

Research Report 233, *Hydrocarbon Extraction and Risk to Groundwater in Pennsylvania: Part 2: An Analysis of Water Quality in the Oldest Hydrocarbon Basin in the United States*, by J. Baka and S.L. Brantley* et al.

INTRODUCTION

The advent of high-volume and multistage hydraulic fracturing combined with horizontal drilling in the early 2000s has led to a substantial increase in onshore oil and natural gas development in the United States. This increase in the rate and scale of energy development now includes longer periods of development, with more materials being brought to and from larger well pads, and more solid and liquid waste being generated on-site. This rapid expansion has increased opportunities for human exposure to chemical and nonchemical stressors and has generated concerns about their effects on human health.

This form of oil and gas production — often referred to as unconventional oil and gas development (UOGD)[†] — allows operators to access oil and gas in sandstone or shale formations. While UOGD has expanded into new areas, it is often co-located in areas with a history of extractive energy practices, such as conventional oil and gas development or coal mining. A challenge to understanding exposure to UOGD in areas with legacy energy development is that many potential contaminants of concern are the same.

In 2020, HEI Energy issued Request for Applications [RFA E20-2: Community Exposures Associated with Unconventional Oil and Natural Gas Development](#) to fund research to assess community exposures to chemicals in surface or groundwater originating from UOGD. Specifically, HEI was interested in research that (1) would help determine the UOGD processes that have led or may lead to releases to water, (2) quantify the magnitude, frequency, and duration of potential exposures to chemicals released to water from specific UOGD processes, and (3) identify and define the influence of various factors (e.g., varying geology) on exposures. The proposed research would engage local communities and should maximize the generalizability of the research, inform

Jennifer Baka's and Susan L. Brantley's 1-year study, "An Analysis of Water Quality in the Oldest Hydrocarbon Basin in the United States," began in May 2024. Total expenditures were \$350,771. The draft Investigators' Report from Baka, Brantley, and colleagues was received for review in March 2025. A revised report, received in September 2025, was accepted by the HEI Energy Review Committee in October 2025.

During the review process, the HEI Energy Review Committee and the investigators had the opportunity to exchange comments and clarify issues in both the Investigators' Report and the Review Committee's Commentary. This Commentary has not been reviewed by public or private party institutions, including those that support HEI Energy, and may not reflect the views of these parties; thus, no endorsements by them should be inferred.

*Co-principal investigators.

†A list of abbreviations and other terms appears at the end of this volume.

decision-making, and, to the extent practicable, distinguish potential UOGD exposures from those associated with other conventional oil and gas development and any other background sources.

In response to the RFA, Drs. Jennifer Baka and Susan L. Brantley (The Pennsylvania State University) submitted a successfully funded application.¹ Baka, Brantley, and colleagues used statistical analyses and machine learning to identify links between various UOGD sources and potential water contamination and used focus groups to understand community concerns regarding UOGD. During their initial investigation, the investigators found evidence of potential groundwater contamination in localized areas, and they reported that residents in Southwestern Pennsylvania were principally concerned about potential health effects of UOGD related to water quality, waste disposal, and radioactive contaminants. Drs. Baka and Brantley, therefore, additionally proposed conducting water quality surveys in areas where evidence suggested that groundwater may have been contaminated by UOGD. HEI's Energy Research Committee recommended funding this additional study because it added value to the ongoing research by measuring water quality in areas where their research suggested groundwater might be contaminated by UOGD and by addressing concerns of people living in these locations.

This Commentary provides the HEI Energy Review Committee's independent evaluation of Part 2 of the study, entitled "An Analysis of Water Quality in the Oldest Hydrocarbon Basin in the USA." It is intended to aid the sponsors of HEI Energy and the public by highlighting both the strengths and limitations of the study and by placing the results presented in the Investigators' Report in a broader scientific and regulatory context.

SCIENTIFIC AND REGULATORY BACKGROUND

UOGD OVERVIEW

UOGD refers to the development and production of oil and natural gas through multistage hydraulic fracturing in horizontal wells.² UOGD processes occur on and off the well pad and include

- **Field development:** exploration, pad preparation, vertical and horizontal drilling, well completion (casing and cementing, perforating, acidizing, hydraulic fracturing, millout, flowback, and well testing) in preparation for production, and management of wastes

- **Production operations:** extraction, gathering, processing, and field compression of gas extraction and processing of oil and natural gas condensates; management of produced water and wastes; and construction and operation of field production facilities
- **Post-production:** well closure and land reclamation

High-volume, multistage hydraulic fracturing along lengthy horizontal wells — often extending more than a mile — injects millions of gallons of water and chemicals, sometimes in proprietary mixtures, into tight formations under high pressures to release oil or natural gas. This mixture of water and anthropogenic chemicals, along with naturally occurring compounds (such as arsenic or petroleum hydrocarbons), is returned to the surface during flowback. Oil and gas wastewater, known as produced water, is generated at the onset of the production phase and continues to be generated over the life of the well.

Although some UOGD operations are regulated at the federal level under the Clean Air Act, the Clean Water Act, and the Safe Drinking Water Act, state-level regulations play a larger role in governing UOGD more generally. Such regulations vary among states, with some states defining minimum setback distances between UOGD and specific land uses, such as residential homes and schools, to protect local populations.

UOGD AND WATER QUALITY

The rapid expansion of UOGD has given rise to concerns about effects on human health from potential exposure to contamination of water sources. This concern is particularly acute in rural areas where many residents rely on private groundwater wells. An early review by the US Environmental Protection Agency (US EPA) did not identify extensive contamination of water related to UOGD but cited instances in which contamination has occurred.³ To date, relatively few studies have examined the likelihood or frequency of exposure to drinking water sources potentially contaminated by UOGD.^{4,5}

UOGD-related chemical releases to surface or groundwater can result from authorized or accidental discharges to the environment. Examples of authorized releases include permitted discharge of produced water to surface water or for applications outside the oil and gas production site (e.g., road treatments for dust or ice). Although protections have been put in place to prevent unintentional chemical releases to groundwater and surface water, releases can occur as a result of wellbore failures, malfunctioning equipment, or other accidental conditions.⁶

Research on changes in surface water or groundwater quality from accidental UOGD releases is challenging given the practical limits on knowing when and where such releases might occur. When accidental releases do occur, determining the extent and severity of impacts and the subsurface conditions that influence the mobility of contaminants often requires substantial effort and resources.

One of the major challenges to understanding or quantifying potential human exposures to UOGD-contaminated water is distinguishing UOGD-related exposures from other geogenic or anthropogenic sources of the same chemicals. Many UOGD basins overlap with ongoing or historical conventional oil and gas development or coal extraction. Furthermore, many of the contaminants associated with leaks of oil and natural gas occur naturally or have other possible sources. Because produced water is highly saline, contamination from produced water can be inferred through increased salt species. For example, barium and strontium have been used previously as tracers for produced water released to the environment.⁷ While a subset of water quality studies has used isotopic tracers and other markers associated with UOGD to isolate its effects from other sources, this type of fingerprinting is not typically conducted outside of specialized labs or for research purposes.⁵

The amount of data on levels of UOGD-related chemicals in the environment continues to increase along with efforts to use the data to quantify human exposure. In [Part 1](#) of the study, Baka, Brantley, Xue, and colleagues used previously collected, publicly available data to predict areas of potential contamination.^{1,8} Part 2 of the study is designed to evaluate these predictions and address community concerns about contamination in privately owned drinking water wells by collecting and analyzing new water samples.

STUDY OBJECTIVES AND APPROACH

The overarching objective of this study was to confirm or refute the investigators' previous findings in [Part 1](#) and evaluate potential exposures to contaminants from UOGD through drinking water. The original study, based on publicly available water quality data primarily collected before 2014, suggested slight increases in groundwater salinity potentially linked to UOGD activities, such as produced water spills or surface leaks. In Part 2, discussed here, Baka, Brantley, and colleagues collected water samples near hotspots, impoundments, and spills for evidence of ongoing contamination from UOGD-related analytes in Southwestern Pennsylvania. The investigators analyzed water quality to address two questions. The first was whether drinking water sources contain contaminants associated with UOGD that are of concern for human health. The second was whether water sources identified in [Part 1](#) of the study as being at elevated risk of contamination from UOGD exhibited evidence of actual impact attributable to those activities.

To achieve their objectives, the investigators conducted multiple field campaigns in 2024 to collect and analyze water samples from private groundwater wells, springs, and streams in areas potentially affected by UOGD to compare with samples taken outside those areas. They also identified "goodwill" sample sites to increase goodwill and interest in the study. They then surveyed residents using these water sources to assess any potential exposures if evidence of contamination was found.

The investigators focused on the following analytes: measures of salinity that may indicate potential impacts from UOGD wastewater; analytes found in produced water at higher concentrations than other types of wastewaters; and analytes that are indicators of contamination given their sensitivity to dissolved oxygen and other ambient chemical conditions. Overall, the investigators focused primarily on produced water-related chemicals that are of concern to human health to better understand the effects of exposure to oil and gas development through drinking water. Therefore, the investigators compared the results to US EPA Drinking Water Standards or, lacking those, other health-based benchmarks.

Finally, they conducted a literature review to determine possible health risks resulting from exposure to any metals and metalloids identified in the water sampling analysis.

SUMMARY OF METHODS

SITE IDENTIFICATION

The investigators defined three types of sites for sampling (hotspots, impoundments, and spill sites), collectively referred to as “treatment” areas. “Hotspot” areas occurred in locations where groundwater chemistry showed evidence that chloride concentrations were increased near one or more unconventional oil and gas wells,⁹ and sample sites were defined to be within a 2-km radius of unconventional oil and gas wells.

“Impoundment” sites were defined as those located within 2 km of produced water impoundments that were ultimately directed by the Pennsylvania Department of Environmental Protection to either close or store only fresh water. Well pad locations for these impoundments were used as the centroid of the area targeted for water sampling.

“Spill” sites were defined to be within a 3-km radius of three spills that had occurred in Greene County in 2022 and 2023, and a produced water spill that occurred during the ongoing water sampling campaign in September 2024. The sampling area was expanded from 2–3 km because of low population density within the original buffer zone. Additionally, the investigators included 12 UOGD-related brownfield sites in Washington County in the spill site sample sets.

Finally, “control” sites were defined by the investigators to be located within 5 and 7 km from the centroids of impoundments and hotspots and more than 5 km from the recent spill or brownfield sites.

RECRUITMENT AND SAMPLING

The investigators used information from tax records to identify homes within the three types of treatment areas and control areas. Overall, the investigators were able to recruit 68 volunteers who would allow their private water sources to

be sampled within the treatment and control areas. They also collected water samples from 13 “goodwill” sites that did not meet the outlined criteria but were included to generate interest and goodwill in the study. They sampled 14 homes that were thought to represent control sites but were ultimately determined to be less than 5 km from a spill. Those were included in the goodwill sample set.

During seven field campaigns conducted between May 2024 and November 2024, the investigators used a standardized sampling plan to collect 97 water samples from 79 groundwater wells, 14 springs, and four streams at 94 sites, comprised of 91 residential properties and three public sites. Sixty-two samples were collected from treatment areas, roughly evenly distributed among the three treatment types (hotspots, impoundments, and spill sites), with some samples drawn from overlapping treatments (**Commentary Figure 1**). An additional eight samples came from control areas, and 27 in total were classified as goodwill samples.

FIELD WORK

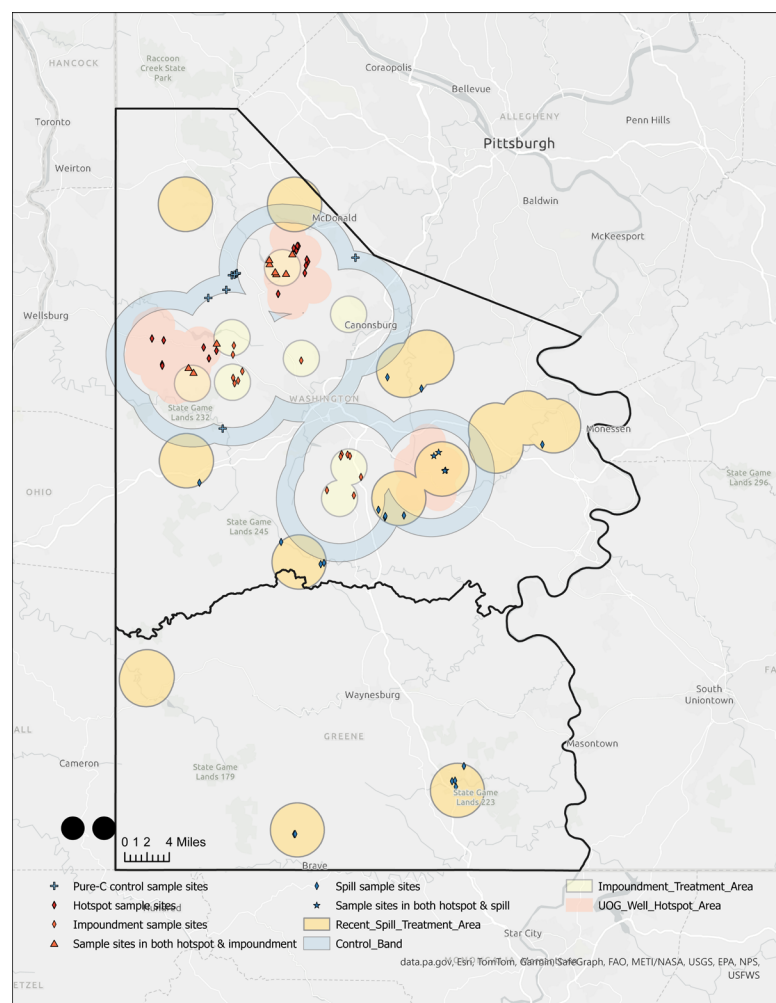
Water Sampling and Chemical Analysis

Baka, Brantley, and colleagues analyzed samples from each site for six field parameters and a range of chemical analytes. Details of these analyses are summarized in **Commentary Table 1** and in the IR Appendix A.

The investigators selected these analytes for two reasons. First, *Part 1* of this study had shown these analytes were the chemical species most likely to be elevated if UOGD contamination had occurred. Specific conductivity, chloride, and sodium are measures of groundwater salinity that may indicate potential impacts from UOGD wastewater. Other analytes were chosen because (1) they are found in produced water at higher concentrations than other types of wastewaters, or (2) are indicators of contamination given their sensitivity to dissolved oxygen and other ambient chemical conditions. However, the investigators focused primarily on produced water-related chemicals that are of concern to human health to better understand the effects of exposure to oil and gas development through drinking water.

Survey Design

The investigators developed and administered a household survey to better characterize household demographics, drinking water sources, and land use practices of sampled homes. The survey sought to solicit information on possible exposure pathways to any contaminants — should they be found — in residential water sources through questions on household water systems and use, water well characteristics (including well construction, screening levels, and well-depth estimations), and resident demographics.



Commentary Figure 1. Map of the study treatment and control areas and sample locations in Washington and Greene Counties, Pennsylvania.
Source: Investigators' Report Figure 1.

DATA ANALYSIS

To determine whether the water samples had chemicals at concentrations of concern for human health, the investigators compared the results to US EPA Primary and Secondary Drinking Water Standards^{10,11} and, when these standards were not available, other health-based benchmarks established by federal agencies.

Statistical and Geospatial Analyses

The investigators employed several different statistical analyses to elucidate any potential effects specifically on groundwater from UOGD. See **Commentary Table 2** for a summary of the datasets and comparative and geostatistical methods used in the study. For this assessment, they excluded stream samples because surface water chemistry is influenced by different hydrologic processes. To assess whether groundwater in the treatment areas exhibited higher analyte concentrations than groundwater did in the control areas, the investigators used two nonparametric statistical tests, which can be applied under various assumptions of the underlying dataset. The investigators applied the Benjamini-Hochberg

procedure to account for potential false discoveries, which are significant results that appear real but are actually due to chance. Additionally, the investigators conducted geospatial analyses using a combination of regression and correlation methods to evaluate relationships between analyte concentrations and distance from UOGD wells.

Origin of Salt and Gas Analytes

To develop additional lines of evidence for evaluating potential UOGD impacts on groundwater in the treatment areas, the researchers used isotopic data and element ratios to interpret the origin of light hydrocarbon gases and major elements in the water samples.

First, they plotted strontium isotopic signatures (⁸⁷Sr/⁸⁶Sr) against strontium-to-chloride ratios ([Sr]/[Cl]) for the groundwater samples and compared these values with regional ranges for UOGD produced water. The investigators also compared strontium isotopic signatures alone across treatment and control areas to those from conventional and UOGD produced water.

Commentary Table 1. Summary of Analytical Methods of Field Parameters and Water Sample Analytes

Analytes	Method
Field Parameters and General Water Quality Characteristics	
pH, temperature, dissolved oxygen, specific conductance	YSI ProDSS multiparameter digital water quality meter with pH/ORP (oxidation reduction potential), dissolved oxygen, conductivity and temperature sensors
Methane concentration (in air)	Bascom-Turner Gas Rover
Radon	Durridge RAD7 radon detector with H2O attachment
Alkalinity	Sulfuric acid titration
Anions	
Chloride, fluoride, bromide, sulfate, nitrate	Ion chromatography (IC)
Major Elements	
Aluminum, barium, calcium, iron, potassium, magnesium, manganese, sodium, phosphorus, silicon, strontium	Inductively coupled plasma atomic emission spectroscopy (ICP-AES)
Trace Elements	
Lithium, beryllium, nickel, copper, arsenic, cadmium, thallium, lead, uranium	Inductively coupled plasma mass spectrometer (ICP-MS)
Dissolved Carbon Compounds	
Dissolved inorganic carbon	TOC-L analyzer
Hydrocarbon gases (methane, ethane, propane)	Gas chromatography at commercial lab (IsoTech Laboratories)
Isotopes	
Strontium (87/86 Sr)	Thermal ionization mass spectrometry (TIMS)
Methane ($\delta^{13}\text{C}$, δD), ethane ($\delta^{13}\text{C}$)	Chromatographic separation followed by combustion and dual-inlet isotope ratio mass spectrometry
Radionuclides	
Radium	Gamma Ray Spectrometer
Gross alpha	Alpha disintegrations were measured using a PerkinElmer Tri-Carb Liquid Scintillation Analyzer
Volatile Organic Compounds	
Benzene, toluene, ethylbenzene, and xylene (BTEX)	Headspace gas chromatography coupled with mass spectrometry (GC MS/MS)

To assess gas origins, the investigators plotted methane concentrations (expressed as the fraction of methane relative to the sum of ethane and propane) against the carbon-13 isotopic signature of the methane measured in groundwater.

Finally, the investigators examined chloride-to-bromide ratios to evaluate potential chloride sources such as organic waste, road salt, or deep formation water.

Literature Review

The investigators searched the scientific literature for studies assessing the potential human health effects associated with exposure to water contaminated with metals or

metalloids. They used findings from the literature search to contextualize findings in outreach materials

RESULTS DISSEMINATION

As described in Appendix B of the Investigators' Report, the investigators developed a Community Engagement Plan with their approach to disseminating the results of the water sampling campaign. The investigators provided all participants with letters written at a 5th-grade reading level. Additionally, the investigators held a community outreach session to share results in person and be available to answer any questions.

Commentary Table 2. Summary of Statistical Methods

Analysis Type	Treatment Areas ^a	Method	Rationale
Comparison with standards or other guidelines (IR Appendix E)	All samples: $n = 97$ (79 groundwater wells, 14 springs, 4 streams)	Compare all values with standards ^b or other guidelines (where available)	Determine whether residents are potentially exposed to contaminants of concern through drinking water
Descriptive statistics (IR Appendix D)	Total sample set: $n = 90$ samples ^c (76 groundwater wells; 14 springs), for each chemical analyte	Minimum and maximum concentration; mean and median concentrations; concentrations at 5th, 25th, 75th, and 95th percentiles	Describe main characteristics of the dataset
Statistical comparison of sample treatment groups (IR Tables 6–7)	$n = 63$ samples ^d for each chemical analyte Samples within hotspots ($n = 30$), impoundment ($n = 24$), and/or recent spill areas ($n = 17$) versus the control areas ($n = 8$)	Nonparametric tests: Wilcoxon–Mann–Whitney rank sum (WMW) test, assumes homoscedastic conditions (similarly shaped distributions), and the Brunner–Munzel (BM) test, assumes heteroscedastic conditions (nonsimilar distributions)	Determine whether the treatment groups are significantly different from the control areas
Geospatial analysis (IR Tables 8–10; IR Appendix C)	$n = 63$ samples ^d for concentrations of the following chemical analytes: Specific conductivity, chloride, sodium, sulfate, barium, strontium, bromide, iron, methane, radon, radium-226, radium-228 Samples within hotspots ($n = 30$), impoundment ($n = 24$), and/or recent spill areas ($n = 17$) versus the control areas ($n = 8$)	Ordinary Least Squares (OLS) linear regression Spearman rank correlation Kendall's tau Theil–Sen (ATS) slope estimator	Examine the correlations between concentration of brine- or hydrocarbon-related chemical species relative to the closest wells within hotspots, impoundments or recent spills, and quantify the strength, direction and magnitude of observed trends

^aSome water sources fell within multiple areas of treatment. These sources included 10 samples within impoundment and hotspot areas, and four samples within both spill and hotspot areas.

^bEighty-six samples were analyzed for radon, 96 samples were analyzed for radium, and 93 samples were analyzed for gross alpha.

^cDoes not include the four samples taken from streams. Furthermore, after analyzing the groundwater samples, the investigators found that two samples had low pH and elevated aluminum and sulfate, indicating the water was likely influenced by acid mine drainage sites found to be located nearby. They also found a third sample that appeared to be mainly rainwater, as suggested by its geochemistry and corroborated by information provided by the homeowner. These additional three samples were removed from the dataset.

^dIn addition to excluding the stream samples and the rain and acid mine drainage impacted samples, this dataset also excluded the 27 goodwill samples.

SUMMARY OF KEY RESULTS

FIELD MEASUREMENTS AND LABORATORY ANALYSIS

In *Part 1* of the study, the investigators' findings suggested that certain metals and metalloids could be present at concerning levels.¹ However, the findings from Part 2 of the study indicate concentrations of most of the metals and metalloids selected for this study did not exceed regulatory standards or other guidance values (**Commentary Table 3**). Concentrations

of BTEX compounds did not exceed drinking water standards in any sample. None of the 96 water samples collected and analyzed for radium exceeded the maximum contaminant levels established for drinking water. Furthermore, the investigators note that the radium concentrations were within the typical range reported for principal aquifers across the United States.

Some samples exceeded secondary drinking water standards for aluminum, iron, or manganese. Secondary standards are nonenforceable guidelines intended to support aesthetic quality of drinking water (taste, color, odor, or staining); con-

Commentary Table 3. Summary of Measured Analytes That Exceeded Either Drinking Water Standards or Other Guidance Values

Analyte	Exceedances	
	US EPA Primary Drinking Water Standards	Secondary Drinking Water Standards or Other
pH	0	12
Fluoride	0	1
Chloride	0	5
Sulfate	0	2
Bromide	0	1
Aluminum	0	2
Barium	1	0
Iron	0	7
Manganese	0	19
Lithium	0	46
Radon	0	33
Methane	0	3
Calc. Total Dissolved Solids	0	19

*One sample equaled the Primary Drinking Water Standard for barium.

taminants present at these concentrations are not considered health hazards. The investigators note that aluminum, iron, and manganese are the most common elements in Pennsylvania bedrock. Nineteen samples were above the secondary standard for total dissolved solids, and five samples equaled or exceeded the secondary standard for chloride. One sample equaled the primary drinking water standard for barium.

Currently, no drinking water standard exists for radon. The primary human health risk from radon in water comes from inhalation, as radon is released into indoor air during household water use, such as showering or washing dishes. The investigators, therefore, compared the radon concentrations in water samples to the US EPA proposed standard of 300 pCi/L, which has not been promulgated. Concentrations above this proposed level could lead to risk from radon in indoor air as it escapes from the water into the air during its use. Of the 86 samples tested for radon, 33 samples exceeded the proposed standard of 300 pCi/L. In these instances, the investigators recommended indoor air radon tests.

Similarly, no drinking water standard has been established for lithium, but EPA has set a health-based screening level of 10 µg/L. This screening level was exceeded in 46 of the samples.

The investigators measured detectable levels of methane in ambient air at 15% of the total sites, with a maximum reading of 132 ppm. They found dissolved methane in the groundwater of 70% of samples, including two with concentrations above the Department of Interior (DOI) action level for further investigation (10 mg/L) and a third with concentrations above the DOI action level for explosion concern (28 mg/L).

UOGD INFLUENCE ON GROUNDWATER DRINKING WELLS

Statistical Comparison of Analyte Concentrations

Baka, Brantley, and colleagues conducted statistical comparisons only on samples taken from treatment and control areas (Commentary Table 2), excluding goodwill samples, stream samples, and three samples that were later found to be likely influenced by either rainwater or acid mine drainage (polluted runoff from mining sites). When comparing the treatment and control samples, the investigators found that concentrations of nine of the analytes were statistically higher in the treatment areas and two were lower in the treatment areas, although the chemicals identified as significantly higher or lower varied by statistical test.

The investigators found that the 10 spring water samples (including one sample from a control area) showed statistically higher concentrations of nitrate, which they hypothesized came from agricultural contamination. They therefore removed this subset of samples from the dataset and repeated the statistical comparison. Here, the investigators found that only seven species were higher in the treatment areas. However, when accounting for potential false discovery rates for each of the comparisons, they found that only radium concentrations were significantly higher in hotspots and impoundments as compared to control sites.

Geospatial Analysis

To understand whether concentrations of 12 UOGD-related analytes were associated with distance to UOGD wells within treatment areas (hotspot, impoundment, and spill sites), the investigators used regression and correlation analysis on the same set of samples as described above (i.e., excluding goodwill samples, stream samples, and the rainwater- and acid mine drainage-impacted samples). Similarly, they repeated these analyses on the sample set with and without spring water samples and obtained similar results.

In hotspot treatment areas, the investigators found no analyte concentrations increased closer to wells; instead, sodium and methane concentrations increased farther away. Near impoundment areas, they found that strontium concentrations increased closer to impoundments, while sodium and barium increased farther away. Near spill areas, sodium, barium, and methane concentrations all increased closer to spill sites, whereas sulfate concentrations increased farther away. The researchers did not find any correlation (positive or negative) for radium concentrations with respect to distance to wells.

The investigators concluded that the presence of some analytes (strontium, sodium, barium, and methane) in groundwater wells and springs may be associated with produced water leaks from impoundment sites or spills at well pads rather than with the UOGD wells themselves.

Origin of Salt and Gas Analytes

The assessment of isotopic data and element ratios, which can help identify the geological source of dissolved constituents in groundwater, provided additional lines of evidence for the investigators to evaluate the potential influence of UOGD. The assessments of isotopic strontium versus strontium-to-chloride ratios showed no consistent patterns between groundwater from treatment and control areas, indicating that these combined signatures do not distinguish between the two areas. Furthermore, a comparison of strontium isotopic signatures alone in groundwater was similar across all samples (control and treatment) but was aligned more closely with UOGD produced water than with conventional sources.

When the investigators plotted methane concentrations against the carbon-13 isotopic signature of the methane measured in groundwater, the results indicated mixtures of biogenic and thermogenic gases, with thermogenic components typically linked to oil and gas development. Even the most methane-rich sample, however, contained a significant fraction of biogenic gas. This mixed signature makes it difficult to attribute the presence of thermogenic gas conclusively to UOGD.

Finally, chloride-to-bromide ratios, which can help distinguish organic waste or road salt, from deep formation water, suggested chloride primarily originated from organic wastes in all but one sample; however, this single outlier could not be used to confirm whether its signature reflected natural upwelling or produced water.

Combined Results

The results of this 2024 sampling campaign showed no conclusive evidence of UOGD-related contamination in private drinking water. Collectively, the statistical comparison of analyte concentrations, geospatial comparisons, and examination of salt and gas analyte origins could not identify UOGD as the source of these analytes in groundwater. Observed variations in analytes between treatment and control areas, including radium, strontium, sodium, barium, and methane, may instead reflect differences in local geology or land use.

HEI ENERGY REVIEW COMMITTEE’S EVALUATION

In its independent evaluation, the HEI Energy Review Committee found that this follow-on study provided valuable evidence to assess predictions of potential groundwater

contamination and addressed community concerns, with results indicating no conclusive evidence of UOGD impact on the sampled groundwater wells. By implementing a robust and transparent sampling campaign, the researchers found that few analytes exceeded drinking water standards, and exceedances were primarily limited to secondary standards, which are based on aesthetic qualities rather than health effects. This study contributes valuable data that can inform future monitoring and risk assessment efforts. The following sections describe the strengths and limitations of the research.

STUDY DESIGN, DATASETS, AND ANALYTICAL APPROACHES

The Committee recognized that a key strength of this study lies in its rigorous analytical approach, which focused on a well-considered subset of water quality analytes relevant to both potential UOGD-related contamination and health effects if present at concerning levels. Additionally, the investigators included analyses to examine the provenance of methane and major elements to generate additional lines of evidence for source apportionment. The sampling plan included protocols that incorporated multiple quality assurance and quality control steps, a thorough sampling and collection design, and included best practices, such as using field duplicates and blanks to ensure accurate sampling and analyses.

The Committee acknowledged the quality of the study design, which incorporated multiple types of treatment areas to assess different sources of potential UOGD contamination through groundwater, along with limited control sites, where available. Implementing this study design is a considerable achievement given the challenges posed by the regional history of legacy hydrocarbon development and other extractive activities.

The Committee also appreciated the statistical analyses, which employed multiple approaches and accounted for false discoveries using the Benjamini–Hochberg procedure. This approach helps to ensure that findings are not artifacts and that they are more likely to be reliable. The investigators provided transparent reporting of both significant and nonsignificant findings.

Finally, the Committee recognized the value of the community-centered approach, which responded directly to concerns about water quality identified through the first study and accommodated community requests for increased and transparent water sampling. The investigators not only provided each participant with a letter explaining the findings and their relevance to homeowners but also held a community meeting and offered follow-up calls to discuss the findings. While the study was not directly aimed at indoor air quality, the researchers paid special attention to potential radon or methane hazards and included recommendations to the homeowners informed by their findings.

The Committee recognizes that, given a study of this size and scope, many analyses cannot be conducted and types

of data are difficult or impossible to obtain. By design, the investigators relied on existing groundwater wells, which is beneficial in two ways. First, this study was able to directly measure potential exposure to contaminants of concern by sampling drinking water sources. Second, it reduced costs because drilling new groundwater sampling wells is time-intensive, costly, and beyond the scope of this project.

However, the authors did not discuss how limitations of relying on existing wells may have affected the conclusions of the study. The study approach does not account for the complexity of subsurface groundwater flow paths and directionality of the hydraulic gradient. While the Committee recognizes that in-depth hydrogeologic modeling was outside the scope of this work, some approaches could have been considered to explore likely flow paths and clarify the relevance or limitations of a proximity-based correlation study, such as conservative solute modeling or desktop hydraulic gradient estimation. Even though modeling was not included in the scope of the study, a discussion of this limitation would have strengthened the report. Furthermore, the investigators were unable to find control groundwater wells that were more evenly distributed over the study area (Commentary Figure 1). This uneven spatial distribution of control samples may have affected the ability of the investigators to establish representative background conditions. These limitations might introduce uncertainty into the conclusion that there is no significant statistical difference between the treatment and control areas, which were not discussed by the investigators in the report.

Additionally, there was insufficient data on groundwater well construction, including no information on screening levels, reliance on self-reported well-depth estimates, and missing data for approximately 30% of the wells. These limitations can lead to a potential mismatch between contamination sources and the sampled wells. The Committee acknowledges that these data are difficult, if not impossible, to obtain. It also recognizes that these limitations do not affect whether the measured analyte concentrations in these samples reflect the level of exposure of residents who use these water sources. However, it is important to note that these missing data are an additional limitation to collecting water samples that can be used to delineate potential groundwater contamination impacts from UOGD in the region, which were not discussed by the investigators.

The Committee also found that, as presented, the study population and demographic data were underutilized. While the water quality findings may not have warranted additional analyses given the low likelihood of exposure, this was not discussed, nor was how the demographic data might have been used. There was no clear indication that these data were collected with a follow-up assessment in mind, for example, to examine whether exposure differed among subpopulations or to evaluate the generalizability of the findings to the broader population.

FINDINGS AND INTERPRETATION

Irrespective of the findings of the water quality analysis, the investigators shared each result via mail and email with each study participant. The investigators found a few instances of analytes at concentrations above standards or guidelines. In those cases, they provided a cover letter describing the specific findings and information on potential mitigation resources and followed up with phone calls with the homeowners. The Committee appreciated the strong, consistent communication with the community.

This report gives a balanced presentation of the analytical results and statistical analyses of the data, including reporting of significant and null results before and after false discovery rate correction. However, there are several examples of findings that were reported without further explanation or discussion. While the Committee acknowledges that some results may lack clear explanations, researchers could have drawn on existing science and professional judgment to explore plausible interpretations. For example, further discussion could have addressed the patterns of strontium isotopic ratios ($^{87}\text{Sr}/^{86}\text{Sr}$) observed across different treatment areas, and why both treatment and control samples appear more similar to produced water from unconventional wells than to that from conventional wells. Another example is the absence of discussion on the implications of the positive correlation between sulfate and other analyte concentrations and distance from treatment areas.

Other findings are presented without context to understand the significance of such results. In the discussion of public health observations, the report does not address the implications of the 46 samples that exceeded the EPA's health-based screening level for lithium, nor does it indicate whether or how this information was communicated to participants. Some analytes, such as manganese, may only have secondary maximum contaminant levels established for aesthetic concerns; however, they may also have other nonregulatory, health-based guidance values, which were not explored further here. The report also says the levels of radium found in drinking water were concentrations that are "within the typical range reported for principal aquifers across the United States." The Committee questioned why these data were not reported relative to regional radium concentrations, which would be more relevant to interpreting the findings, or, if unavailable, why this was not noted as a data gap.

The Committee also questioned why the investigators suggest in future work that analyses of blood and hair of residents could be used to discern the potential effects of contamination. Given the findings of this study, such an intervention seems unwarranted and unsupported.

CONCLUSIONS

In [Part 1](#) of the study, Baka, Brantley, Xue, and colleagues found statistically significant increases in certain inorganic constituents near UOGD wells, produced water spills, and

impoundments. They also found through community focus groups that residents in Southwestern Pennsylvania were concerned about potential drinking water contamination, particularly radioactive elements, from wastewater management practices. Importantly, Part 2 of the study directly addressed these community concerns by investigating whether private drinking groundwater wells were contaminated, and whether UOGD activities were affecting their water quality. Exceedances of drinking water standards were rare and limited to secondary drinking water standards, which are based on aesthetics. Although the investigators found that radium concentrations in hotspot and impoundment areas were higher than those in the control sites, isotopic analyses of geochemical tracers and methane did not indicate produced water influence on groundwater, and measured concentrations were below drinking water standards.

This study tested whether private drinking groundwater wells presumed to be at higher risk of UOGD contamination showed evidence of UOGD-related impacts and found no conclusive evidence that they did. Overall, these results contribute to the broader understanding of groundwater quality in areas proximate to UOGD and add valuable data that may help distinguish localized UOGD impacts from broader regional effects of legacy extraction and geological factors.

ACKNOWLEDGMENTS

The HEI Energy Review Committee thanks the ad hoc reviewers for their help in evaluating the scientific merit of the Investigators' Report. The Committee is also grateful to Donna Vorhees for oversight of the study, to Cloelle Danforth for assistance with review of the Investigators' Report and preparation of its Commentary, to Tara Hamilton for editing the Investigators' Report and Commentary, and to Kristin Eckles for her role in preparing Research Report 233, Part 2 for publication.

REFERENCES

1. Baka J, Brantley SL, Wen T, Xue L, Shaheen S, Harrington O. 2025. Hydrocarbon Extraction and Risk to Groundwater in Pennsylvania: Part 1. Using Geoscientific Analysis and Community Engagement to Analyze Exposures to Potential Groundwater Contamination Related to Hydrocarbon Extraction in Southwestern Pennsylvania. Research Report 233. Boston, MA: Health Effects Institute. Available: <https://www.healtheffects.org/system/files/baka-research-report-233-report.pdf>.
2. HEI Special Scientific Committee on Unconventional Oil and Gas Development in the Appalachian Basin. 2015. Strategic Research Agenda on the Potential Impacts of 21st Century Oil and Natural Gas Development in the Appalachian Region and Beyond. Boston, MA: Health Effects Institute. Available: https://www.healtheffects.org/system/files/uogd-research-agenda-nov-4-2015_0.pdf.
3. US Environmental Protection Agency (US EPA). 2016. Hydraulic Fracturing for Oil and Gas: Impacts from the Hydraulic Fracturing Water Cycle on Drinking Water Resources in the United States (Final Report No. EPA/600/R-16/236F). Washington, DC: US EPA. Available: <https://cfpub.epa.gov/ncea/hfstudy/recordisplay.cfm?deid=332990>.
4. HEI Energy Research Committee. 2020. Human Exposure to Unconventional Oil and Gas Development: A Literature Survey for Research Planning. Communication 1. Boston, MA: Health Effects Institute. Available: <https://www.health-effects.org/system/files/heie-energy-comm-1-exp-lit-survey.pdf>.
5. Ariana A, Cozzarelli I, Danforth C, McDevitt B, Rosofsky A, Vorhees D. 2025. Pathways for potential exposure to onshore oil and gas wastewater: What we need to know to protect human health. *GeoHealth* 9:e2024GH001263, <https://doi.org/10.1029/2024GH001263>.
6. Maloney KO, Baruch-Mordo S, Patterson LA, Nicot JP, Entekin SA, Fargione JE, et al. 2017. Unconventional oil and gas spills: Materials, volumes, and risks to surface waters in four states of the US. *Sci Total Environ* 581–582:369–377, <https://doi.org/10.1016/j.scitotenv.2016.12.142>.
7. Llewellyn GT, Dorman F, Westland JL, Yoxthimer D, Grieve P, Sowers T, et al. 2015. Evaluating a groundwater supply contamination incident attributed to Marcellus Shale gas development. *Proc Natl Acad Sci USA* 112:6325–6330, <https://doi.org/10.1073/pnas.1420279112>.
8. Shaheen SW, Wen T, Zheng Z, Xue L, Baka J, Brantley SL. 2024. Wastewaters coproduced with shale gas drive slight regional salinization of groundwater. *Environ Sci Technol* 58:17862–17873, <https://doi.org/10.1021/acs.est.4c03371>.
9. Shaheen SW, Wen T, Herman A, Brantley SL. 2022. Geochemical evidence of potential groundwater contamination with human health risks where hydraulic fracturing overlaps with extensive legacy hydrocarbon extraction. *Environ Sci Technol* 56:10010–10019, <https://doi.org/10.1021/acs.est.2c00001>.
10. US Environmental Protection Agency (US EPA). National Primary Drinking Water Regulations, 40 C.F.R. §141. Available: <https://www.epa.gov/ground-water-and-drinking-water/national-primary-drinking-water-regulations>.
11. US Environmental Protection Agency (US EPA). National Secondary Drinking Water Regulations, 40 C.F.R. §143. Available: <https://www.epa.gov/sdwa/secondary-drinking-water-standards-guidance-nuisance-chemicals>.