into surface water using data from Lauer et al. (2016)	UOGD
(Van Sice et al. 2018)	PA	Marcellus	Soil monitoring	Sediment in surface water	Samples of sediment cores in surface water bodies around wastewater treatment plants	Both
(Wang 2021)	NM	Permian	Water monitoring	Groundwater	Samples of produced water from active wells	Both
(Warner et al. 2013a)	PA	Marcellus	Water monitoring, Soil monitoring	Surface water, sediment	Samples of effluent from wastewater treatment plants to surface water and sediments	Both
(Warner et al. 2013b)	AR	Fayetteville Shale	Water monitoring	Groundwater, drinking water	Samples of groundwater in shallow aquifers overlying producing shale formations	N/A
(Weaver et al. 2015)	PA	Marcellus	Water modeling	Drinking water	Samples of surface water around commercial wastewater treatment plant	Both
(Wilson and Van Briesen 2013)	PA, WV	Marcellus	Water monitoring	Surface water, drinking water	Samples of surface water taken over a 3-year period	Both
(Wilson and VanBriesen 2012)	PA	Marcellus	Water modeling	Surface water, drinking water	No samples taken; data from the Pennsylvania Department of Environmental Protection	Both
(Wright et al. 2019)	CA	Fruitvale Oil Field	Water monitoring	Drinking water	Samples of groundwater and produced water	N/A
(Zhang et al. 2015)	PA	Marcellus	Exposure assessment using water modeling	Flowback	Samples of flowback water over a 2.5-year period	N/A

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