

Research Report 243, *A Groundwater Modeling Framework for Understanding Potential Population Exposures to Groundwater Contamination Associated with Oil and Gas Development Across the Marcellus Region*, by J.E. Saiers et al.

INTRODUCTION

The advent of high-volume and multistage hydraulic fracturing combined with horizontal drilling, known as unconventional oil and gas development (UOGD),* in the early 2000s has resulted in a marked increase in onshore oil and natural gas development in the United States. This increase in the rate and scale of development has created additional instances for potential human exposure to chemical and nonchemical stressors and has generated concerns about their effect on human health.

UOGD releases to groundwater or surface water may occur under accidental conditions (e.g., spills), posing a risk of groundwater contamination. Thus, they have been the subject of much public attention and concern, especially in regions such as the Marcellus of Appalachia where there is substantial UOGD alongside populations that rely heavily on groundwater for drinking water. Although a review by the US EPA¹ did not find extensive contamination of water associated with UOGD, it did cite instances where contamination of groundwater had occurred. It concluded that understanding remained limited regarding how UOGD releases to groundwater and surface water could lead to population exposures through contaminated water. Data on the likelihood, magnitude, frequency, or duration of exposure to water potentially contaminated by UOGD are limited, highlighting the need for studies quantifying potential population exposures to water contamination associated with UOGD processes.²

In 2023, HEI Energy issued a Request for Qualifications [RFQ E23-2](#): Regional Groundwater Modeling to Understand Community Exposures Associated with Oil and Gas Development. The goal of the RFQ was to develop a novel groundwater quality modeling approach to better understand the potential for documented UOGD spills in the Marcellus region to adversely affect water quality and lead to population exposures.

James E. Saiers's 1-year study, "Potential Groundwater Vulnerability to Spills Associated with Unconventional Oil and Gas Development Across the Marcellus Region," began in May 2024. Total expenditures were \$250,000. The draft Investigators' Report from Saiers and colleagues was received for review in March 2025. A revised report, received in October 2025, was accepted by the HEI Energy Review Committee in November 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.

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

In November 2023, Dr. James E. Saiers submitted the application, "A Groundwater Modeling Framework for Elucidating Community Exposures Across the Marcellus Region to Contamination Associated with Oil and Gas Development." The Energy Research Committee thought the proposed study was very responsive to the RFQ and had several notable strengths, one being the clearly articulated modeling approach. This study is the only study funded under [RFQ E23-2](#).

This Commentary provides the HEI Energy Review Committee's independent evaluation of the study. It is intended to aid the sponsors of HEI and the public by highlighting the study's strengths and limitations and 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.³ UOGD processes occur on and off the well pad and include the following:

- **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 waste management.
- **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.

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. For example, in Ohio, Pennsylvania, and West Virginia, which form part of the Marcellus region examined in this study, setback distances separating well pads from buildings or occupied dwellings are 150 feet, 500 feet, and 625 feet, respectively.⁴⁻⁶

UOGD AND WATER QUALITY

UOGD releases to groundwater and surface water may occur through authorized or accidental releases. Authorized releases include permitted discharges of treated UOGD wastewater to surface water or the use of produced water outside oil and gas operations for applications such as road treatment.^{2,7} Accidental releases, or spills, include those that may occur because of wellbore failure, malfunctioning equipment, or other circumstances.⁸ The potential effect of a spill on groundwater or surface water quality depends on the chemical and physical properties of the spilled constituents and the characteristics of the receiving surface water body or subsurface aquifer.

Prior research has documented thousands of spills related to UOGD across several states, and other studies have demonstrated associations between documented UOGD spills and contaminants in nearby groundwater.^{8–11} Quantifying any UOGD-related exposures is challenging because it can be difficult to distinguish potential exposures associated with UOGD from other sources, such as conventional oil and gas development, other anthropogenic sources, or naturally occurring conditions.² Some researchers have used geochemical signatures to detect effects on water quality from surface spills attributable to UOGD.¹² However, detecting changes in water quality from UOGD-related spills to the subsurface is more difficult given the complexity and uncertainty in understanding hydrogeologic conditions, which affect potential migration or transformation of any contaminants. Novel groundwater modeling studies have begun to make progress on such issues.¹³

Nonetheless, efficient frameworks and methods are still needed that could directly address the challenges in isolating and evaluating UOGD effects on water quality and the potential for population exposures associated with water quality impacts, a need this study aimed to address.

STUDY OBJECTIVES

The goal of Saiers's study was to develop a modeling framework for evaluating the vulnerability of groundwater to potential contamination from spills associated with UOGD in the Marcellus region states of Ohio, Pennsylvania, and West Virginia. The study had two specific aims:

1. **Aim 1.** Develop a physics-based model that is applicable across the region to quantify the vulnerability of groundwater that supplies domestic wells (hereafter "well water vulnerability") to potential contamination from UOGD spills.
2. **Aim 2.** Evaluate associations between UOGD chemical fingerprints measured in well waters and the estimates of UOGD-related well water vulnerability from Aim 1.

For Aim 1, Saiers and colleagues coupled a physics-based groundwater flow model with a particle-tracking algorithm to simulate the transport trajectories of contaminants through

the groundwater flow system in the Marcellus region following their release at a UOGD well pad. They performed multiple model simulations and integrated the results to quantify the probability of a potential contaminant associated with a UOGD spill reaching a drinking water receptor (i.e., estimates of well water vulnerability across the Marcellus region states of Ohio, Pennsylvania, and West Virginia). Well water vulnerability estimates were computed for two scenarios: (1) for all UOGD wells in the region ($n = 25,617$), and (2) for a subset of UOGD wells in the region ($n = 1,761$) with documented spills using information collected from state data repositories in Ohio, Pennsylvania, and West Virginia. The investigators also calculated the total potentially vulnerable land area and population for both scenarios.

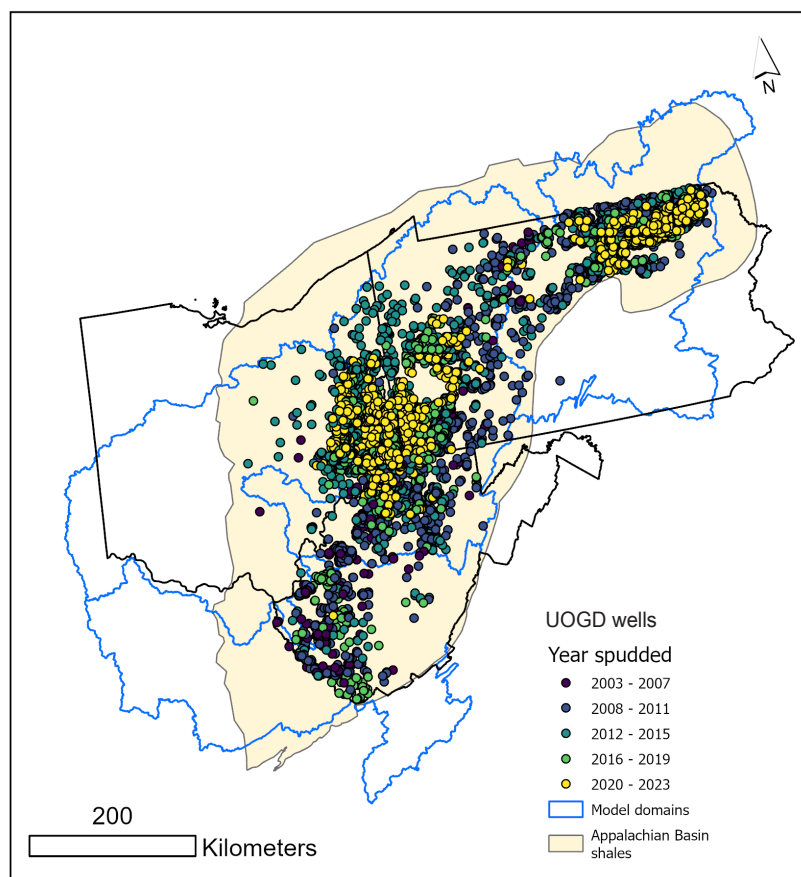
For Aim 2, Saiers and colleagues collated previously published data on well water (which is supplied by groundwater) in these states that included information on chemical signatures. They then used logistic regression models to evaluate associations between the presence or absence of UOGD chemical fingerprints in well water and their computed estimates of well water vulnerability from Aim 1 in areas with documented cases of UOGD spills.

SUMMARY OF METHODS AND STUDY DESIGN

AIM 1. ESTIMATING WELL WATER VULNERABILITY TO POTENTIAL CONTAMINATION FROM UOGD IN THE MARCELLUS REGION

Saiers and colleagues combined two-dimensional physics-based hydrologic models of the study region to simulate advective transport (i.e., the movement of a substance by bulk flow of a liquid) of potential contaminants through the groundwater after their release at UOGD well pads. Specifically, they used MODFLOW 6, which was based on prior models of aquifer systems across the contiguous United States¹⁴ with a particle-tracking algorithm, MODPATH 7.¹⁵ The portion of the Marcellus that constituted the study region spanned four hydrologic model domains and included over 26,000 UOGD wells (**Commentary Figure 1**).

The investigators calibrated the groundwater flow models using multiple hydraulic conductivity fields (i.e., different representations of how easily water moves through subsurface materials such as soil or rock) and performed multiple model simulations of particle-tracking for two scenarios: (1) a particle was released at all grid cells containing a UOGD well in the region, and (2) at grid cells for a subset of UOGD wells in the region with documented spills. Of a total 25,617 wells in the region, approximately 3,853 documented UOGD spills were compiled, broadly covering the 2007–2023 period. Data were obtained from regulatory agencies in Ohio, Pennsylvania, and West Virginia, and supplemented with peer-reviewed publications. Documented spills were not included if they could not be geolocated or collocated with known UOGD well pads, which resulted in a final dataset of 1,761 documented spills across the region that were analyzed. The



Commentary Figure 1. Map of the study region, including the hydrologic model domains and number of UOGD wells (colors indicate the year drilling began [“year spudded”]). Source: Adapted from Investigators’ Report Figure 3.

particle-tracking results across simulations were integrated to calculate estimates of well water vulnerability in each model grid cell for both scenarios. The results were reported as the probability (0–1) of the path line of a particle released from a UOGD well pad intersecting a grid cell across model simulations.

In addition, the investigators calculated the total land area and population dependent on groundwater wells and potentially at risk.¹⁶ At-risk populations are located within “vulnerable” grid cells, as defined by multiple vulnerability thresholds. Specifically, vulnerability thresholds of 0.001, 0.1, or 0.5 were used, with higher values indicating greater agreement among the model simulations that a grid cell lies along the trajectory of potential contaminants released from a UOGD well pad, thereby indicating greater vulnerability. An estimate of 0.5 or more indicated “high vulnerability.” They also aggregated these results to 30-km polygons to explore potential spatial clustering of well water vulnerability in the region.

AIM 2. EVALUATING ASSOCIATIONS BETWEEN WELL WATER VULNERABILITY AND UOGD CHEMICAL FINGERPRINTS IN WELL WATER MEASUREMENTS

Saiers and colleagues next evaluated potential associations between chemical fingerprints indicating the presence of UOGD-related chemicals in well water measurements in the study region and the estimates of well water vulnerability. They used logistic regression models to determine such associations for the subset of UOGD wells with documented spills from Aim 1. Water quality data collected across Ohio, Pennsylvania, and West Virginia between the years 2008 and 2020 were obtained from a publicly available database¹⁷ and from peer-reviewed publications.^{18–20} These data consisted of approximately 27,000 measurements of well water supplied by groundwater.

Well water measurements were classified as either having UOGD chemical fingerprints or not, depending on their chemical compositions. Groundwater studies¹⁸ have used analysis of inorganic ion ratios to determine whether groundwater had been affected by mixing with produced waters (which make up a large fraction of fluids in spills from UOGD well pads). Here, the investigators analyzed the concentration ratios of six different combinations of inorganic ion-ratio pairs (**Commentary Table 1**) to explore their potential for determining chemical fingerprints associated with UOGD. They focused on chemicals often found in high concentrations within produced waters.

Next, the investigators implemented both unadjusted and adjusted logistic regression models to estimate odds ratios (ORs) and *P* values. Adjusted models included covariates such as geographic location (e.g., latitude and longitude), distance to geological structures (e.g., folds, faults), topographic position (e.g., summits, slopes, valleys), and the presence of

Commentary Table 1. Combinations of Inorganic Ion-Ratio Pairs Analyzed in This Study to Classify UOGD Chemical Signatures in Well Water Measurements.

Ion-Ratio Pair Combinations
Barium/chloride vs. bromide/sulfate
Sulfate/chloride vs. bromide
Magnesium/lithium vs. sulfate/chloride
Magnesium/lithium vs. bromide/sulfate
Calcium/strontium vs. calcium/magnesium
Sulfate/chloride vs. magnesium/sodium

nearby (less than 2 km) conventional oil and gas wells. These covariates were introduced to control for other factors known to impart produced water–like fingerprints, such as natural upwelling of deep-basin brines beneath valleys or near fault zones. They ran two sets of models: (1) vulnerability was included as a continuous variable (i.e., $0 \leq V \leq 1$, as computed in Aim 1); and (2) vulnerability was included as a binary variable indicating well water vulnerability was “high” or not (defined as $V \geq 0.5$ or $V < 0.5$).

SUMMARY OF KEY RESULTS

AIM 1. WELL WATER VULNERABILITY TO POTENTIAL CONTAMINATION FROM UOGD IN THE MARCELLUS REGION

Groundwater simulations from the hydrologic models demonstrated robust performance in capturing local groundwater hydrology for the Marcellus region. Estimated mean and median lengths of particle path lines for the trajectory of potential contaminants through the groundwater flow system were 671 m and 532 m, respectively, with a 95th percentile length of 1,790 m, consistent with previous work.¹³ Thus, potential chemical contamination of groundwater associated with UOGD well pads was not expected to occur at distances greater than 2 km. However, the length of these predicted path lines generally exceeds regulatory setback distances between UOGD and wells supplying drinking water in Pennsylvania (152 m), Ohio (15 m), and West Virginia (76 m).⁴⁻⁶

Saiers and colleagues estimated that well water vulnerability to potential contamination from UOGD spills for scenario 1 (i.e., considering all documented UOGD wells in the region as potential sources of spills) encompassed a land area that ranged from 3,538 km² using a vulnerability threshold of 0.1 (i.e., the probability that a particle path line from a UOGD well pad intersected a grid cell in at least 100 of 1,000 model simulations) to 3,758 km² using a lower vulnerability threshold of 0.001. Estimates of well water vulnerability for scenario 2 (i.e., considering only UOGD wells in the region with documented spills) encompassed a total land area ranging from 590 km² to 616 km², using vulnerability thresholds of 0.1 and 0.001, respectively.

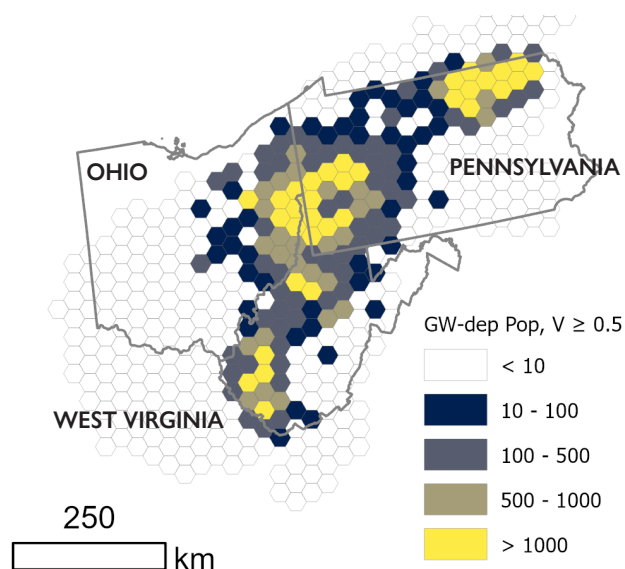
Using existing estimates of populations dependent on groundwater wells in the region,¹⁶ the investigators calculated that for scenario 1, about 3%, or 122,000 people, live in areas that would be considered vulnerable to potential well water contamination from a spill (using a high vulnerability threshold: 0.5). For scenario 2, this estimate would amount to 0.5% of that population, or about 22,000 people.

To estimate potential clustering of exposed populations, they aggregated the data to 30 km polygons. Under scenario 1, they observed that estimates of populations living in locations that have high well water vulnerability ($V > 0.5$) tended to be spatially clustered throughout Northeastern

Pennsylvania, Southern West Virginia, and throughout the tri-state area where the three states meet (**Commentary Figure 2**). The investigators note that such clustering may suggest both regional-scale heterogeneity in local groundwater flow patterns and the accumulation of estimated vulnerability in locations where there are multiple UOGD well pads in proximity to one another.

AIM 2. ASSOCIATIONS BETWEEN UOGD CHEMICAL FINGERPRINTS IN WELL WATER MEASUREMENTS AND WELL WATER VULNERABILITY

Saiers and colleagues analyzed the concentration ratios of six combinations of inorganic ion-ratio pairs in the water quality measurements data to assess their potential for determining chemical fingerprints associated with UOGD (Commentary Table 1). Because of the number of missing or censored measurements, the combinations of ion-ratio pairs that could be evaluated as criteria for identifying UOGD chemical fingerprints in well water measurements were limited to calcium/strontium versus calcium/magnesium and sulfate/chloride versus magnesium/sodium. Of these, calcium/strontium versus calcium/magnesium demonstrated the highest accuracy in correctly identifying samples with UOGD chemical signatures when evaluated against water samples from oil and gas wells in the Marcellus region. Thus, the investigators selected calcium/strontium versus calcium/magnesium as their criterion for classifying whether water quality measurements exhibited the presence of potential UOGD chemical fingerprints. A total of 16,090 water quality measurements were included in their subsequent statistical analysis, of which 865 (5.4%) were classified as having poten-



Commentary Figure 2. Estimated population dependent on groundwater (GW-dep), aggregated to 30 km polygons, with high well water vulnerability ($V \geq 0.5$) to potential contamination from UOGD spills in the Marcellus region. Source: Adapted from Investigators' Report Figure 7.

tial UOGD chemical fingerprints.

The investigators reported positive associations (i.e., statistically significant ORs > 1) between the odds of detecting a chemical fingerprint indicating the presence of UOGD in well water measurements and well water vulnerability (Commentary Table 1). In unadjusted models, when vulnerability was estimated as a continuous variable between 0 and 1, the odds of well water measurements exhibiting UOGD chemical fingerprints increased 14% for every 0.1 increase in well water vulnerability. When vulnerability was estimated as a binary variable indicating high well water vulnerability (or not), the odds of the well water measurement exhibiting UOGD chemical fingerprints increased 271% for high well water vulnerability.

The investigators also ran adjusted models that accounted for covariates such as geographic location, topography, and the presence of nearby conventional oil and gas wells. Using adjusted models, these associations became attenuated but remained elevated and statistically significant (**Commentary Table 2**). For example, in adjusted models, every 0.1 increase in well water vulnerability was associated with a 13% increase in the odds that a well water measurement also exhibited UOGD chemical fingerprints. In both sets of models, the presence of conventional oil and gas wells within 2 km was a statistically significant predictor of increased odds of detecting UOGD chemical signatures in a well water measurement. Given the difficulty in distinguishing between chemicals released from unconventional versus conventional sources without intensive water quality analyses, this result highlights the complexity of how different sources of water influence groundwater chemistry.

Commentary Table 2. Associations Between the Presence of Potential UOGD Chemical Signatures in Marcellus Region Well Water Measurements and Estimates of Well Water Vulnerability^a

Variable	Odds Ratio (P Value)	
	0 ≤ V ≤ 1	V ≥ 0.5
Unadjusted Models		
Well water vulnerability	1.14 (<0.001)	3.71 (<0.001)
Adjusted Models		
Well water vulnerability	1.13 (<0.001)	3.24 (<0.001)
Distance to geological structures	0.82 (<0.01)	0.82 (<0.01)
Presence of conventional oil and gas wells within 2 km	1.47 (<0.05)	1.47 (<0.05)
Upper slopes vs. peaks/summits	0.79 (0.430)	0.79 (0.430)
Lower slopes vs. peaks/summits	0.99 (0.967)	0.99 (0.969)
Valleys vs. peaks/summits	1.77 (0.052)	1.77 (0.052)

^aVulnerability estimates are modeled as either a continuous variable (0–1), or as a binary variable (0 or 1 depicting no versus high well water vulnerability, defined as V > 0.5), with select covariates. Associations are presented as ORs and P values.

HEI ENERGY REVIEW COMMITTEE'S EVALUATION

This study estimated domestic well water vulnerability to potential contamination from UOGD-related spills in three states — Ohio, Pennsylvania, and West Virginia — in the Marcellus region, using combined physics-based hydrologic models with a particle-tracking algorithm. It also examined associations between estimated well water vulnerability and UOGD chemical fingerprints in well water sampled in locations with documented UOGD spills in the same region. Saiers and colleagues found that 0.5% to 3% of populations who rely on groundwater-supplied well water in the region live in locations that may be considered highly vulnerable to potential contamination from UOGD spills. They also found that the odds of detecting chemical fingerprints of UOGD are greater in hydrologically vulnerable locations, even when controlling for other factors known to impart such fingerprints.

In its independent evaluation, the HEI Energy Review Committee found that this study provided an effective modeling framework for examining groundwater vulnerability to potential contamination from UOGD spills that may be useful to inform decision-making. They also appreciated that the framework could be extended to other regions in the United States and applied to other research questions related to examining water quality and UOGD. The Committee broadly agreed with the results but noted that data quality issues for publicly available data on documented UOGD spills were the main limitation of this work. Further details on the strengths and limitations of the study are discussed below.

STUDY DESIGN, DATASETS, AND ANALYTICAL APPROACHES

The Committee identified the overall modeling approach as a key strength of the study. It appreciated the curation of a dataset of water quality measurements from publicly available resources for the three study region states that could be used in future studies. It also appreciated the multiple analytical approaches used to explore well water vulnerability.

Several limitations were highlighted by the Committee. In particular, the Committee thought that the high percentage of missing or incomplete information for documented spills from state regulatory databases (approximately 54% of spills) that were therefore excluded from the analyses was the main limitation of this work. This missing information likely biased the investigators' findings toward an underestimation of well water vulnerability in the region. However, the Committee appreciated that the investigators analyzed all UOGD well pad locations in the region to partially address this limitation. The analysis provides an upper threshold of well water vulnerability to potential contamination from spills. This approach was an appropriate and clever way to address the limitations of the publicly available data on spills.

Second, the Committee remarked that the use of a two-dimensional instead of a three-dimensional hydrologic model to simulate groundwater flow in the region might limit the generated estimates of well water vulnerability. Importantly, a three-dimensional model would have captured considerations of flow across vertical variations. In addition, to simulate transport trajectories of potential contaminants through the groundwater flow system, the investigators used a particle-tracking algorithm that was based on advective transport rather than advective-dispersive transport. Advective transport is based on bulk flow, whereas advective-dispersive transport would account for mixing and spread of contaminants. Using advective transport might also limit the generated estimates of well water vulnerability. However, the Committee noted that the investigators appropriately acknowledged these limitations, noting that simplifying assumptions in the modeling approaches were used to address data and computational limitations.

Third, the Committee commented on the statistical analyses conducted to evaluate associations between estimates of well water vulnerability and chemical fingerprints of UOGD in water quality measurements. It observed that the inclusion of geographic location (latitude and longitude) as a covariate to account for potential spatial autocorrelation likely only captures larger-scale spatial correlation. This approach thus might not capture smaller, local-scale spatial correlation given that such geographic coordinates do not represent the nuance of local-scale distances and relationships.

FINDINGS AND INTERPRETATION

In their estimates of well water vulnerability, Saiers and colleagues reported a range of results that depended on different thresholds of vulnerability and scenarios of UOGD spills. For example, they considered all UOGD well pads as potential spill sources and considered only UOGD well pads with documented spills as sources. This approach affected the estimates for the vulnerable land area (up to 3,758 km²) and groundwater well-dependent populations (up to 122,000 people). The Committee thought that the findings were presented both prudently and thoughtfully given some of the limitations of the study's datasets and analytical approaches. In addition, the investigators highlighted the utility of the findings in informing future decision-making concerning UOGD and water quality. For example, they discussed results in the context of regulatory setback distances.

In statistical analyses evaluating associations between well water vulnerability and UOGD chemical fingerprints in well water measurements, Saiers and colleagues reported a large (up to 271%) increase in the odds of detecting UOGD chemical fingerprints in well water samples. This result came from analyses when considering estimated vulnerability as a binary indicator (i.e., highly vulnerable well water, or not). However, the investigators recognized that the chemical fingerprints defined as indicators of UOGD in this analysis did not constitute the range of chemicals known to occur in spills that are known to be of human health concern, such as some semivolatile or volatile organic compounds, which the Committee appreciated.

CONCLUSIONS

In summary, Saiers and colleagues found that up to 3% of people who depend on groundwater-supplied well water in the region live in areas that may be "highly vulnerable" to well water contamination. This number resulted from an analysis that considered all UOGD well pads as potential contaminant sources, regardless of whether actual spills had been recorded. The affected area corresponded to clusters of locations among Northeastern Pennsylvania, Southern West Virginia, and the area where those two states meet with Ohio.

Saiers and colleagues also reported a higher likelihood of detecting chemical fingerprints of UOGD in water quality measurements and when well water vulnerability was high for locations with documented UOGD spills in the region. The study is limited by the quality of publicly available data on documented spills in the region and by some simplifying assumptions related to the groundwater flow and contaminant transport simulations. However, overall, this study provides a strong modeling framework and valuable datasets that can be used to inform decision-making, for example by helping to predict the location of drinking water wells that are most vulnerable to UOGD spills.

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