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Communication 1

HEI energy
A Health Effects Institute Affiliate

Human Exposure to Unconventional Oil and Gas Development: A Literature Survey for Research Planning

HEI-Energy Research Committee

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Trusted Science, Clean Environment, Better Health

Human Exposure to Unconventional Oil and Gas Development: A Literature Survey for Research Planning

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Health Effects Institute – Energy
Boston, MA

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ABOUT HEI-ENERGY

The Health Effects Institute–Energy was formed to provide a multiyear national research program 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 (UOGD) across the United States. HEI-Energy plans to support population-level exposure research in multiple regions of the United States. 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 high-priority exposure research needs 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 to the public debate about UOGD and provide needed support for 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 (HEI), with several critical features:

- Receives balanced funding from the U.S. Environmental Protection Agency under a contract that funds HEI-Energy exclusively, and from the oil and natural gas industry. Other public and private organizations periodically provide support;
- Independent Board of Directors consisting of leaders in science and policy who are committed to fostering the public–private partnership that is central to the organization;
- A research program that is governed independently by individuals having no direct ties to, or interests in, sponsor organizations;
- HEI-Energy Research Committee consisting 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;
- Research that undergoes rigorous peer review by HEI-Energy's Review Committee. This committee will not be involved in the selection and oversight of HEI-Energy studies;
- Staff and committees that participate in open and extensive stakeholder engagement before, during, and after research, and communicate all results in the context of other relevant research;
- 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, provides impartial science, targeted to make better-informed decisions.

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EXECUTIVE SUMMARY

Unconventional oil and natural gas development (UOGD) has expanded rapidly in the United States in recent years. Accompanying this expansion has been a growing body of scientific literature about human exposures to environmental agents arising from UOGD (hereafter "UOGD exposures"). This report surveys the literature relevant to these environmental exposures. The Energy Research Committee (the Committee) of the Health Effects Institute–Energy (HEI-Energy) conducted the survey as part of a larger effort to understand the current state of the science on UOGD exposures and their potential health effects. The Committee will use results from this survey and a companion review of epidemiology literature on potential health effects of UOGD exposures (HEI-Energy Research Committee 2019) to inform HEI-Energy's planning for future research to better understand exposures associated with UOGD.

UOGD Defined

UOGD refers to the development and production of oil and natural gas as practiced starting around the beginning of the 21st century through multistage hydraulic fracturing in horizontal wells. UOGD processes occur on and off the well pad and include:

- *field development*: exploration, site preparation, vertical and horizontal drilling, well completion (casing and cementing, perforating, acidizing, hydraulic fracturing, flowback, and well testing) in preparation for production, and management[1] 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[2] and wastes; and construction and operation of field production facilities; and
- *post-production*: well closure and land reclamation.

Approach to the Survey

The Committee consists of multi-disciplinary scientists from across the United States with expertise in air quality, epidemiology, exposure assessment, hydrology, medicine, petroleum engineering, risk assessment, and toxicology. Along with HEI-Energy staff, the Committee conducted a survey of peer-reviewed and gray scientific literature that provides information about potential UOGD exposures. The goals for the survey are to summarize research efforts to date and the approaches investigators have used to characterize releases from UOGD that might lead to exposures, identify knowledge gaps about potential exposures, and begin planning for research that addresses the gaps. The Committee also toured UOGD operations and convened two public workshops at the outset of the survey to hear from knowledgeable representatives from federal and state government, the oil and gas industry, environmental and public health nongovernmental organizations, academia, and community organizations about their priorities for research.

Although this document was produced with partial funding by the United States Environmental Protection Agency under Contract No. 68HERC19D0010 to the Health Effects Institute–Energy, it has not been subject to the Agency's review and therefore does not necessarily reflect the views of the Agency, and no official endorsement by the Agency should be inferred. Oil and natural gas companies also provided funding to produce this document; however, it has not been subject to their review and therefore does not necessarily reflect the views of any of the oil and natural gas companies, and no endorsement by them should be inferred.

[1] Management of wastes and produced water refers to their handling from creation to disposal, including collection, storage, transport, treatment, reuse, recycling, and disposal.

[2] Produced water is naturally-occurring water that comes out of the ground along with oil and gas. (Adapted from: American Geosciences Institute 2019). The characteristics of produced water vary and use of the term often implies an inexact or unknown composition. (Adapted from: Schlumberger 2019)

Conceptual Framework

Understanding human exposures to UOGD-related chemical agents (e.g., criteria and hazardous air pollutants, radioactive material, and odorous compounds) and non-chemical agents (e.g., noise, light, and vibration) represents a complex undertaking. UOGD processes involve a multitude of agents released to air, water, and other environmental media, with levels varying by region, extent of operations, operator practices, and other factors. Furthermore, variation in time–activity patterns (e.g., time spent at residential versus work locations and indoor versus outdoor locations) among potentially exposed populations complicates efforts to quantify human exposures to agents originating from UOGD.

The Committee framed its literature survey within a conceptual model of exposure (Figure ES-1) to facilitate understanding of research related to potential exposures and where knowledge gaps exist. An ideal exposure study would provide information about each element of the conceptual model, including identification of specific UOGD chemical or non-chemical agents, documentation of the release to the environment (e.g., emissions rate or noise measurement) and transport to a specific medium, route of exposure (e.g., inhalation of air in a residential area or ingestion of drinking water), and the magnitude, freqency, and duration of exposure for a specific population. In so doing, the study would allow one to determine whether a complete exposure pathway connects a specific UOGD agent with a specific population and, if so, to have the exposure information necessary to judge its importance for health.

Figure ES-1. Conceptual model of potential exposure pathways associated with UOGD.

Survey of the Literature

The survey of the literature was guided by the following question:

What is known about potential UOGD-related human exposures?

The Committee surveyed peer-reviewed and gray literature published between January 1, 2000 and July 10, 2019 that contribute to understanding how people might be exposed to chemical agents or non-chemical agents released directly from UOGD to the environment. Such releases may be operational (e.g., permitted air emissions), accidental (e.g., spills and leaks), or unauthorized (e.g., illegal discharges).

All potentially useful studies were considered whether or not the investigators set out to study human exposures. This included studies that characterized one or more elements of an exposure pathway, such as the chemical and non-chemical agents associated with UOGD operations, the ways that these agents are released to and behave within the environment, the concentrations of agents in air, water, and other environmental media, and the potentially exposed populations and their time–activity patterns, which influence whether and how exposures occur. The Committee developed a set of questions to facilitate its survey for understanding exposures to UOGD and identifying knowledge gaps (Box ES-1).

Overview of the Exposure Literature

In response to the rapid increase of UOGD in the United States, scientific inquiries about human exposure to chemical and non-chemical agents from UOGD operations also increased (Figure ES-2). The literature search revealed hundreds of citations for studies that have been conducted to understand environmental impacts associated with UOGD, including many reporting measured or predicted levels of UOGD-related agents in air, water, and other environmental media. These studies focused on major oil and gas

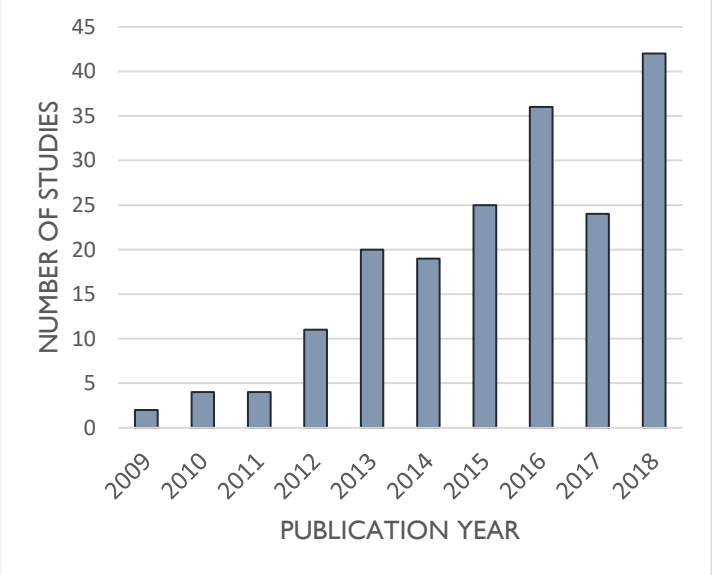
producing regions in the United States; that is, in shale plays located within sedimentary basins where UOGD is active (Figure ES-3).

Box ES-1. Questions to facilitate the review of literature for understanding exposures to UOGD

1. Did the investigators demonstrate a link between their monitoring or modeling results and UOGD?
2. Did the investigators identify which human populations, if any, could be exposed to the chemical or non-chemical agent(s) investigated in the study?
3. Are the monitoring or modeling results potentially useful for understanding exposure to UOGD-related agents (e.g., likelihood, frequency, duration, or magnitude) for:
   a. The location and population under study?
   b. Other locations and populations?
4. Monitoring studies: Did the investigators select appropriate sampling and analytical methods and use them properly (e.g., proper calibration)?
5. Modeling studies: Was model selection, parameterization, and evaluation appropriate?
6. Is there information missing from the paper that limits inferences about realized or potential exposures to UOGD-related agents? If so, explain.
7. Are study results subject to important uncertainties with respect to addressing the study objectives? If yes, what are they, and are they quantified or discussed qualitatively?
8. How does the paper inform the potential design of a future exposure study (consider both positive and negative aspects of the study)?

The majority of studies focused on levels of agents in the air (n=114), with most measuring or modeling concentrations of non-methane volatile organic compounds (VOCs) and particulate matter in or near areas with UOGD, and with some assessing air quality from secondary pollutant formation (e.g., ozone). Other studies focused on levels of agents in water (n=82), primarily as a result of accidental releases, with most measuring or modeling concentrations of VOCs, metals, and other chemicals associated with flowback and produced water.

Figure ES-2. Number of studies reporting measured or predicted levels of UOGD-related chemical and non-chemical agents by year of publication (Publication year based on year of electronic publication; Appendix A includes the list of publications).

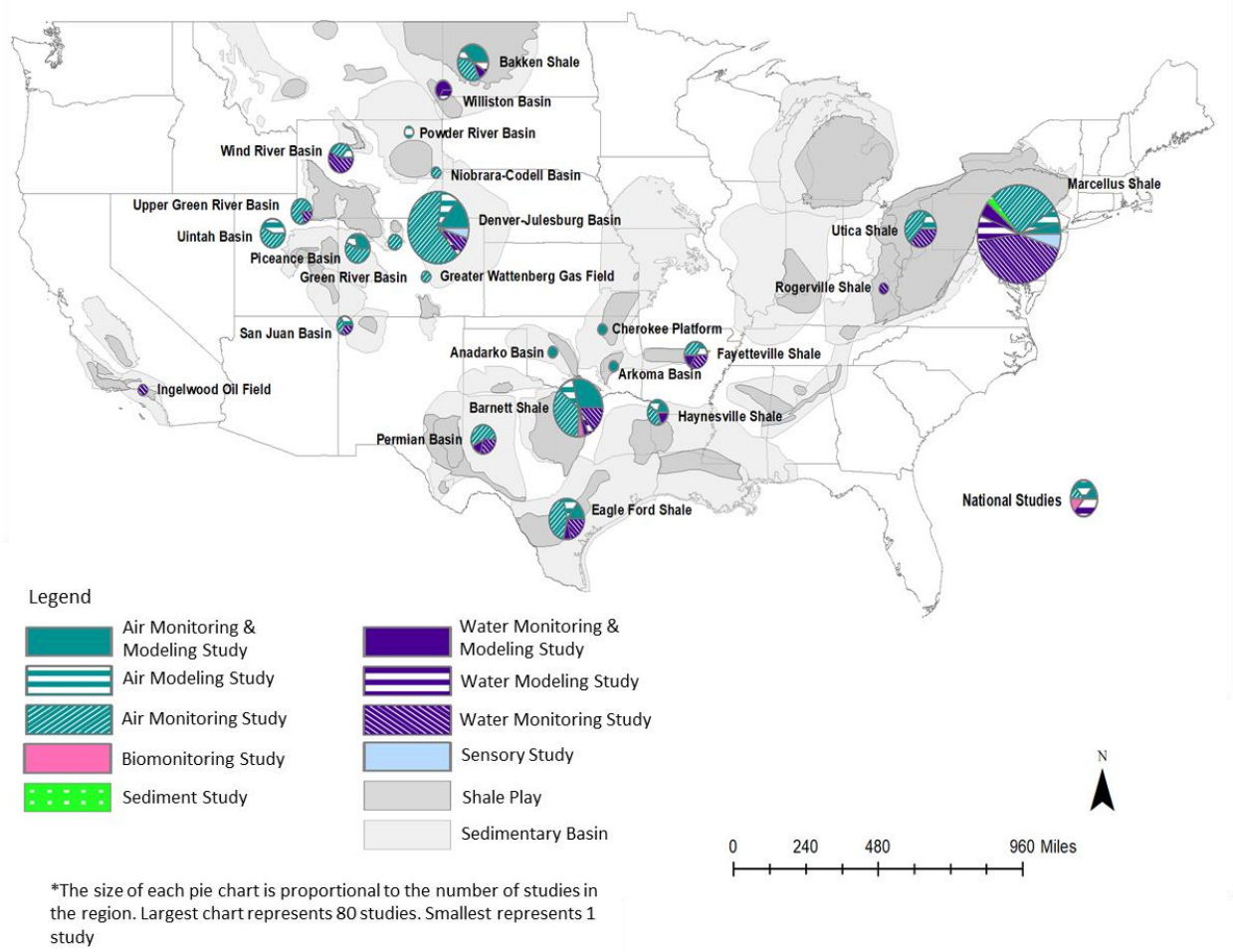


Many of the water-related studies were conducted in the Marcellus region. Fewer studies characterized noise, odor, and light exposures (n=7) or UOGD-related agents in soil (n=28). Five studies used biomonitoring techniques to measure concentrations of chemicals or related metabolites in people's blood, urine, or hair.

Most studies focused on a single environmental medium. Methods used in these studies varied from direct sampling and analysis of the media of interest to modeling levels of agents in a given medium over time and space. For example,

several regional air studies used modeling techniques to predict secondary pollutant formation under different atmospheric conditions.

Figure ES-3. Study locations relative to shale basins and plays, by media investigated. Appendix A includes the list of publications.



THE COMMITTEE'S FINDINGS

Strengths of the Literature in Assessing Human Exposure to UOGD

Overall, the studies contained useful information for understanding human exposures, including those conducted without this specific goal. The studies helped to characterize UOGD-related human exposures by contributing to our understanding of atmospheric and hydrological conditions that affect fate and transport of agents through the environment, the relationship between operations and types or levels of emissions, and pathways of potential exposures. In addition, some investigators were resourceful in their use of previously published data, such as air quality data collected as part of state monitoring programs.

Some investigators used methods that were useful for isolating UOGD sources. Some measured emissions on well pads and used the data, along with meteorological and topographical data, to analyze air quality changes over space and time. Studies sometimes involved the use of various tracers or markers to estimate the levels of agents in air or water that were attributable to UOGD. Other investigators

assessed the chemical concentrations before, during, and after UOGD activities, enabling an evaluation of potential impacts specific to those activities.

Studies of greatest utility for addressing the Committee's guiding question were those that shed light on spatial variability of agent concentrations (e.g., by sampling at various distances from a well pad) and temporal variability (e.g., by sampling over multiple sampling periods during a variety of UOGD activities, meteorological conditions, seasons, and times of day).

A subset of studies was conducted with the aim of characterizing human exposure to chemicals, noise, and light. To do so, investigators collected samples in areas where people spend much of their time, including air sampling in residential communities and water sampling of drinking-water wells. Some studies involved affected communities through discourse and participation, thereby providing results to the affected communities and benefiting from local knowledge. In addition, some state agencies conducted air sampling in response to community concerns.

Knowledge Gaps about Human Exposure to UOGD

The quantity of data on levels of UOGD-related agents in the environment continues to increase along with efforts to use the data to quantify human exposure. Nevertheless, important knowledge gaps remain in our understanding of who might be exposed, how exposures might arise, how exposures vary over time and across regions, and the likelihood of exposure.

Few studies provided the information necessary for linking environmental concentrations of agents to specific UOGD-related sources (e.g., diesel-powered equipment) or to distinguish between contributions from UOGD and other sources, such as conventional oil and gas development. In addition, the generalizability of study results to UOGD operations, geographic areas, and populations beyond those investigated in the studies is not clear.

PLANNING FOR EXPOSURE RESEARCH

Given the current state of knowledge on UOGD and potential exposures, the Committee recommends further investigation to improve understanding of human exposures to UOGD to support decision-making by community members, public health officials, regulators, oil and gas operators, and others. Informed by its review and input received from workshop participants, the Committee identified priority knowledge gaps and developed a set of characteristics critical to high-quality and policy-relevant research.

Research Questions

The Committee framed knowledge gaps as research questions within the conceptual model of exposure (Figure ES-1; Table ES-1). In general, understanding the agents and mechanisms by which human exposures arise is central to being able to generalize study results to different sets of regional conditions, operational practices, and population characteristics. For each knowledge gap, the Committee provided examples of research activities.

Anticipated Attributes of Research

Based on findings from this review, a parallel review of UOGD-related epidemiology literature (HEI-Energy Research Committee 2019), and consultations with stakeholders, the Committee will prepare a Research Solicitation requesting proposals to fill knowledge gaps about human exposures to UOGD. The Committee is charged with overseeing selection and implementation of all research and ensuring its quality and utility for understanding human exposure to UOGD.

Although the knowledge gaps in Table ES-1 represent separate elements of the conceptual model of exposure, future research projects funded by HEI-Energy will ideally include multiple, if not all, elements of an exposure pathway. In defining the scope of research, the Committee recognizes the value of a better understanding of air- and water-related exposures, achieved with comprehensive, high-quality research that characterizes the range of exposure conditions across regions of the United States.

Table ES-1. Knowledge gaps framed as example research questions.

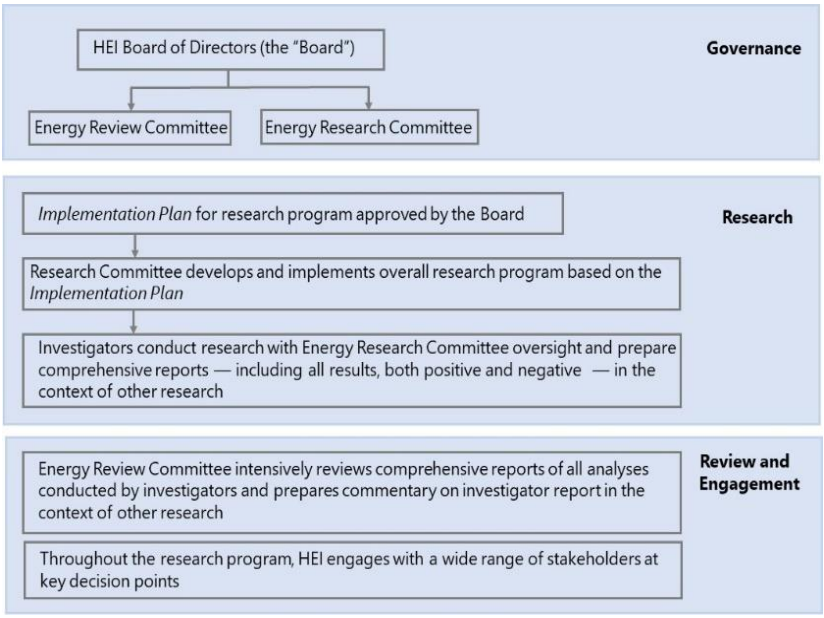
UOGD SOURCES
1. How do the characteristics (i.e., the likelihood, composition, magnitude, frequency, and duration) of potential environmental releases from UOGD vary over space and time as a function of differences in the geological formations, meteorology, and variable practices among operators, across phases of development, or in response to technological innovation, changing regulations and guidance, and community concerns?
2. **a.** What is the relative contribution of operational, accidental, and unauthorized releases to environmental concentrations of UOGD agents[1] in air? How might they contribute disproportionately to total emissions? How can emissions from individual UOGD processes be best quantified? Can measurements of the release of methane or other chemicals be used to help inform estimating non-methane emissions associated with UOGD operations? How can we use longer term observations (e.g., routine ground-based and satellite, including flares) observations to estimate historical trends in emissions? **b.** What is the relative contribution of operational, accidental, and unauthorized releases to environmental concentrations of UOGD agents in surface water and groundwater?
RELEASE MECHANISMS AND TRANSPORT PATHWAYS
3. **a.** How does variation in regional conditions (e.g., meteorology and topography) affect the levels of UOGD agents in air over various temporal scales (e.g., hourly, diurnally, and seasonally) as a result of chemical transformation and transport? What methods are available to characterize the fate and transport of UOGD releases to the air? **b.** How does variation in regional conditions (e.g., topography, geochemistry, geophysics, and hydrology) affect the levels of UOGD agents in water over various temporal scales (e.g., seasonally) as a result of chemical transformation and transport? What methods are available to characterize the fate and transport of UOGD releases to water? **c.** To what extent does UOGD contribute to increased levels of non-chemical exposures (e.g., noise, light, and vibration) within and across regions and operations?
4. **a.** How can levels of UOGD agents in air be distinguished from levels contributed by other natural (e.g., naturally occurring methane) and anthropogenic (e.g., conventional oil and gas development) sources? What is the relative contribution of air emissions from UOGD to local and regional concentrations? **b.** How can levels of UOGD agents in water be distinguished from levels contributed by other natural and anthropogenic sources? What is the relative contribution of water releases from UOGD to local and regional concentrations?
POPULATIONS
5. What are the characteristics[2] of populations potentially exposed to UOGD agents at local and regional scales?
6. Which population behaviors (e.g., time–activity patterns) influence the potential for exposure to UOGD agents? To what extent do exposures to UOGD agents differ among individuals within and among exposed populations?
7. How can exposure monitoring methods (e.g., study design, instrumentation, and other technologies) accurately characterize total personal and population-wide exposures to UOGD over time and space?

[1]UOGD agents might be released to the environment as:

- Operational releases: In accordance with applicable regulations (e.g., permitted discharges to surface water, equipment emissions to ambient air, and vehicle exhaust),
- Accidental releases: As a result of poor practices (e.g., improper waste disposal, malfunctioning equipment, and explosions), or
- Unauthorized releases: As a result of illegal activities (e.g., unapproved disposal of waste materials).

[2]Population characteristics include numerous factors, such as age, sex, race, ethnicity, socioeconomic status, health status, size of the population, activity patterns, and other factors.

Figure ES-4. Overview of HEI-Energy model for providing impartial scientific research.



In preparing its Research Solicitation and reviewing proposals submitted in response, the Committee seeks research that possesses the characteristics in Table ES-2. In its Research Solicitation, the Committee will specify that several key components are required for a research program to be selected, including study of agents of potential concern for health, relevant geographic areas, necessary technical and community engagement expertise on the investigator team, a detailed quality assurance project plan, and an a priori study interpretation and communication plan, among other general components of a high-quality study.

Looking Ahead to HEI-Energy's Research Solicitation

HEI-Energy will fund research that informs policy decisions about how best to protect public health in the oversight of UOGD. The new research program is modeled after HEI's existing successful model for providing high quality, impartial scientific information about air quality and health (Figure ES-4). Key components include:

- *Independent governance* of the research program with leadership by a board of directors unaffiliated with sponsors;
- *Balanced funding* from governmental agencies, the oil and gas industry, and occasionally private foundations;
- *High-quality science* with research competitively selected for funding and overseen by the Energy Research Committee, which consists of knowledgeable scientists that have been vetted for bias and conflict of interest;
- *Extensive peer review* of science by an Energy Review Committee, which consists of knowledgeable scientists that have been vetted for bias and conflict of interest, that works independently of the Energy Research Committee to provide peer review and commentary on research;
- *Open and extensive engagement with stakeholders*, including local community members and officials in study locations;
- *Communication* of all results, including both positive and negative findings, in the context of other relevant research; and
- *Provision of impartial science* for better informed decisions without advocating policy positions.

HEI-Energy expects to distribute the Research Solicitation to the broad scientific community, seeking multi-disciplinary teams with the skill and capacity to mobilize exposure studies in one or more major oil

and gas-producing regions of the United States. The Research Committee will prioritize proposals that align with the characteristics listed in Table ES-2. Throughout the selection, implementation, and review of research projects, HEI-Energy and the Committee will provide oversight to ensure quality and effective communication with stakeholders about research progress.

Table ES-2. Characteristics of appropriate research identified by HEI-Energy Research Committee (in alphabetical order).

Criterion	Description
Brings value to and informs decision-making	Is useful to communities in study areas, government officials, industry, and other stakeholders. Ideal study designs will be informed by successful engagement with the communities in study areas and other stakeholders.
Broadly generalizable	Designed to be broadly generalizable across geographic regions, UOGD operating conditions, or communities over time, including periods of low and high UOGD activity, without sacrificing validity.
Determines whether an exposure pathway links a UOGD process with a community	Links one or more chemical or non-chemical agents directly released to the environment from a UOGD process to a potentially exposed community. The research allows for the detection of possible causal links between one or more UOGD processes (e.g., specific equipment, activity, or phase of development) and resulting human exposures. The study is designed to distinguish between agents released from UOGD and non-UOGD sources.
Expands understanding of temporal and spatial variability of exposure	Selected study locations and designs will substantially fill important gaps in understanding of variability in exposure conditions over temporal and spatial scales relevant for decision-making by communities, regulators, industry, and other stakeholders.
Optimizes use of the research budget by maximizing efficiency	Ensures that the research budget is spent on gathering data and information that is not already available (e.g., by incorporating or complementing existing data and information) and that prioritization and sequencing of data collection maintains a focus on exposures of possible concern.
Useful for assessing health risk	Collects data or analyzes existing data (or establishes practical exposure assessment methodologies) that is useful for assessing the potential for human health effects at resolutions relevant for application in an epidemiology study or risk assessment.

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HUMAN EXPOSURE TO UNCONVENTIONAL OIL AND GAS DEVELOPMENT: A LITERATURE SURVEY FOR RESEARCH PLANNING

1.0 INTRODUCTION

Onshore development of oil and natural gas from unconventional resources (or "unconventional oil and gas development" [UOGD] and defined in Box 1-1 and Section 2) has expanded rapidly in the United States since the early 2000s, along with concern about potential health effects. In 2015, the Health Effects Institute (HEI) released a Strategic Research Agenda to help guide future research about the potential impacts from UOGD (HEI Special Scientific Committee on Unconventional Oil and Gas Development in the Appalachian Basin 2015). HEI-Energy was formed as an affiliate of HEI to address a subset of questions in the Research Agenda related to human exposures and health.

The Research Committee of HEI-Energy (the Committee) will use results from this report and a companion report reviewing epidemiology literature (HEI-Energy Research Committee 2019) to inform HEI-Energy's planning for research to better understand exposures associated with UOGD.

1.1 BACKGROUND

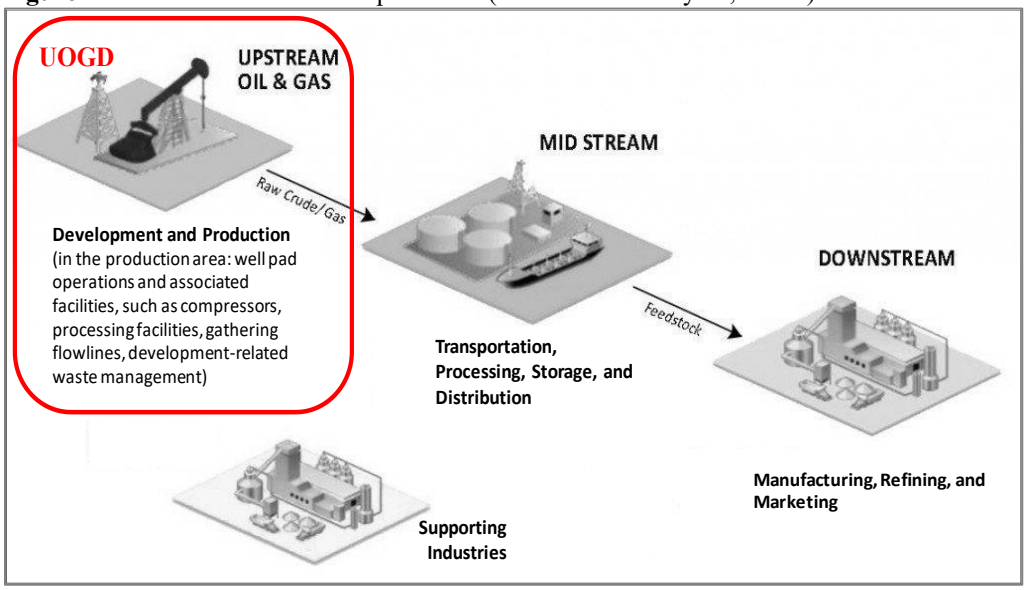
1.1.1 UOGD Defined

UOGD refers to the onshore development and production of oil and natural gas from shale and other unconventional, or low permeability, geologic formations as practiced starting around the beginning of the 21st century through multistage hydraulic fracturing in horizontal wells. Figure 1-1 provides a graphic illustration of UOGD operations, which occur on and off the well pad and include:

- *field development*: exploration, site preparation, vertical and horizontal drilling, well completion (casing and cementing, perforating, acidizing, hydraulic fracturing, flowback, and well testing) in preparation for production, and management of wastes (i.e., handling of waste from its creation to disposal, including collection, storage, transport, treatment, reuse, recycling, and disposal);
- *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; and
- *post-production*: well closure and land reclamation.

Although this document was produced with partial funding by the United States Environmental Protection Agency under Contract No. 68HERC19D0010 to the Health Effects Institute–Energy, it has not been subject to the Agency's review and therefore does not necessarily reflect the views of the Agency, and no official endorsement by the Agency should be inferred. Oil and natural gas companies also provided funding to produce this document; however, it has not been subject to their review and therefore does not necessarily reflect the views of any of the oil and natural gas companies, and no endorsement by them should be inferred.

Figure 1-1. Schematic of UOGD operations. (Source: Debra Bryant, Avata)



1.1.2 Increased Rate and Intensity of Oil and Gas Development in the United States

Oil and natural gas development is not new to the United States, with development beginning in the mid-1800s. Historically, oil and natural gas were extracted either without hydraulic fracturing or with lower volumes of hydraulic fracturing fluid than are often used today. Changes in technology have altered industry practices and prompted new questions that need to be answered.

The scale and rate of oil and natural gas development since the early 2000s differ markedly from previous development, stemming from technological changes involving increased use of hydraulic fracturing combined with horizontal drilling to develop low-permeability geologic formations that could not previously be developed profitably (Soeder 2018). Evolving technologies influence where development is economically feasible. As a result, UOGD now sometimes takes place in regions unaccustomed to the current scales of activity. The changes in technology also enable a substantial increase in the rate and intensity of development as described in Section 2. The modified practices affect the potential for both positive and negative consequences on oil and gas workers, people in nearby communities, the structure and function of those communities, and the local, regional, national, and possibly, global environment.

The recent controversy about UOGD in the United States — as well as much of the research in response to it — has been focused largely on potential human exposures, health effects, and climate change. Substantial efforts are underway within industry, government, and the broader scientific community to assess climate change impacts of UOGD (e.g., Allen et al. 2016). The amount of research assessing human exposure and health effects has also increased in recent years. This review and the broader HEI-Energy program are focused on understanding what has been learned about potential exposures and supporting research to address important knowledge gaps that remain.

1.1.3 Increased Attention to Potential Exposures and Health Effects Associated with UOGD

Today, many people in the United States live near oil and gas development (Czolowski et al. 2017). With this proximity comes the potential for people to be exposed to a variety of chemical and non-chemical agents directly released to the environment from UOGD. Examples include vehicle and equipment emissions, chemicals released during drilling, well completion, and production, and noise and light from drilling and hydraulic fracturing. As the United States shale oil and gas boom accelerated in the early 2000s, scientists began to assess the potential for human health effects from UOGD exposures (e.g., Adgate et al. 2014; Brown et al. 2014; Czolowski et al. 2017).

Research to understand potential exposures and effects continues. Some investigators have reviewed information on the chemicals used in UOGD operations as a starting point for identifying possible exposures (Camarillo et al. 2016; Crosby et al. 2018; Elliott et al. 2016, 2017; He et al. 2017; Inayat-Hussain et al. 2018; Kassotis et al. 2016c; Russo and Carpenter 2019; Stringfellow et al. 2016, 2017; Webb et al. 2014, 2016, 2017; Xu et al. 2019a; Yost et al. 2016a, 2016b). Other investigators have presented original toxicity data (Boulé et al. 2018; Crosby et al. 2018; Hansen et al. 2019; He et al. 2018a, 2018b; Kassotis et al. 2014, 2015, 2016a, 2016b, 2018a, 2018b; Robert et al. 2018, 2019; Sapouckey et al. 2018; Wang et al. 2019) or reviewed published toxicity data (Balise et al. 2016; Bolden et al. 2018; Colborn et al. 2011; Elliott et al. 2017; Kassotis et al. 2016c; Webb et al. 2016, 2017) for some UOGD-related chemicals, and still others have attempted to understand the risks that they might pose to human health by conducting epidemiology studies (reviewed in HEI-Energy Research Committee 2019) and risk assessments (Agency for Toxic Substances and Disease Registry 2010, 2016; Bunch et al. 2014; Colorado Department of Public Health and Environment 2016, 2017a, 2017b, 2018a, 2018b, 2018c, 2018d; Coons and Walker 2008; Crowe et al. 2016; Ethridge et al. 2015; Gradient Corporation 2013, 2019; McClellan and Snipes 2010; McKenzie et al. 2012, 2018; McMullin et al. 2017, 2018; Paulik et al. 2016; Pennsylvania Department of Environmental Protection 2018; Regli et al. 2015; Walther 2011).

1.2 Overview of the Report

1.2.1 Scope

Acknowledging the full range of potential beneficial and adverse exposures associated with UOGD is important to understanding effects on health[1]. As a practical step forward, this review focuses on environmental exposures to chemical and non-chemical agents released directly from UOGD that have the potential to adversely affect health so that action can be taken where needed to protect public health (blue highlighted portion of Figure 1-2). Analysis of past studies and their limitations can facilitate designing a study that addresses many of the complexities in quantifying exposure (Box 1-2) to support future exposure and health studies that consider a broad range of exposures (i.e., acute versus chronic exposures and local versus regional-scale exposures).

[1] In addition to environmental exposures to chemical and non-chemical agents released directly from UOGD, people might be exposed to UOGD-related physical hazards such as traffic accidents (Blair et al. 2018a; Casey et al. 2019; Graham et al. 2015; Maryland Institute for Applied Environmental Health 2014; Muehlenbachs and Krupnick 2013; Witter et al. 2013), fires and explosions (Blair et al. 2017), and earthquakes (Andrews and Holland 2015; Ellsworth 2013; Hornbach et al. 2015; National Research Council 2013). They also might experience social change and community disruption (Becker 2018; Considine 2010; Cooper et al. 2016; Fernando and Cooley 2016; Ferrar et al. 2013a; HEI Special Scientific Committee on Unconventional Oil and Gas Development in the Appalachian Basin 2015; The Academy of Medicine Engineering and Science of Texas 2017) and economic change (e.g., Jacquet et al. 2018; Krupnick and Echarte 2017; Newell and Raimi 2018) that can come with a new or modified industry and its workers. While these types of exposures are important, they fall outside the scope of this literature survey.

Box 1-2. Why is understanding people's exposures to UOGD-related chemicals and other agents so complex?

Communities near UOGD, regulators, members of industry and others can benefit from an improved understanding of whether and to what extent people are exposed to chemicals and other agents (like noise) from UOGD operations. Information on exposure is needed to determine whether people may experience adverse health effects from UOGD-related agents. Scientists have to collect information that allows them to follow the path from the source of the agents all the way to contact with people who may be exposed. This path is shown here in a simplified flowchart:

Exposure conditions are not static across time and vary among locations. Levels of UOGD agents in the environment can vary over the course of a day, season, year, and longer periods, depending on the level and type of UOGD activity, the medium of exposure (e.g., air and water), and characteristics of the local environment. Good design of an exposure study accounts for this variability to allow for assessment of short-term peak (acute) exposures and longer term (chronic) exposures. Levels of UOGD agents in the environment can also vary across regions and even across well pads as a function of geology, operator practices, local regulation, and other factors.

Why is it difficult to get this information? At each step in the path, there are challenges. Here are a few examples:

UOGD Sources: UOGD involves a collection of complex industrial processes involving numerous chemicals and the processes change through the various stages of oil and gas extraction to longer term changes (Section 2). Processes also differ among locations and operators. These complexities make it difficult to determine the composition and magnitude of releases from place to place and over time.

Release Mechanisms and Transport Pathways: After chemicals are released into the environment, they are transported by wind and water and other physical mechanisms. Chemicals can also change due to contact with other chemicals and the sun's energy. As a result, the composition of mixtures of chemicals is constantly changing from the time they are released to the time they come into contact with people. Scientists struggle with how to best capture air, water, or other environmental samples that reflect these changes and with how to model these changes.

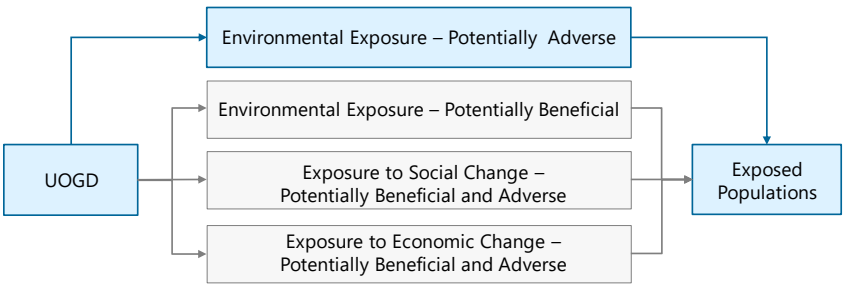
Media or Types of Exposure: People are exposed to chemicals in different media (e.g., air and water) to varying degrees because concentrations in these media will vary. For example, some soils may be more likely to hold onto some chemicals than others, so depending on the type of soil in a community, people's exposures can differ by large amounts. Chemicals measured in media may also represent contributions from a variety of different sources (e.g., traffic and other industries), so researchers need to employ methods to understand the contribution of each source.

Routes of Exposure: Part of exposure assessment is understanding how much of a chemical or chemicals people come into contact with. But people vary in terms of how much air they breathe (consider the difference in breathing rates between a runner and someone watching television), how much water they drink, and so on.

Exposed Populations: Scientists need to understand how people behave in order to assess exposure and the potential for health risks. Here again things are complicated: some people spend a lot of time outdoors while others spend most of their time inside. Some have lived in a community near UOGD for years while others may have moved nearby recently.

To understand exposure, we may not need information on *all* of these factors, but with more complete information, scientists can have more confidence in their studies on links between exposure and health outcomes.

Figure 1-2. Potential human exposures associated with UOGD. This review focuses on potential environmental exposures that might adversely affect health (designated in blue).



1.2.2 Objectives

The primary objectives for this review are to (1) summarize current understanding of potential UOGD exposures in the United States, (2) move the science forward by identifying gaps in knowledge about potential exposures that merit research, and (3) develop research questions to address the knowledge gaps along with a set of anticipated characteristics critical to high-quality and policy-relevant research.

1.2.3 Organization of the Report

This report is organized into four primary sections. *Section 2* provides an overview of UOGD operations in the United States, emphasizing aspects that may be important when formulating exposure research. *Section 3* summarizes the methods used to survey the literature. *Section 4* provides the Committee's summary of the literature, what it tells us about potential exposures, lessons learned about exposure assessment methods, and gaps in the exposure literature. *Section 5* lists a set of research questions defined by the Committee to address gaps in knowledge about potential human exposures to UOGD, along with characteristics that the Committee seeks in a research proposal.

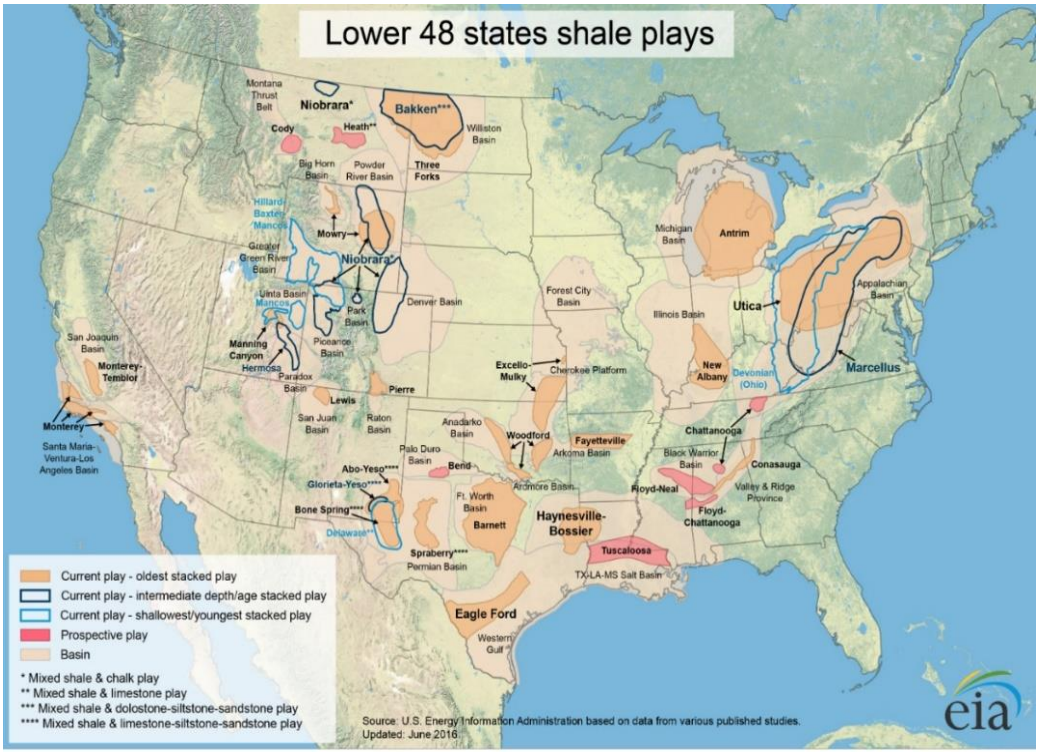
2.0 UNCONVENTIONAL OIL AND GAS DEVELOPMENT

UOGD shares features with conventional oil and gas development, which has been ongoing in the United States since the 1800s, but UOGD differs in ways that can be important for understanding the potential for human exposures associated with it. Therefore, the assessment of human exposure to UOGD requires a fundamental understanding of the underlying operations. This discussion of UOGD is intended to provide a basic overview of UOGD operations, emphasizing operational and regulatory aspects that may be important when formulating exposure research.

2.1 GEOGRAPHIC EXTENT OF UOGD IN THE UNITED STATES

Many of the UOGD operations today extract oil and gas from shale resources (Figure 2-1), which are distributed across the United States in areas with widely varying topographies, climates, levels of industrial and urban development, and population densities.

Figure 2-1. Map of shale plays in the United States (Source: U.S. Energy Information Administration. *(https://www.eia.gov/maps/images/shale_gas_lower48.pdf)*



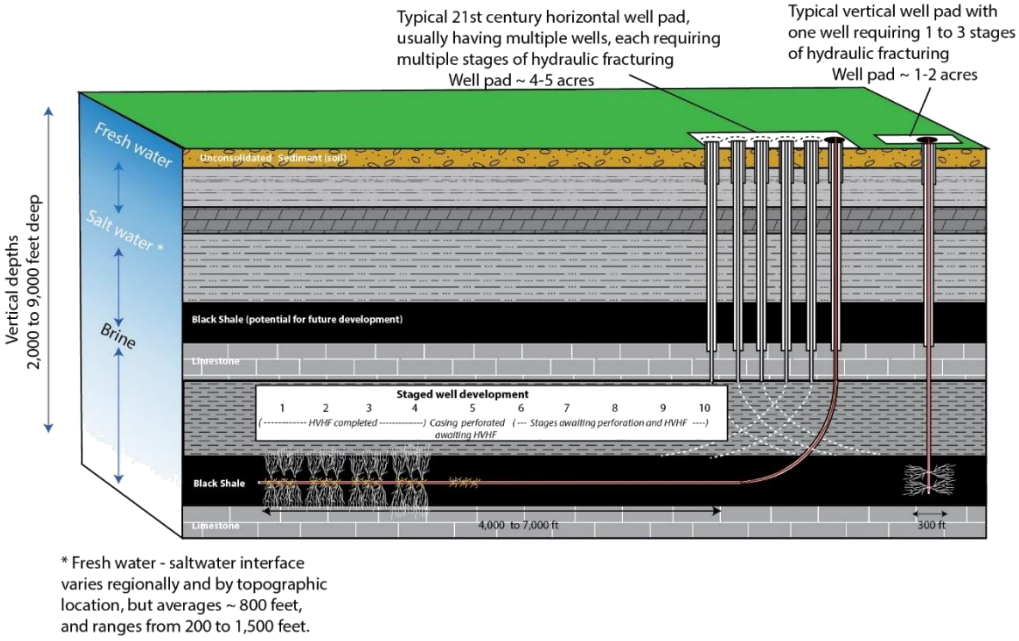
2.2 DISTINGUISHING BETWEEN CONVENTIONAL AND UNCONVENTIONAL DEVELOPMENT

Some operations employed in UOGD have been used in developing conventional oil and gas reservoirs. Conventional formations are more permeable than unconventional formations (King 2012). In conventional formations, the oil or gas has migrated from source rock to a porous formation and is held

there by a sealing rock unit that prevents further migration. Oil or gas from conventional reservoirs flows readily or requires only a small stimulation with hydraulic fracturing for economical extraction by vertical wells. An unconventional formation is one with extremely low permeability (Ahmed and Meehan 2016) in which the oil or gas essentially does not flow without the application of multiple stages of well-stimulation treatments applied along horizontal wells.

Multi-stage fracturing occurs along the lateral section of a horizontal well, which provides massive contact with the formation compared to a vertical well (Figure 2-2). UOGD wells are stimulated, in stages, from the farthest point back to the curve between the horizontal and vertical well sections, as shown. Multiple horizontal wells are drilled from a single, large well pad for operational efficiency (U.S. Energy Information Administration 2012).

Figure 2-2. Conceptual layout comparing a vertical well with a horizontal well in the Marcellus Shale. Note: The illustration is not to scale, and actual fracture distances vary by depth and the type of resource under development. Illustration by William Kappel.



Today, oil and gas are extracted from wells drilled into both conventional formations and unconventional formations, and while extraction from conventional formations continues, focus in the United States has shifted to UOGD. Most commonly, UOG formations underlie conventional oil and gas formations because the hydrocarbon-rich shales are source rocks for conventional oil and gas reservoirs. The co-location of conventional and unconventional oil and gas development, and use of similar operations, presents a challenge in differentiating exposures emanating specifically from UOGD.

Although the individual development activities used in extracting oil and gas from unconventional formations are not new, their combined application in developing shale plays is new as of the early 2000s, particularly as stimulation volumes have continuously increased (Box 2-1).

Box 2-1. What is new about oil and gas development in the 21st century?

Hydraulic fracturing, horizontal (or directional) drilling, and extraction of oil and gas from unconventional formations, such as tight (i.e. low permeability) sandstone and shale, are not by themselves new.

What is new is the adoption of technology that uses *high-volume* (millions of gallons of water per well) multistage hydraulic fracturing combined with horizontal drilling (thousands of feet drilled within the target formation). This combination of technological innovations has made previously uneconomical oil and gas resources valuable enough to develop.

Today's unconventional oil and gas wells, with their extensive number of fracture stages along lengthy horizontal segments, intersect more of the targeted oil- or gas-bearing rock than earlier vertical wells, which consequently requires the following:

- Larger well pads with extensive amounts of equipment that is transported to and from the pad;
- More raw materials that must be transported to the well pad for drilling, cementing and hydraulically fracturing the target hydrocarbon-bearing formation to produce the oil or gas;
- More liquid and solid waste from multiple wells drilled on one well pad that must be captured, transported, and treated, for reuse or ultimate disposal;
- A longer period of industrial activity required at a single well pad when multiple wells are developed on it; and
- Increased truck traffic, changing demands on community infrastructure, and other possible community effects associated with population mobility

2.3 PHASES OF UOGD

Operational activities in each phase of UOGD differ in duration and in potential for a release to the environment. This section describes UOGD phases and illustrates some of the temporal, spatial, and operational variations across the United States.

2.3.1 Pad Development

UOGD begins with constructing a well pad, which is a site specifically designed to provide a level area sufficient for the equipment used to drill and then complete a horizontal well, while simultaneously providing space for the logistical support operations. Pads are created using diesel-operated construction equipment (e.g., excavators, backhoes, and bulldozers). Other vehicles may deliver construction materials and personnel to the site. Pad construction (including road building) normally is completed in 2–7 weeks.

Engines, which power trucks and the equipment used for site preparation, emit nitrogen oxides (NO_x), particulate matter (PM), volatile organic compounds (VOCs), polyaromatic hydrocarbons (PAHs), and methane (CH_4), among other releases to air (Moore et al. 2014). Well pad construction, truck traffic and other on-pad activities can also generate PM by re-suspending dust. Vehicles moving on and off the site may interfere with local traffic. Depending on the location, traffic interruption is often temporary.

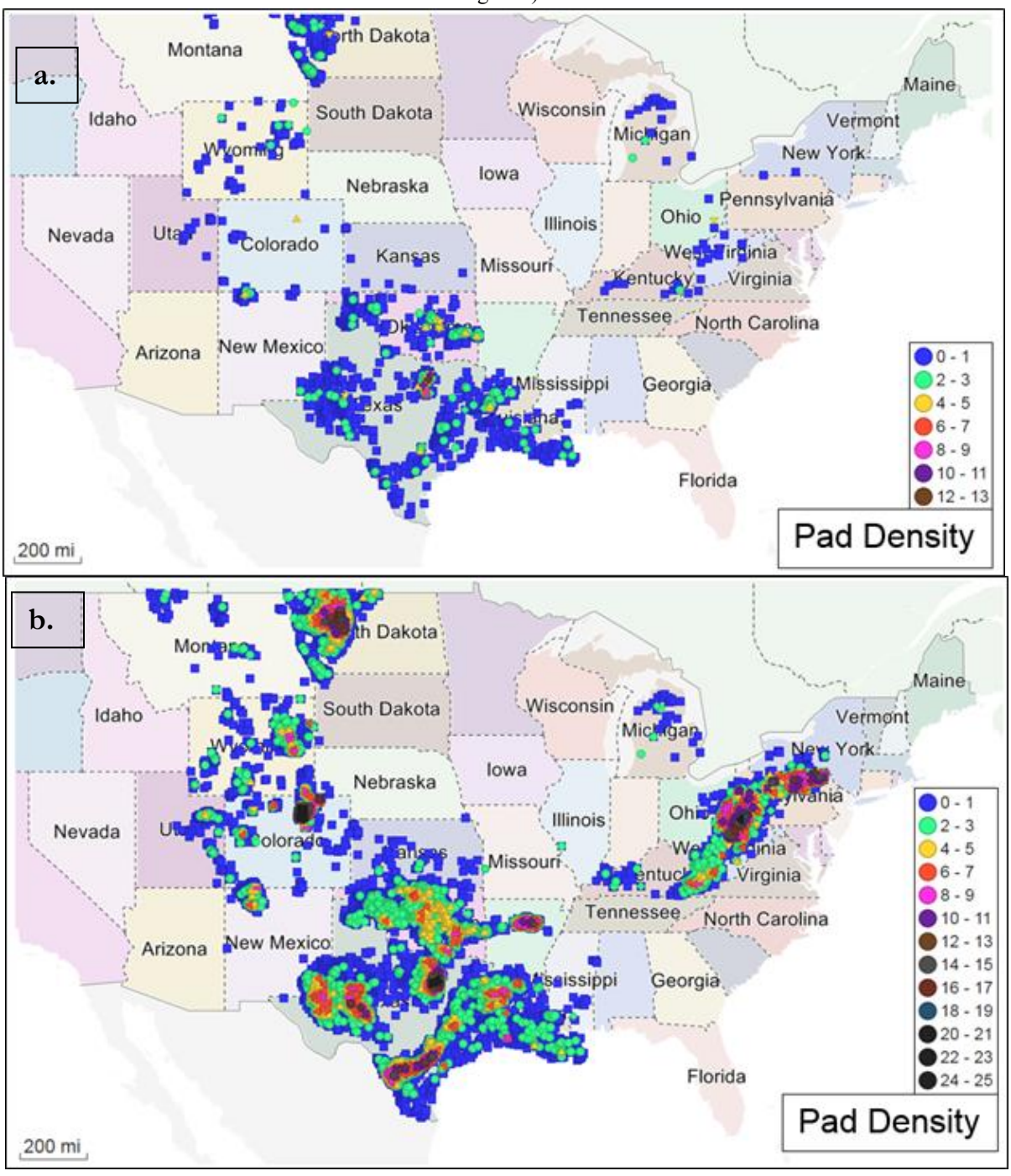
UOGD well pads typically occupy multiple acres with size varying depending on the number of wells per pad. For example, UOGD well pad size in the Pinedale Field, Wyoming increases with the number of wells on the pad (Figure 2-3). The number of horizontal wells drilled per well pad has increased since the early 2000s (Figure 2-4a and 2-4b), and pads with 20 wells or more have been constructed in recent years. Note that these figures reflect wells drilled, not the ultimate planned pad density.

Figure 2-3. Satellite image of three well pads with 1, 2, and 16 wells, respectively, in the Pinedale Field. (Source: Satellite photo from DrillingInfo.)

Oil and gas infrastructure, such as well pads, new roadways to access pads, gathering flowlines, and compressors, has been constructed on a variety of landscapes, including agricultural land, core forest habitat, and lands with soil that is vulnerable to erosion and sedimentation (Drohan et al. 2012; Pennsylvania Department of Conservation and Natural Resources 2014). Some studies have suggested that runoff related to UOGD may be linked with increased levels of turbidity (Entrekin et al. 2011, 2015) and total suspended solids (Olmstead et al. 2013) in receiving waters.

States have various pad design requirements to protect the environment, including spill protection. Pads can be built with multiple types of protections (e.g., protective liners, protection mats, containment units, and earthen berms). Walls may be used around the pad site during drilling and completion to reduce noise and visual disturbances.

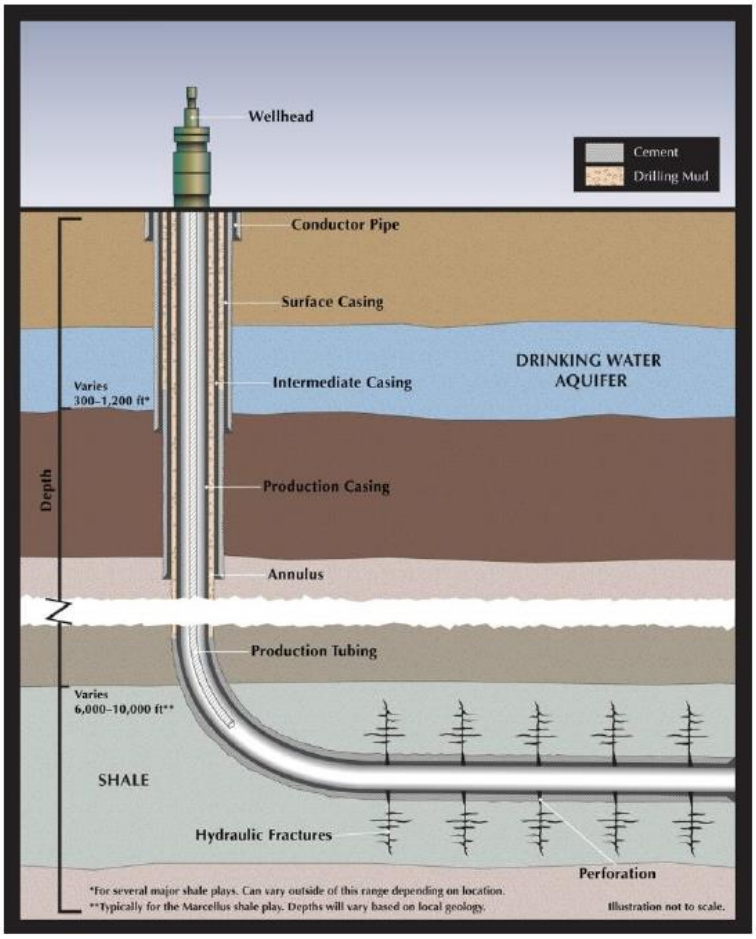
Figure 2-4. Number of horizontal wells drilled per well pad, or pad density, across U.S. shale plays as of January 1, 2005 (a) and January 1, 2019 (b). Each icon represents a single well pad, and the color of the icon indicates the number of horizontal wells drilled on each well pad. (Created by M. Al-Alwani, merging horizontal well records from FracFocus and DrillingInfo.)



2.3.2 Drilling

Drilling creates the borehole required to access the shale formation. Drilling occurs in stages: drilling, then running and cementing casing to isolate each successive portion of the well. Casing is defined as steel pipe cemented into the borehole to isolate fluids in the well from the geological formations being penetrated and vice versa. Each diameter of casing is known as a string, and successive strings of casing are narrower in diameter to fit through the shallower casing. The space between casing strings is known as the annulus, normally filled with cement. The final casing string that runs from the wellhead all the way down to the target zone is known as the production casing. This casing is perforated at the depth of the target formation to allow the desired fluids to enter the well.

Figure 2-5. Well construction design for a Marcellus gas well. This figure shows three casing strings (surface, intermediate, and production) covering the drinking water aquifer.
(Source: Clark et al. 2012. Used by permission.)



Multiple strings of casing are used to isolate the well from surrounding strata (Figure 2-5). Once the drilling rig is assembled and ready to drill, the well is "spudded in," a phrase referring to the commencement of drilling. A short conductor pipe is installed to stabilize the initial hole and secure equipment needed for the deeper parts of the well.

Surface casing is set below the deepest underground source of drinking water, and this casing string is commonly cemented to the surface to protect ground water. The depth of the surface casing varies across shale plays. State regulations often indicate specific impermeable geological layers for setting the bottom of the casing string (referred to as the casing "shoe"). Additional casing is included for deeper sections of the well (Figure 2-5).

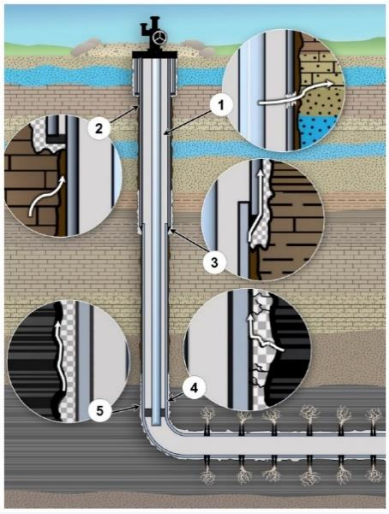
An intermediate casing string is frequently used today and may be required by state regulation. The production casing, or liner, is the final casing run in the well and may not be cemented, depending on the hydraulic fracturing system to be used. The current trend is to cement the production casing along the lateral section as shown in Figure 2-5. The multiple strings of casing and cement together are designed to prevent impacts to surrounding groundwater, but the potential for leaks remains, so monitoring of annular spaces is conducted to detect possible upward fluid movement (Box 2-2).

Drilling mud is a circulating liquid used to cool the drill bit, remove rock cuttings and transport them out of the hole, and provide pressure to keep the borehole walls from caving in until casing can be installed. It circulates through a continuous loop system from storage tanks (or a lined pit) through mud pumps to the well, then back through equipment that removes sand and natural gases before passing over shale shakers, which separate rock fragments from the drilling fluid. The rock fragments, referred to as "drill cuttings," are accumulated for disposal, generally in a confined area near the rig after passing through a centrifuge and dryer to reduce the oil content. The drilling mud is recirculated through the mud pit to the pump and reused in the drilling system. Any drilling mud that has had its physical or chemical properties altered such that it no longer meets the requirements for reuse needs to be stored separately for later treatment and disposal at a licensed facility.

Box 2-2. Well Integrity

Concerns remain regarding upward fluid movement in the cemented annulus between the production casing and formation wall into groundwater. The pathways (represented by white arrows) include: (1) casing and tubing leak into a permeable formation, (2) migration along an uncemented annulus, (3) migration along microannuli, or the space, between the casing and cement, (4) migration through poor cement, and (5) migration along microannuli between the cement and formation.

Routine, direct measurements of fluid movement behind casing are currently impractical. Alternatively, annulus pressure is monitored at the wellhead and positive pressures, referred to as sustained casing pressure, are noted.



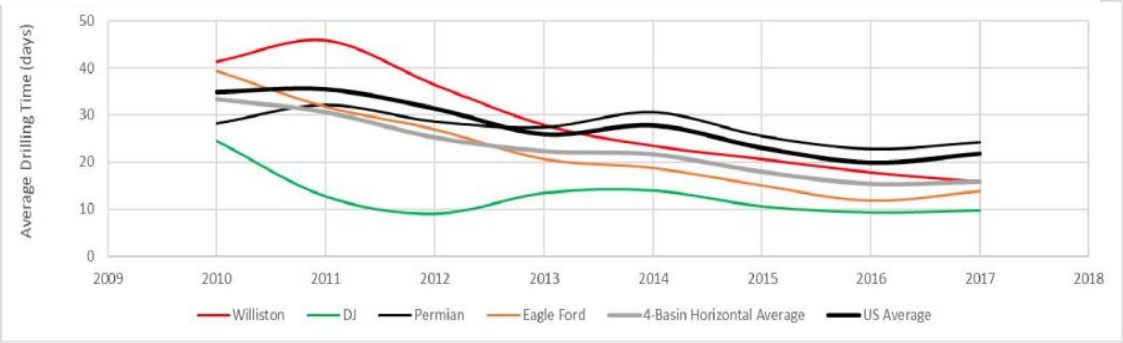
Source: U. S. Environmental Protection Agency 2016a

Drilling muds can be water-based, oil-based, or synthetic-based. Both water-based and oil-based muds include chemical additives such as salts, friction reducers, corrosion inhibitors, foamers, and surfactants and, consequently, they vary with respect to their VOC emissions and odor. In addition, oil-based muds absorb methane, resulting in higher gas emissions at the surface than with use of water-based muds (Thomas et al. 1984). Gas emission estimates from de-gassing drilling mud must be reported under federal regulations (CFR 40, Part 60, Subpart OOOO).

Drilling creates noise and visual disturbances that vary depending on the operation. Near urban settings, operators might erect solid walls surrounding the drilling rig area to reduce these impacts. With increased efficiency, the time required to drill a single well has declined over time (Figure 2-6). Drilling patterns and timing for multiple wells may differ among operators or as a function of market conditions.

Surface emissions during drilling are related to exhaust from non-electric generators on the rig as well as support vehicles, resuspended dust from unpaved access roads, drilling mud de-gassing, and any fluid leaks or spills emanating from the mud circulation system. An uncontrolled surface release of drilling mud and well fluids, referred to as a "well blowout," can occur in approximately one well in a thousand (Patterson et al. 2017).

Figure 2-6. UOGD well drilling time compared across shale plays. (Republished from Weijers et al. 2019 with permission of the Society of Petroleum Engineers; permission conveyed through Copyright Clearance Center, Inc.)



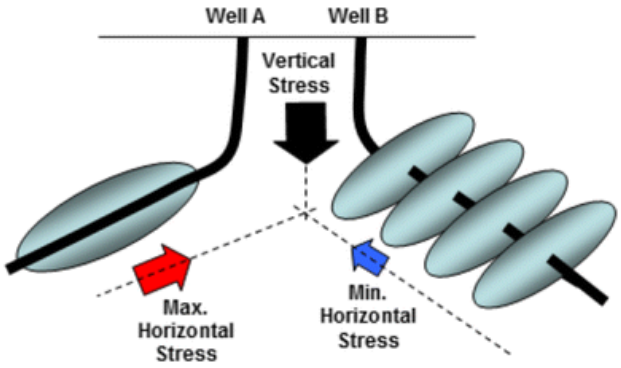
2.3.3 Well Completion (Hydraulic Fracturing)

After drilling is complete, the drilling rig is removed and well completion equipment is brought to the well pad. The well completion process may begin immediately or up to months after drilling. For example, in March 2019, there were approximately 8500 drilled but not completed wells, a one-year increase of 26% (U.S. Energy Information Administration 2019).

Well completion refers to the processes and materials required to establish flow from the formation to the ground surface. In UOGD, well completion includes hydraulic fracturing, a method of stimulating flow. In hydraulic fracturing, fluid is combined with proppant (normally sand or ceramic) and pumped into the formation containing oil or gas under pressures sufficient to fracture the rock, creating a large surface area that is held open by the proppant, which enhances the flow of oil or gas into the wellbore.

Hydraulic fractures orient and grow perpendicular to the direction of the smallest of three principal subsurface stresses (vertical, horizontal maximum, horizontal minimum) as illustrated in Figure 2-7 (Ahmed and Meehan 2016; Smith and Montgomery 2015; Soliman and Dusterhoft 2016). In most shale basins, the greatest stress is the vertical stress, or "overburden" of the rock strata, and the minimum stress is in a horizontal plane within the shale, as shown by the size and direction of arrows in Figure 2-7. In a horizontal wellbore, drilled in the direction of minimum horizontal stress, it is possible to create many vertical fractures along the lateral, as shown in well B of Figure 2-7. Although the geomechanics of this kind of fracturing has been long understood, the evolution of methods for placing multiple fractures along the lateral section of a horizontal well made it possible to economically produce oil and gas from extremely tight, or low permeability, shale formations.

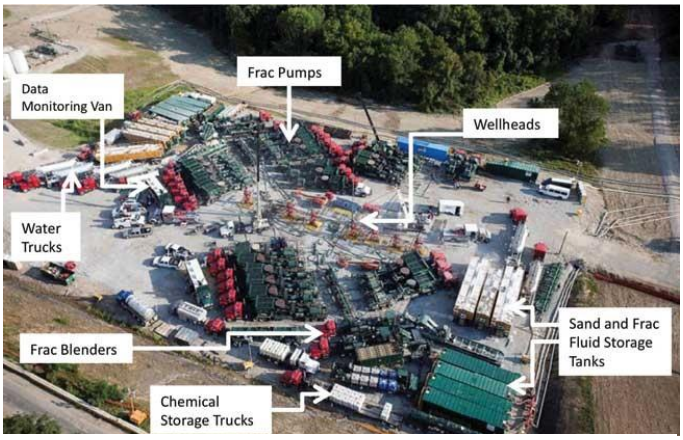
Figure 2-7. Fracture orientation as a function of horizontal wellbore orientation (Bahrami et al. 2016). Each gray oval represents a "'stage"' in a hydraulic fracturing treatment. Well A illustrates drilling in the direction of maximum horizontal stress, resulting in longitudinal fractures that are likely to be parallel to the wellbore. Well B illustrates drilling in the direction of minimum horizontal stress, which allows for the creation of many vertical fractures along the horizontal well.



Fisher and Warpinski (2012) used microseismic data (obtained via a diagnostic method that measures acoustic responses as a fracture propagates through the formation) to investigate whether hydraulic fractures are likely to propagate upward into groundwater. They presented a series of plots demonstrating that it is improbable that fractures can propagate vertically into groundwater. There is significant vertical distance between UOGD completions and groundwater. Well completions in shallower depths will have less vertical height growth due to reduced overburden stress.

In addition to large quantities of fracturing fluid (or "frac fluid"), ample pumping horsepower and pressure are required to create the large fractures needed to produce shale formations economically. Fracturing fluids used in UOGD are most commonly a combination of water and a friction reducer, but gels are sometimes used. Sand is the most common proppant in formations with lower stress and ceramic proppant is used in formations with higher stress values. Higher stresses are typically found in deep formations, such as the Utica shale (Ahmed and Meehan 2016; Smith and Montgomery 2015). The use of finer proppant (similar in particle size to that of flour) has gained popularity in recent years (Kumar et al. 2019).

Figure 2-8. Example UOGD wellsite with tank- and truck-based hydraulic fracturing equipment (Suchy and Newell 2012).



Note: Scale not indicated in original publication.

The fracturing equipment used on a UOGD well pad (Figure 2-8) is a function of the pumping horsepower required for the fracturing treatment and the volumes of fluid and proppant used in each stage of treatment. These, in turn, are a function of the depth of the well and the number of individual stages to be pumped in the well. In the past decade, the number of fracturing stages per well has increased in every shale play (Weijers et al. 2019). A lined water pit (not shown) is often also part of the site.

During fracturing, pumps draw fracturing fluid from tanks (or a lined pit) to the blender tub. Sand is delivered to the blender in several ways. A recent method uses individual closed "boxes" of proppant that are lifted on top of a hopper to reduce sand inhalation during fracturing. The blender mixes the fluid and sand together (referred to as a "slurry") and the slurry is pumped into the well at a high rate (50–90 barrels/minute). The types of fluid and proppant sizes may differ during different portions of the treatment, or between fracturing stages.

The fracturing process will be repeated as many times as the number of fracturing stages designed for the well. Weijers et al. (2019) reported that average total lateral lengths for wells across multiple shale plays have increased from approximately 4000 ft in 2010, to 7500 ft in 2017. In the same period, stage counts have increased from 9–21 stages per well (depending on shale play) to 30–50 stages per well. Treatment volumes have likewise increased accordingly, all in the same period that well density has increased. The time associated with fracturing a well varies across shale plays, and all plays have experienced reductions in completion time with operational efficiency (Weijers et al. 2019). For example, through technological innovation, operators have reduced the amount of time required for fracturing. Instead of stimulating one stage at a time, operators have developed methods (e.g., zipper fracs) to alternate between stimulating stages in adjoining wells.

Much attention has been focused on chemicals used in hydraulic fracturing (Box 2-3). Although most of the frac fluid used in UOGD is water and proppant, frac fluid also contains biocides, corrosion inhibitors, friction reducers, scale inhibitors, oxygen scavengers, potassium chloride, surfactants and cross-linkers. The U.S. EPA (2016a) provides information regarding chemicals most frequently used in hydraulic fracturing between 2011 and early 2013 and Montgomery (2013) provides an overview of their classification. The types of fluid systems vary across shale plays because formation temperatures and rock properties (such as minerology, clay content, and brittleness), vary among the different formations (Ahmed and Meehan 2016; Dobson and Houseworth 2013; Li et al. 2019; Yuyi et al. 2016).

Releases during hydraulic fracturing can occur from spills or leaks during fluid transport on or offsite, casing failures during injection (Beak et al. 2015), and failures in surface pipe or surface equipment during completion. The U.S. EPA (2016a) extensively discussed spill size and frequency and challenges in characterizing spills and their fate and transport. The specific chemicals released by a spill will vary depending on the fracturing treatment and activity associated with the spill (e.g., leak from a holding tank).

Operators may transport water via trucks, requiring hundreds of truck trips per well. Based on median water volume per well, water use has intensified between 2011 and 2016, ranging from a 20% increase in the Marcellus to a 770% increase in the Permian basin (Kondash et al. 2018), exacerbating the potential for releases that can occur during water transport. Transporting water by truck can increase exposure to PM, diesel, and traffic accidents and congestion. More recently industry operators have increasingly employed centralized, lined water pits or lakes, which can provide water directly to multiple well pads.

The American Petroleum Institute (API) has published new standards for shale development to reduce impacts from hydraulic fracturing (Benge et al. 2018). These API standards provide guidance and recommendations for pressure containment and well integrity as well as environmental safeguards for groundwater protection, waste management, emissions reduction, site planning, and worker training. The standards are described in American National Standards Institute (ANSI)/API recommended practice (RP) 100-1 and 100-2. Industry has also developed a stewardship decision-making tool for operators to support UOGD decisions that minimize UOGD impacts and improve sustainability (Wilson 2018).

Box 2-3. Chemical Use in UOGD and FracFocus Database

The chemical composition of hydraulic fracturing fluids varies, and some of the chemicals are classified as confidential business information. In a 2016 report, EPA (2016a) reported on 599 chemicals that have been detected in produced water and 1,606 chemicals associated with hydraulic fracturing, including 1,084 chemicals that have been used in hydraulic fracturing fluid, with typical fracturing treatments consisting of 12 or fewer chemicals (https://fracfocus.org/water-protection/drilling-usage). Additionally, EPA reported that the majority of the 1,606 chemicals lack toxicity reference values for assessing the potential for cancer and non-cancer effects, making risk assessments focused on UOGD releases to water difficult to conduct. In addition to EPA's review, UOGD operators in 26 states provide hydraulic fracturing fluid chemical use data on a voluntary or regulatory basis. These data are made available through FracFocus (www.fracfocus.org), a publicly available database managed by the Groundwater Protection Council (GWPC) and Interstate Oil and Gas Compact Commission (IOGCC). While most chemicals are disclosed to FracFocus, some remain proprietary or confidential.

2.3.4 Flowback

After all fracturing treatments are pumped, pressure is released and the injected fluids, mixed with brines naturally present in the host rock, are allowed to flow back to the surface for a period of time. This period

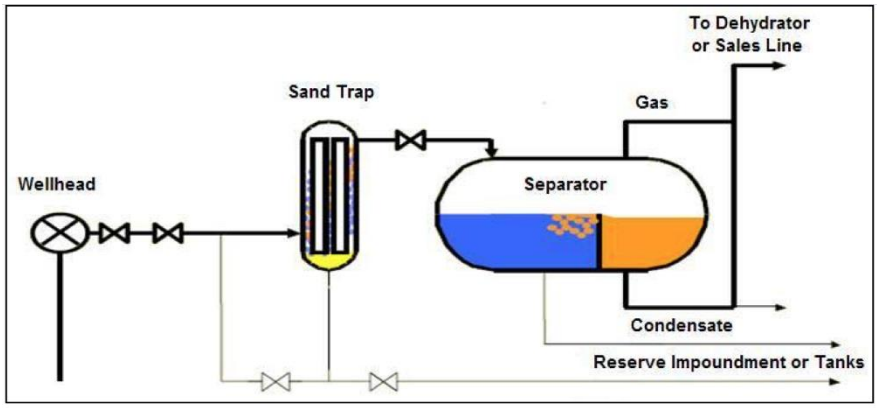
is referred to as "flowback," and may last from 1–4 weeks. Flowback rates can be several thousand barrels a day per well (Guarnone et al. 2012).

The flowback fluid initially contains dominantly frac fluid, mixed with oil, gas, and sand. Salinity increases occur during long flow back periods, which normally indicates natural formation brine (produced water) is returning with the frac fluid. Much of the frac fluid does not return to the surface after treatment (Kondash and Vengosh 2015). Kondash et al. (2018) reported that across six shale basins, the volume of flowback and produced water generated in the first year has increased by from 55% (Niobara) to 550% (Eagle Ford) between 2011 and 2016 as the volume of injected water increased across this period.

U. S. EPA (2016a) identified 599 unique chemicals in flowback and produced water reported from laboratory studies, including salts, metals, naturally occurring organic compounds, radioactive materials, and hydraulic fracturing chemicals. It was noted that, in general, the composition of these waters is similar to produced water from conventional oil and gas development.

Flowback water may be directed to a lined pit, closed tanks, or through pipelines to a central processing location. In the United States, flowback is handled as a reduced-emissions completion in the case of a gas well or wells that produce both oil and gas. A reduced-emissions completion routes flowback through production equipment (Figure 2-9). The gas is routed for use on site, to a sales line, or to a flare if state regulations permit flaring. The liquids from the bottom of the separator are routed to a lined pit or to tanks. Since August 2011, U.S. EPA regulation (CFR 40, Part 60, Subpart OOOO) requires UOGD completions to be handled as reduced-emissions completions unless an exception is granted.

Figure 2-9. Production facilities for reduced-emissions completions.
(Source: U.S. EPA (2011b) and adapted from BP.)



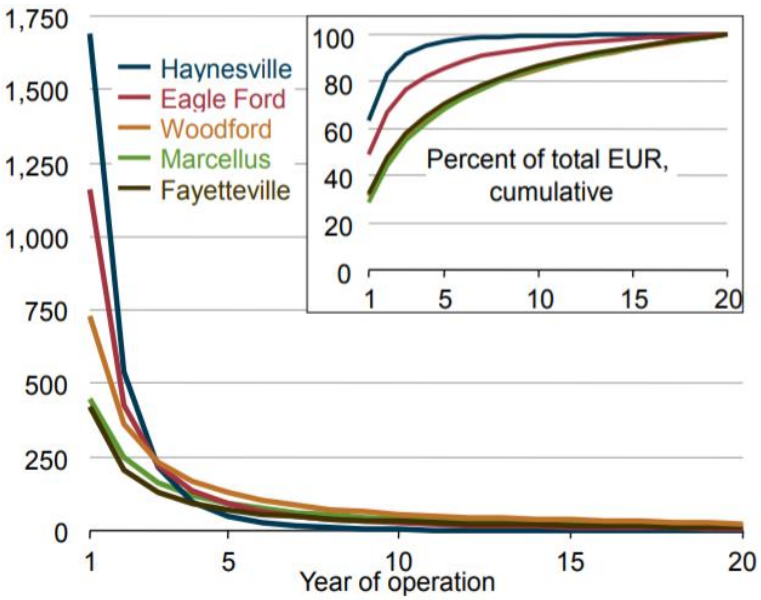
Flowback water is most commonly disposed of in saltwater disposal wells and in many cases is trucked to the disposal location. In the Marcellus Shale most flowback water is treated and reused in future hydraulic fracturing treatments as saltwater disposal well options are limited in Pennsylvania (*www.dep.pa.gov/Business/Energy/OilandGasPrograms/OilandGasMgmt/Pages/Underground-Injection-Wells.aspx*). U.S. EPA is currently examining options for broadening water reuse and disposal options (U.S. Environmental Protection Agency 2019c).

2.3.5 Production

Production refers to the stage when the well is hooked up to permanent production equipment, which allows for continuous flow of fluids. Production facilities include a wide range of equipment that first separates gas from liquid (water and oil or condensate), then separates produced water for holding and disposal, and moves the fluids through flowlines to sales (e.g., compressors are used to bring gas pressure

to transportation or sales line pressures, oil may be pumped through lines or trucked for sales). Oil facilities utilize somewhat different equipment and processes than gas facilities (Arnold and Stewart 2007, 2014).

Figure 2-10. Production decline and estimated ultimate recovery (EUR) for several shale plays. (U.S. Energy Information Administration 2012)



A well's production rate is a function of formation pressure as well as formation permeability and flow area. Formation pressure decreases over time and, at some point, there is insufficient energy to bring fluids to the surface. At this point some form of artificial lift is installed, which includes technologies such as rod pumps, gas lift, and electric submersible pumps for producing liquids (Pankaj et al. 2018). The production rate from a UOGD well declines rapidly over time, with the well's initial rate declining by 40% to 60% in the first year of production (Figure 2-10). Production from the well will last for years, a much longer time than the previous UOGD phases. At this point, the pad will contain only the wellhead(s) and possibly some production-related equipment. The rate of production is monitored by lease operators who visit the well site every 24–48 hours. Some companies remotely and continuously monitor producing rates and pressures from wells, along with pressure and fluid levels in facilities. Pressure and level alarms are a common means to alert operators to potential problems so action can be taken to minimize releases.

Emissions of methane and VOCs to the atmosphere can occur during the production phase, both at the well and production facilities. For example, in a gas well, liquids can accumulate in the well and decrease or interrupt the flow of gas as reservoir pressure is not sufficient to drive production. If this happens, well production is stopped, allowing the pressure to build up again. Once pressure has built to a sufficient level, the well is reopened and the liquids, along with some gas, can be unloaded to a vented tank. During this period of "liquid unloading," emissions of volatile components to air result (Allen 2016). At present, most emissions from liquid unloading are occurring from older, conventional wells (The Academy of Medicine Engineering and Science of Texas 2017). Changes in rules and regulations pertaining to air emissions and the continuing development of new technologies have been aimed at decreasing such emissions.

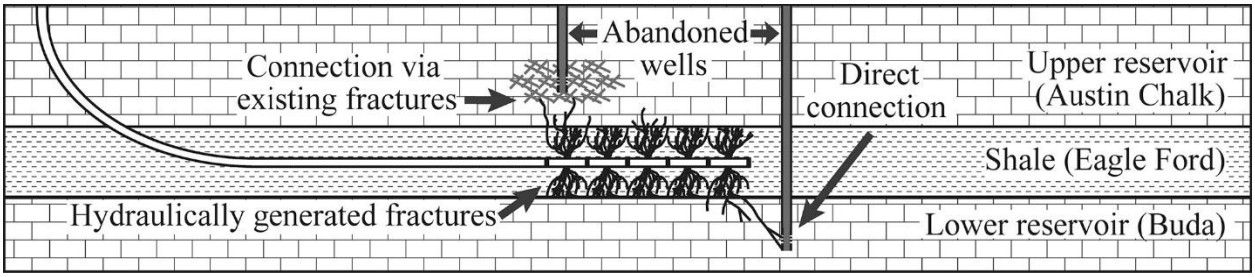
Production facilities emit methane and other VOCs from tank vents, compressors, and other equipment. These facilities are subject to federal regulation (CFR 40, Part 60, Subpart OOOO). More recent U.S. EPA regulation (CFR 40, Part 60, Subpart OOOOa) established emission standards and compliance schedules for the control of methane, VOC, and SO_2 emissions from affected facilities in the crude oil and gas category that were constructed or modified after September 18, 2015.

2.3.6 Post-Production

When a well is no longer economically viable, an operator may decide to permanently plug the well with cement (plug and abandonment, referred to as P&A). Few UOGD wells have reached this point as yet, but when that occurs, operators are expected to obtain the necessary permit and follow state regulations in the placement of multiple downhole cement plugs. Once a well is closed, operators are typically required by state regulations to reclaim the well pad to original or near-original landscape conditions, including vegetation, contour, and drainage.

Thousands of conventional wells have been plugged and abandoned. Locations for many P&A wells are known, yet states have large numbers of "orphaned" wells (wells which were abandoned without proper closure) for which their location is unknown (U.S. EPA 2018). While rare, UOGD wells stimulated near older P&A wells or unidentified orphaned wells may fracture into these older wellbores, creating releases at the surface (Figure 2-11).

Figure 2-11. Schematic of hydraulic fractures intersecting abandoned, vertical wells (Brownlow et al. 2017). Reprinted from *Groundwater* with permission of the National Ground Water Association. Copyright 2017.



2.3.7 Waste Management from UOGD

Waste management refers to containment, handling, storage, and disposal of solid and liquid wastes generated from UOGD activities. Such wastes include drill cuttings, fluid on cuttings, drilling fluid dilutions, tank bottoms, flowback water, and produced water.

Non-hazardous wastes typically are disposed at a licensed facility, such as a landfill, or are sent to an intermediate company for processing and recovery of some waste components, with the remainder sent to a landfill. Drill cuttings are primarily disposed of in landfills, although cuttings containing natural radioactive material may be treated first. Some wastes generated by UOGD can be classified as hazardous (e.g., wastes with naturally occurring radioactive material (NORM) concentrations that result in classification as hazardous waste) and must be handled by industries that specialize in hazardous waste management. The U.S. EPA has authority over both hazardous and non-hazardous solid waste disposal; however, states have the primary authority to implement and enforce these standards.

Most shales produce some amount of water along with hydrocarbons. Total dissolved solid concentrations in produced water vary widely across the shale plays. This flowback and produced water contains various chemicals and naturally occurring radioactive materials. Depending on shale play area, flowback and produced water are piped or trucked to disposal wells, piped directly to the disposal location, or reused (e.g., in future well stimulation treatments). The U.S. EPA has promulgated a series of underground injection control regulations associated with subsurface injection and disposal wells. States with primacy directly regulate these wells through the state's underground injection control program.

Operators are not allowed to discharge untreated flowback or produced water to streams, rivers, or to publicly operated treatment works. Onshore oil and gas extraction activities may discharge produced water to surface water in the western part of the United States (west of the 98th meridian) if it is of sufficient quality (low in total-dissolved-solids and treated appropriately), and for agriculture or wildlife

uses during the period of discharge. Regulation regarding above-ground disposal of liquid waste has changed over time (U.S. EPA 2019b). The U.S. EPA (2019c) has summarized the challenges and possible directions for produced water disposal, recycling, and reuse.

2.4 SUMMARY

UOGD is a complex process, involving an intricate interplay of technologies, markets, and regulation. As the industry evolves, the potential for human exposures will vary across regions and over time. A thorough understanding of UOGD operations and how they are changing over time is essential for understanding and studying human exposures associated with UOGD.

3.0 METHODS USED TO SURVEY THE LITERATURE

The Committee, along with HEI-Energy staff, surveyed peer-reviewed and gray scientific literature that provides information about potential UOGD exposures to determine what is already known, to identify knowledge gaps, and to begin planning for research that addresses the gaps. They also toured UOGD operations and convened two public workshops at the outset of the survey in July 2018 in Denver, Colorado (*https://hei-energy.org/meeting/Jul-2018-workshop*) and in September 2018 in Austin, Texas (*https://hei-energy.org/meeting/Sept-2018-workshop*). The workshops provided opportunities for participants to engage in a productive exchange with the Committee and other meeting participants about HEI-Energy's plans for its review of the literature and identification of future research challenges and opportunities. Speakers and other meeting participants represented sponsor organizations, federal and state government, industry, academic research scientists, environmental and public health nongovernmental organizations, community organizations, and HEI-Energy's Committee and staff.

3.1 SURVEY QUESTION

The Committee's survey of the literature was guided by a primary question: *What is known about potential UOGD-related human exposures?*

To answer this question, the Committee sought full text studies that contribute to understanding how people might be exposed in the United States to chemical agents (e.g., benzene) or non-chemical agents (e.g., noise) released directly from UOGD to the environment. All potentially useful studies were considered whether or not the investigators set out to study human exposures. This included studies that characterized one or more elements of an exposure pathway, such as the chemical and non-chemical agents associated with UOGD operations, the ways that these agents are released to and behave within the environment, the concentrations of agents in air, water, and other environmental media, and the potentially exposed populations and their time–activity patterns, which influence whether and how exposures occur.

While UOGD worker exposures fall outside the scope of this survey, literature on this topic was reviewed as worker exposures may inform assessments of community exposures. There is also a sizable literature focused solely on methane emissions (e.g., Allen et al. 2013), and a subset of this literature was reviewed in the context of understanding the potential for exposures to other chemicals (e.g., from fugitive emissions and leaks).

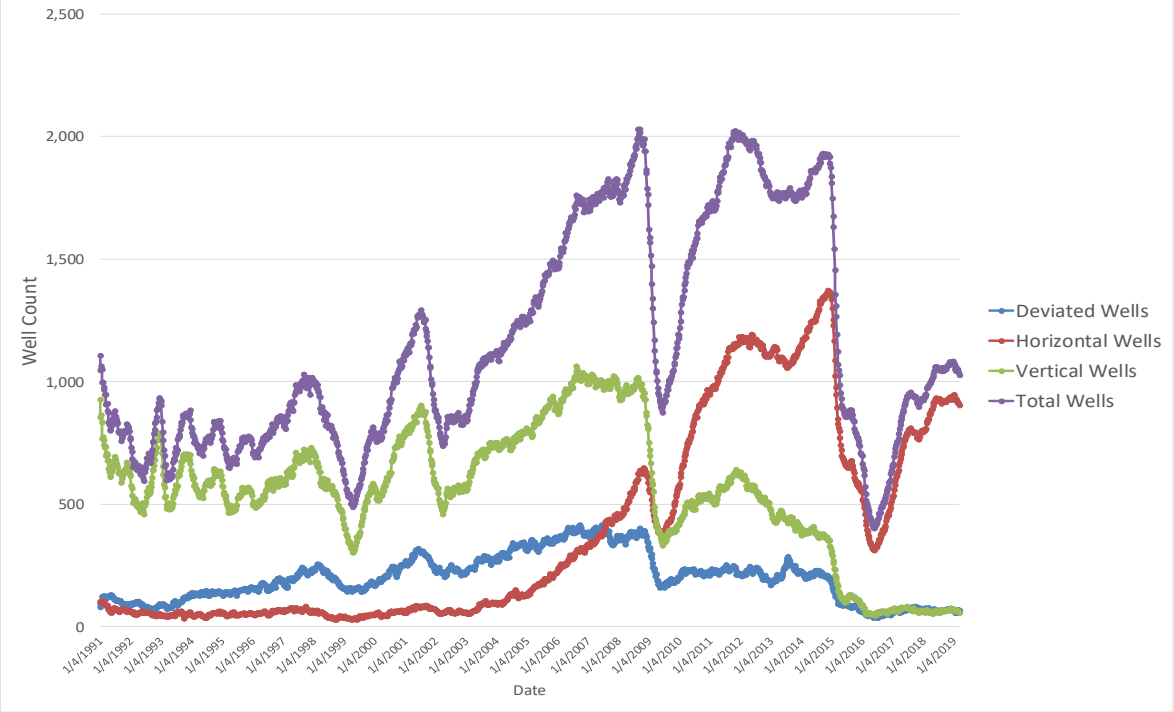
3.2 LITERATURE SEARCH

The Committee searched full text peer-reviewed and gray literature published in English between January 1, 2000 and July 10, 2019. The search period was selected based on an understanding of when UOGD began in the United States (see Section 2). Well development data, well geometry data (Figure 3-1), and other information indicate the increasing development of shale and other unconventional resources using horizontal wells combined with multistage hydraulic fracturing. This development began in the early 2000s, peaking around 2014 before declining steeply in 2014, then rising again in 2016.

Peer-reviewed literature was identified using four electronic databases: PubMed (https://www.ncbi.nlm.nih.gov/pubmed/), Web of Science (https://www.webofknowledge.com/), Embase (https://www.embase.com/) and Google Scholar (https://scholar.google.com/). Gray literature was identified using Google Scholar and from literature provided by stakeholders in conjunction with the two

HEI-Energy workshops. Endnote management software was used to download and maintain a literature library.

Figure 3-1. North American well geometry since 1991, showing the increasing prevalence of horizontal wells over time.



A broad search phrase was employed to capture papers with information potentially useful for assessing exposure from UOGD in the United States:

Web of Science

((TS=('oil and gas' OR shale OR petroleum OR 'natural gas' OR 'shale gas' OR 'tight gas' OR 'tight resource' OR 'shale oil' OR 'tight oil' OR 'unconventional gas' OR 'unconventional oil' OR 'unconventional resource' OR drilling OR 'well stimulation' OR 'hydraulic fracturing' OR fracking OR flowback OR 'produced water' OR flar*) AND TS=(Appalachian OR Devonian OR Bakken OR Barnett OR Chattanooga OR Cherokee OR 'Denver-Julesburg' OR 'Eagle Ford' OR Fayetteville OR 'Fort Worth' OR 'Greater Green River Basin' OR Haynesville OR Ingelwood OR Marcellus OR Niobrara OR Permian OR Piceance OR San Juan OR Uinta OR Utica OR Wattenberg OR Williston OR 'Wind River Basin' OR Woodford)) AND TS=(brine OR bromide OR BTEX OR 'hydrogen disulfide' OR PAH or hydrocarbon OR isotop* OR methane OR NMHC OR NORM OR radioact* OR silic* OR 'total dissolved solids' OR trace* OR VOC OR noise OR light OR odor OR vibration OR accident OR explosion OR fire OR 'chemical transport' OR concentration OR contamina* OR emission OR leak OR migrat* OR spill OR environment OR quality OR air OR water OR 'drinking water' OR groundwater OR 'surface water' OR wastewater OR soil OR sediment OR food OR 'solid waste' OR inhal* OR dermal OR ingest* OR expos* OR biomarker OR biomonitor OR population OR community OR boomtown OR endocrine OR carcin* OR tox* OR impact OR hazard OR risk OR health OR safety OR social* OR anxiety OR stress OR depression OR symptom OR epidemiology OR trauma))

PubMed and Embase

(((“oil and gas” OR shale OR petroleum OR “natural gas” OR “shale gas” OR “tight gas” OR “tight resource” OR “shale oil” OR “tight oil” OR “unconventional gas” OR “unconventional oil” OR

"unconventional resource" OR drilling OR "well stimulation" OR "hydraulic fracturing" OR fracking OR flowback OR "produced water" OR flar*) AND (Appalachian OR Devonian OR Bakken OR Barnett OR Chattanooga OR Cherokee OR "Denver-Julesburg" OR "Eagle Ford" OR Fayetteville OR "Fort Worth" OR "Greater Green River Basin" OR Haynesville OR Ingelwood OR Marcellus OR Niobrara OR Permian OR Piceance OR "San Juan" OR Uinta OR Utica OR Wattenberg OR Williston OR "Wind River Basin" OR Woodford)) AND (brine OR bromide OR BTEX OR "hydrogen disulfide" OR PAH OR hydrocarbon OR isotop* OR methane OR NMHC OR NORM OR radioact* OR silic* OR "total dissolved solids" OR trace OR VOC OR noise OR light OR odor OR vibration OR accident OR explosion OR fire OR "chemical transport" OR concentration OR contamina* OR emission OR leak OR migrat* OR spill OR environment OR quality OR air OR water OR "drinking water" OR groundwater OR "surface water" OR wastewater OR soil OR sediment OR food OR "solid waste" OR inhal* OR dermal OR ingest* OR expos* OR biomarker OR biomonitor OR population OR community OR boomtown OR endocrine OR carcin* OR tox* OR impact OR hazard OR risk OR health OR safety OR social* OR anxiety OR stress OR depression OR symptom OR epidemiology OR trauma))

To find additional peer-reviewed and gray literature not identified with electronic searches, the Committee used the following methods:

- Consulted various databases established for the UOGD literature, such as the Shale Research Clearinghouse (https://www.rff.org/sharc/), the FrackHealth database (https://endocrinedisruption.org/audio-and-video/fracking-related-health-research-database/search-the-database), and the Repository for Oil and Gas Energy Research (https://www.psehealthyenergy.org/our-work/shale-gas-research-library/).
- Consulted with knowledgeable government officials (e.g., National Institute of Environmental Health Sciences, U.S. EPA, U.S. Geological Survey, and National Institute of Occupational Safety and Health), academics, industry experts (e.g., toxicologists, physicians, epidemiologists, and others responsible for health and safety), nongovernmental organization representatives (e.g., environmental health organizations, public health organizations, and community groups) and relevant websites.
- Consulted reference lists of studies, commentaries or letters on studies, relevant reviews, and other non-research articles.

The literature search yielded a diverse set of studies that may help in understanding human exposures to UOGD. Studies included in figures and tables are those that measured or modeled levels of agents in various media, as these provide information most relevant for understanding magnitude, frequency, and duration of potential exposure.

3.3 SURVEY OF THE LITERATURE

The term exposure encompasses the way in which individuals come into contact with an agent over space and time. The Committee performed a broad survey of the literature to identify the ways in which people might be exposed to chemical and non-chemical agents associated with UOGD.

3.3.1 Potential Human Exposures Framed in a Conceptual Model

An ideal exposure study would provide information that allows one to determine whether a complete exposure pathway exists between the source of a specific UOGD agent and a population (Figure 3-2). Exposure pathways are the course an agent takes from the source to the individual or population. People might be exposed to multiple chemical and non-chemical agents and by more than one exposure pathway, the summation of which is referred to as their "total exposure."

Figure 3-2. Conceptual model of potential exposure pathways associated with UOGD. Adapted from the U.S. EPA's "Guidelines for Human Exposure Assessment" (U.S. EPA 2016a).

The Committee reviewed how studies contributed to understanding the temporal variability, spatial variability, and likelihood (i.e., probability) of potential exposures to chemical and non-chemical agents and framed its review in the conceptual model of exposure (Figure 3-2). This framing was intended to facilitate understanding of what is known about potential exposure pathways and where knowledge gaps exist. In reviewing each paper, the Committee looked for whether investigators presented data supporting each component of an exposure pathway: UOGD source, release mechanisms and transport pathways, media or type of exposure, routes of exposure, and exposed populations.

The Committee sought clear identification of the ***UOGD source*** of the release under investigation. Incorporation of source apportionment methods (e.g., collection of detailed operational time–activity information and use of tracers or chemical ratios) might be needed to distinguish between chemical or non-chemical agents originating from UOGD and from other sources. Ideally, investigators would specify whether environmental releases from UOGD sources resulted from operational, accidental conditions, or unauthorized activities (e.g., illegal dumping). To aid in the interpretation of study results and the generalizability to other conditions, the Committee looked for information from each study on whether information on temporal and spatial variations in environmental releases was provided.

The committee examined whether exposure studies identified the ***release mechanisms and transport pathways*** for specific chemical and non-chemical agents. Following release of a chemical or non-chemical agent from a UOGD source to the environment, its fate in the environment is a function of its own physical and chemical properties and characteristics of the local environment. An understanding of these factors is essential for determining whether a human population might be exposed and by what ***medium,*** through what ***type (e.g., noise) of exposure,*** and by which ***route of exposure***.

In the data collection and analytical stages, the committee considered how investigators employed quality assurance and quality control measures, data validation, analytical techniques, and data management. Importantly, the Committee evaluated how investigators contextualized their results within the space and time that the results were collected and provided information that allows for extrapolation to a variety of spatial and temporal conditions and over time.

Potentially ***exposed populations***, including vulnerable subpopulations, need to be identified to understand whether an exposure might occur and, if so, to interpret its importance. Information about the population, such as time–activity patterns, and the UOGD source ideally would be sufficient to quantify the magnitude, frequency, and duration of a potential exposure and its likelihood of occurrence. The likelihood of exposure depends on factors related to when and where UOGD operations occur, whether emissions are associated with normal operating conditions, accidents, or unauthorized incidents, atmospheric conditions, and behaviors of both the operator and the exposed individual (i.e., time–activity factors) that influence the extent to which someone might be exposed to the releases. The Committee sought data that indicated the likelihood for an exposure to occur.

3.3.2 Relevance of the Literature to the Range of Possible Exposure Conditions

Studies included in this review may contain some or all elements of a complete exposure pathway. The Committee developed a set of questions to facilitate its survey of the literature for understanding exposures to UOGD and identifying knowledge gaps:

1. Did the investigators demonstrate a link between their monitoring or modeling results and UOGD?
2. Did the investigators identify which human populations, if any, could be exposed to the chemical or non-chemical agent(s) investigated in the study?
3. Are the monitoring or modeling results potentially useful for understanding exposure to UOGD-related agents (e.g., likelihood, frequency, duration, or magnitude) for:
    a. The location and population under study?
    b. Other locations and populations?
4. Monitoring studies: Did the investigators select appropriate sampling and analytical methods and use them properly (e.g., proper calibration)?
5. Modeling studies: Was model selection, parameterization, and evaluation appropriate?
6. Is there information missing from the paper that limits inferences about realized or potential exposures to UOGD-related agents? If so, explain.
7. Are study results subject to important uncertainties with respect to addressing the study objectives? If yes, what are they, and are they quantified or discussed qualitatively?
8. How does the paper inform the potential design of a future exposure study (consider both positive and negative aspects of the study)?

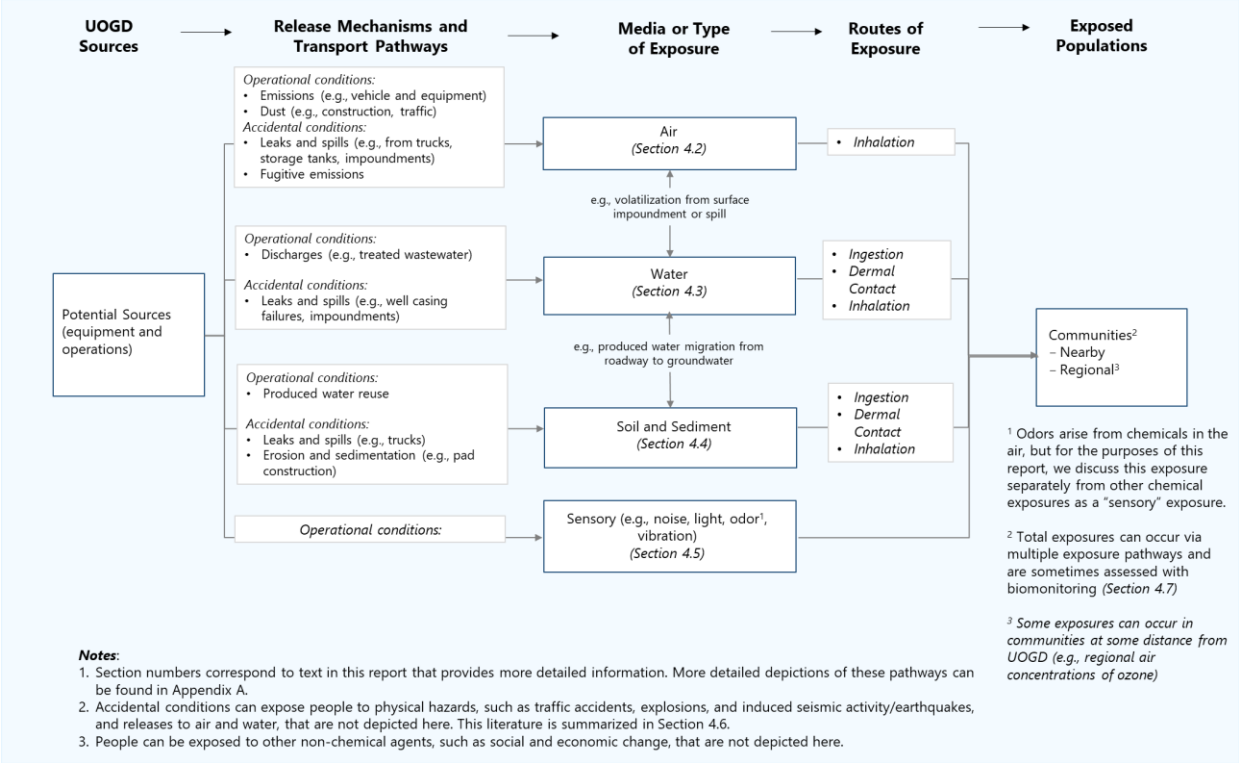
The questions required the Committee to assess the utility of each study for understanding human exposure across various spatial and temporal conditions and to begin to identify knowledge gaps.

4.0 SURVEY OF THE LITERATURE

People can be exposed to chemical and non-chemical agents released to the environment from UOGD during routine operations (e.g., permitted emissions to air), accidental conditions (e.g., leaks or spills), or unauthorized events (e.g., illegal dumping of wastes). The potential for exposure varies among phases of UOGD development (e.g., well pad construction, drilling, well completion, and production).

The discussion of the exposure literature is organized in accordance with a conceptual model of exposure, which illustrates the exposure pathways assessed in the literature (Figure 4-1). This organization facilitates identification of links between potential UOGD sources of exposure and populations, and gaps in our understanding of exposures.

Figure 4-1. Conceptual model of potential exposure pathways assessed in the literature. (More detailed conceptual models of potential exposure are available in an HEI Special Report [Appendix C in: HEI Special Scientific Committee on Unconventional Oil and Gas Development in the Appalachian Basin 2015]).

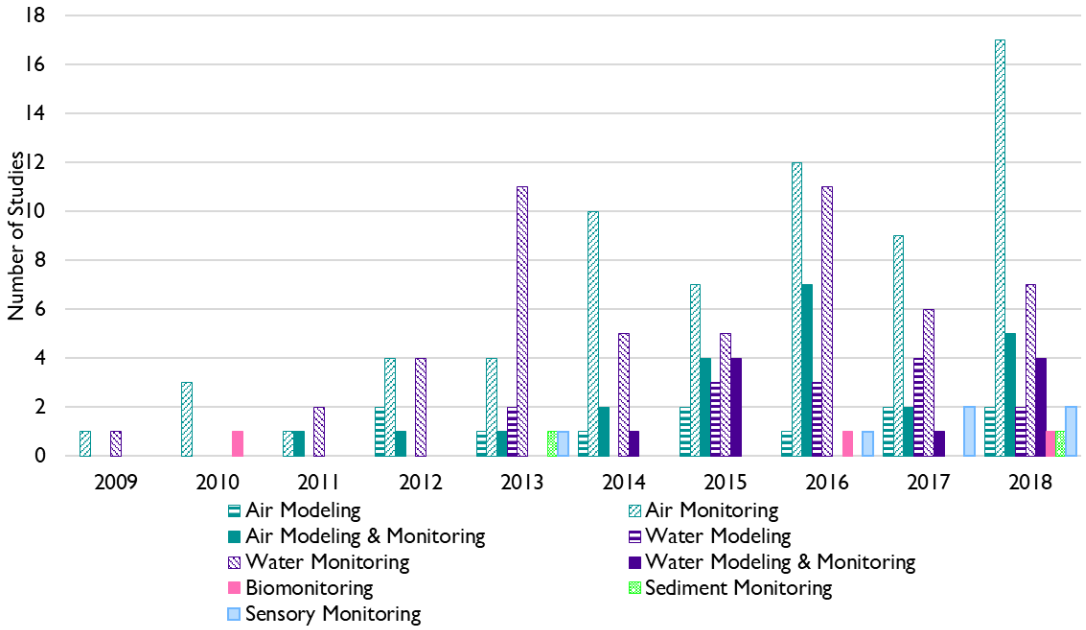


4.1 SUMMARY OF STUDIES

The studies had diverse objectives and designs and, to differing degrees, contributed to an understanding of whether a complete exposure pathway connects a UOGD source with a human population living in communities affected by UOGD. They include studies that reported levels of chemical or non-chemical agents in air, water, and other media based on measurements or modeling (Figures 4-2 and 4-3). The increasing number of studies in recent years (Figure 4-2) parallels the rise of UOGD (Figure 4-4). Most studies measured or modeled VOCs and other chemicals in air, with fewer quantifying VOCs, brines (chemicals associated with flowback and produced water), and other chemicals in water. Only a few

studies reported chemical concentrations in soil or sediment, levels of sensory agents, or biomonitoring data (Figure 4-2).

Figure 4-2. Number of studies published each year by study media. (Appendix A includes the list of publications).



Search period: January 1, 2000 to July 10, 2019; the figure includes studies published through December 31, 2018.

Figure 4-3. Number of studies by chemical agent (Appendix A includes the list of publications).

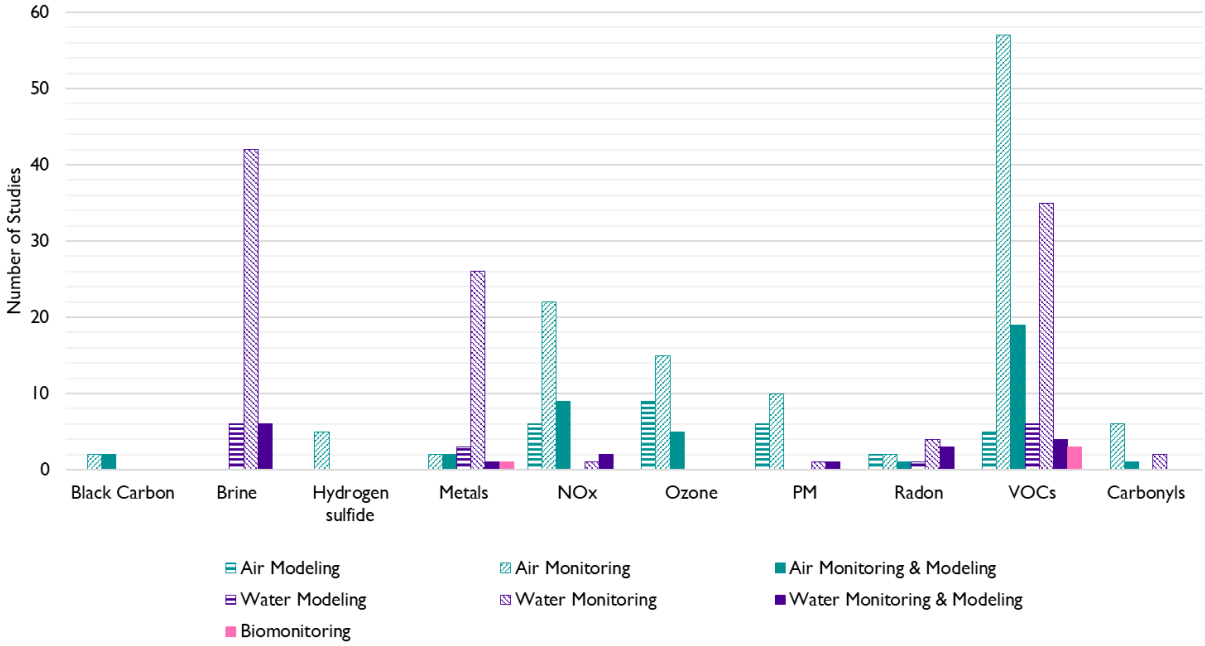
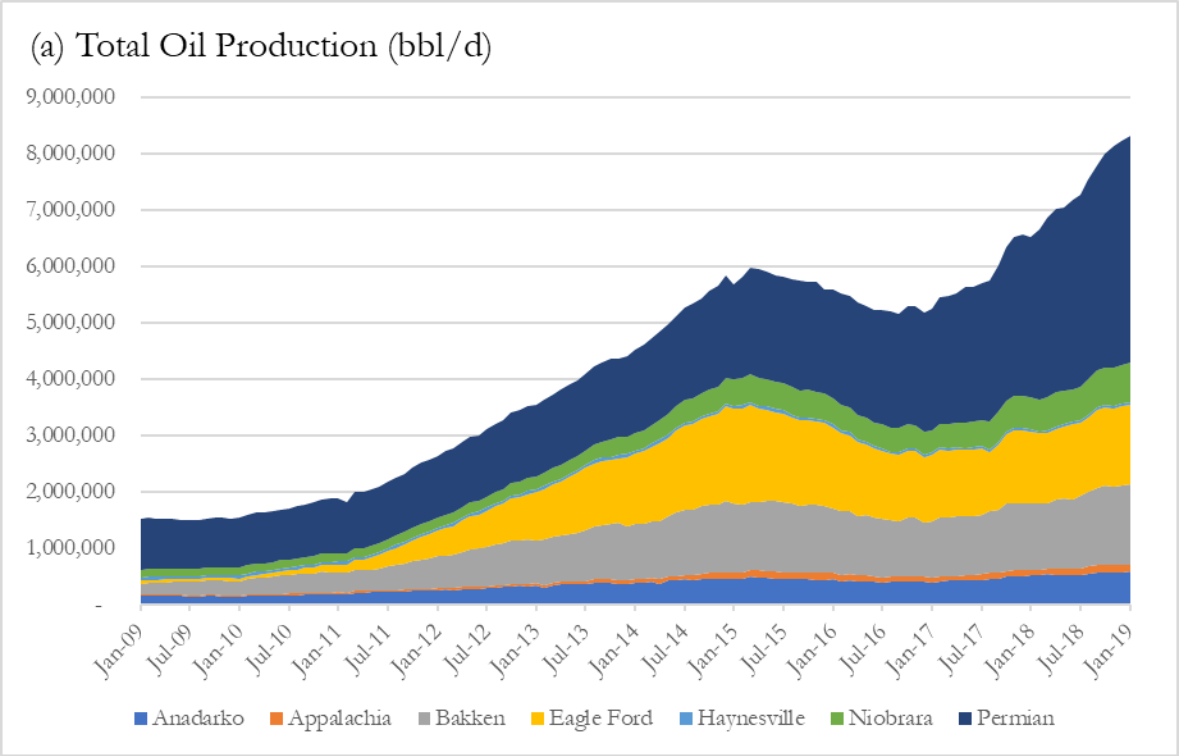
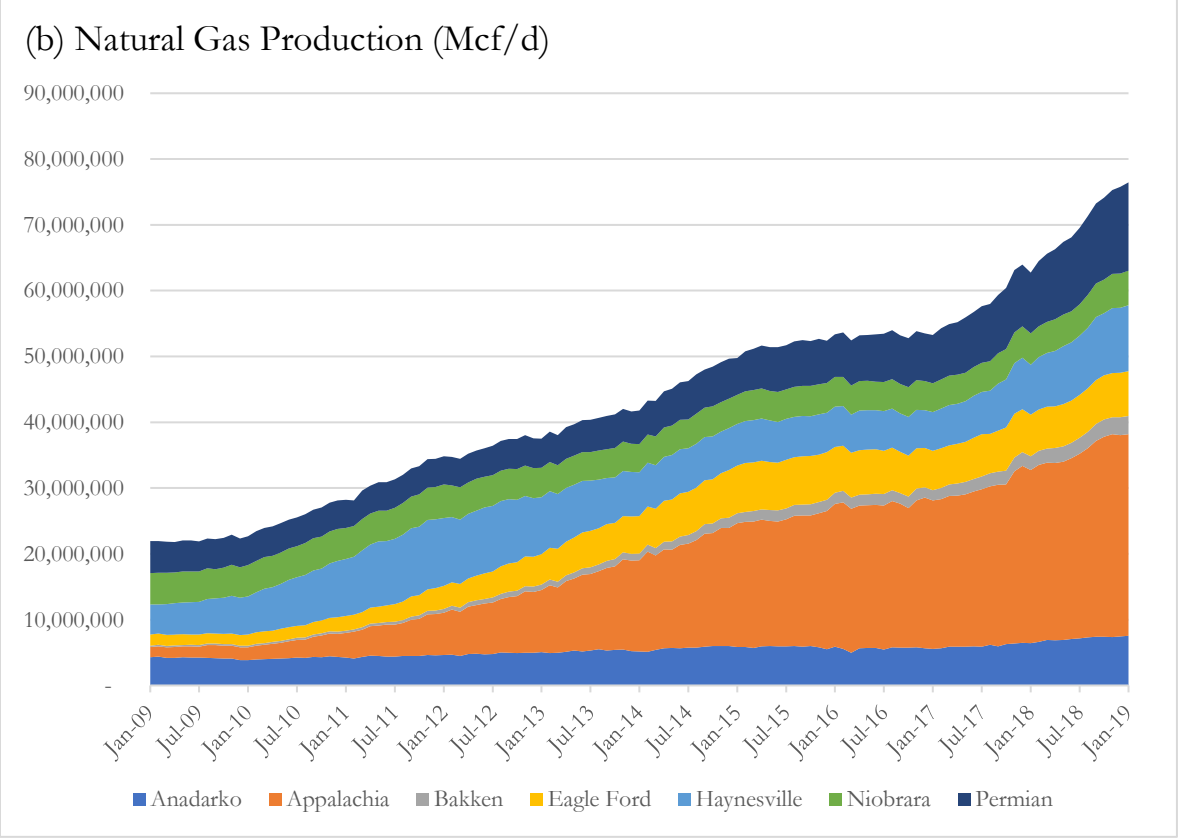


Figure 4-4. Total (a) oil and (b) natural gas production over time by U.S. region.



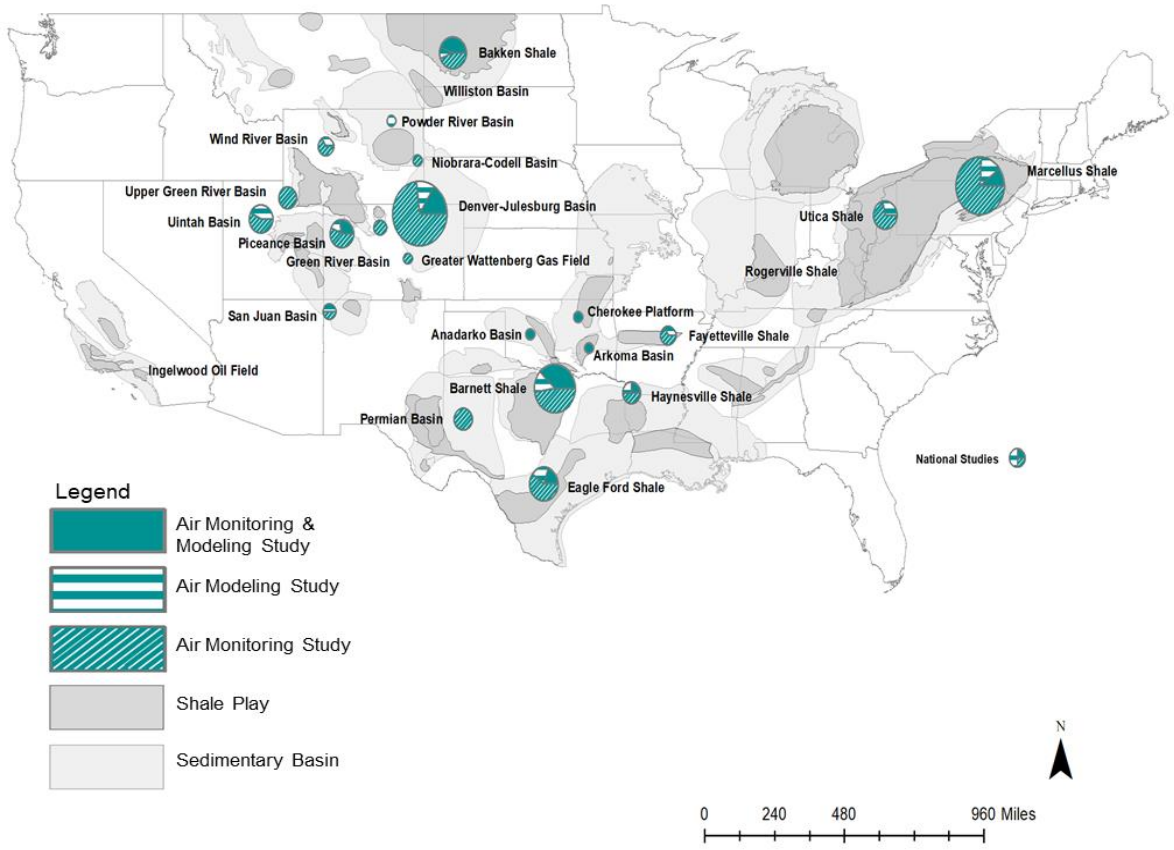


Source of production data: https://www.eia.gov/petroleum/drilling/.

4.2 AIR EXPOSURE PATHWAYS

4.2.1 Summary of Studies – Air Exposure Pathway

Figure 4-5. Air monitoring or modeling study locations (Appendix A includes the list of publications).



Notes:

- The size of each pie chart is proportional to the total number of studies in each shale play.
- The largest pie chart on the map represents 45 studies.

Scientists have investigated the potential air quality impacts of UOGD in several major oil- and natural gas-producing regions of the United States (Figure 4-5). Studies included original measurements of air quality (n=72), modeling of air quality (n=16), and both measurement and modeling approaches (n=26). Investigators have measured chemical concentrations in air using a variety of methods, including personal sampling, mobile and stationary sampling at the ground surface, and measurements collected from aircraft and satellites. Other investigators used modeling approaches to assess chemical concentrations in air, whereas some studies included both approaches. Regional ozone or PM concentrations were the subject of several studies, although most studies investigated air quality in areas near UOGD operations. A few of these studies leveraged air quality monitoring data or modeling to assess setback distances and distance decay gradients between UOGD and residences (Banan and Gernand 2018; Garcia-Gonzales et al. 2019a; Haley et al. 2016; McCawley 2013).

Studies have measured or modeled atmospheric concentrations of several different chemical compounds associated with UOGD operations, including VOCs (Bari and Kindzierski 2018; Eisele et al. 2016; Helmig et al. 2015; Lim et al. 2019; Maskrey et al. 2016; McMullin et al. 2018; Swarthout et al. 2013),

NO_x (Goetz et al. 2017; Koss et al. 2017; Majid et al. 2017; Pacsi et al. 2013; Pennsylvania Department of Environmental Protection 2018), black carbon (BC) (Allshouse et al. 2019), PM (Allshouse et al. 2019; Bean et al. 2018; Fann et al. 2018; Frazier 2009; Roohani et al. 2017), and radionuclides (Casey et al. 2015; Mitchell et al. 2016; Walter et al. 2012; Xu et al. 2019b).

Some investigators discussed the conditions under which they collected data. For example, Olaguer et al. (2014) collected data specific to flaring and Hildenbrand et al. (2016c) collected BTEX concentration data specific to mechanical inefficiencies. Other studies (Evans and Helmig 2017; Oltmans et al. 2014) presented data from monitoring of normal operations. McClellan and Snipes (2010) stated that their data represent concentrations "regularly detected and identified" but did not define what they meant by this phrase.

4.2.2 UOGD Sources and Potential Release Mechanisms – Air Exposure Pathway

4.2.2.1 UOGD Releases to Air

Air emissions from UOGD operations are complex and highly variable in terms of both amount and composition. Emissions result from virtually every step of development, production, and post-production phases and may emanate from operations on or off the well pad (HEI Special Scientific Committee on Unconventional Oil and Gas Development in the Appalachian Basin 2015; Vaughn et al. 2018; Zielinska et al. 2014). State and federal organizations have created emissions inventories using bottom-up and top-down approaches that quantify criteria air pollutant and greenhouse gas emissions from a variety of oil and gas sources (Grant et al. 2016, 2019).

Several UOGD processes lead to air emissions (Table 4-1). These emissions include components from the oil and gas itself (primarily organic gases), drilling and completion fluids (organic gases, PM), diesel and natural gas combustion (VOCs, NO_x, PM), waste management, and subsurface geochemical species (e.g., naturally occurring radioactive material [NORM] and technologically enhanced NORM [TENORM]) (Glass Geltman and LeClair 2018; HEI Special Scientific Committee on Unconventional Oil and Gas Development in the Appalachian Basin 2015; Moore et al. 2014; Academy of Medicine Engineering and Science of Texas 2017; Zielinska et al. 2014). Organic gases and NO_x can react to form ozone and PM (Nsanzineza et al. 2019). Sulfur dioxide (SO_2) and hydrogen sulfide (H_2S) emissions also occur due to the sulfur content in diesel fuel and oil and gas and can also react to form PM. NO_x, SO_2, and PM are regulated by the U.S. EPA and are cited for having both acute and chronic health impacts (Burnett et al. 2014; Cohen et al. 2017; U.S. EPA 2016b). Additionally, some emitted VOCs (e.g., formaldehyde and benzene) are categorized as hazardous air pollutants by the U.S. EPA, as they are known to cause cancer or other adverse health effects.

Many compounds associated with UOGD have been identified, but some remain proprietary and other chemical species might form from drilling or fracturing fluids under high temperature and pressure conditions in the subsurface environment (Allen 2014; Moore et al. 2014).

Table 4-1. Processes leading to ambient emissions.

Organic Gases (including BTEX and other air toxics)	Nitrogen Oxides	Particulate Matter	Radionuclides
▪ Engine exhaust (diesel and natural gas) ▪ Well completion ▪ Tanks ▪ Transfer operations ▪ Flaring	▪ Flaring ▪ Process heating ▪ Engine exhaust from: - Site preparation - Material transport	▪ Proppant handling and use (including silica) ▪ Site preparation and drilling activities (fugitive dust and diesel exhaust)	▪ Drilling completion ▪ Re-use of wastewater

Organic Gases (including BTEX and other air toxics)	Nitrogen Oxides	Particulate Matter	Radionuclides
▪ Equipment leaks ▪ Pneumatic controllers and valves ▪ Storage and transport of drilling waste ▪ Liquid unloadings	- Drilling and fracturing - Compression	▪ Material transport (engine exhaust, tire, brake, and road dust)	

Sources: Allen 2016, 2014; Allen et al. 2016; Luck et al. 2019; Moore et al. 2014; Academy of Medicine Engineering and Science of Texas 2017; Zielinska et al. 2014.

Measured Air Emissions. Direct measurement of emissions from individual UOGD operations and processes have been conducted using a variety of approaches, including tracers, direct measurements, and downwind plume measurement (e.g., Allen 2016; Bell et al. 2017; Nathan et al. 2015). Much effort has been devoted to characterizing methane emissions (e.g., Johnson et al. 2019; Omara et al. 2018; Ren et al. 2019; Sheng et al. 2018), but other chemical emissions have also been measured or modeled, including VOCs (Pétron et al. 2012), black carbon (Schwarz et al. 2015), NO_x (Goetz et al. 2015), and dust (Litovitz et al. 2013).

As discussed in Section 2, emissions vary over time as operational conditions change. Some processes resulting in VOC emissions can be of limited duration, such as liquid unloadings, flowback, flaring, product transfer, and tank inspection. Nevertheless, they can be important emission sources. For example, studies have demonstrated emissions from conventional and unconventional development during liquid unloading events, which last for only minutes may be equivalent to emissions from more than one thousand routinely operating wells (Allen et al. 2015b). Other studies, relying on atmospheric observations, suggest that storage-related emissions (e.g., from product transfer and tank inspection) may be a major contributor to VOC emissions (Pétron et al. 2012). Emissions also vary temporally depending on whether operations are continuous or intermittent (Roy et al. 2014). Flaring, for example, occurs intermittently, and is a source of VOCs, NO_x, and hazardous air pollutants (Allen et al. 2016; Fawole et al. 2016; Franklin et al. 2019; Weyant et al. 2016). The magnitude of emissions may also change over time with the introduction of new technologies and operational practices.

Studies of methane have demonstrated that emissions also can vary by location and equipment. For example, it was found that less than 20% of the pneumatic controllers contributed nearly all of the emissions from this type of equipment (Allen et al. 2015a). Some production sites might be well controlled and maintained, whereas other sites have been found to emit much more than others (Lyon et al. 2016; Schwietzke et al. 2014a, 2014b, 2017; Zavala-Araiza et al. 2015a, 2015b, 2017). These instances of large, concentrated emissions are sometimes called "super-emitters." The potential for super-emitters among UOGD operations is considerable given the variability in operations, site design, construction, and maintenance and the oil and gas composition within and among plays (Allen et al. 2017).

Modeled Air Emissions. The temporal and spatial variation in UOGD operations pose a considerable challenge to characterizing emission rates that represent a given area and have led to large discrepancies in estimated emissions at the regional level (e.g., Allen 2014; Bell et al. 2017; Mitchell et al. 2015; Vaughn et al. 2017, 2018; Zavala-Araiza et al. 2015b). Two broad approaches have been used to estimate emissions: bottom-up (or process-oriented) (e.g., Ahmadov et al. 2015; Townsend-Small et al. 2015) or top-down (observation-oriented) (e.g., Allen 2014; Zavala-Araiza et al. 2015b). Both have their strengths and weaknesses. "Bottom-up" emission estimates have historically been developed by multiplying representative emission rates for various source categories by a measure of activity for each category (i.e., a number of sources multiplied by the emission rate for each source) to estimate the annual emissions from an operation or set of operations. The potential presence of super-emitters can be an important

contributor to uncertainty in these estimates. The top-down approach combines atmospheric concentrations measured from aircraft and other methods with models to infer emission rates (e.g., Albertson et al. 2016; HL Brantley et al. 2014, 2015; Englander et al. 2018; Ezani et al. 2018; Johnson et al. 2017; Nathan et al. 2015; Pétron et al. 2014).

Recent basin-scale comparisons of the two approaches reveal that top-down methane emissions estimates typically exceed bottom-up estimates, the magnitude of which depends on the study area (Vaughn et al. 2018; Zavala-Araiza et al. 2015b; Zimmerle et al. 2016). Efforts to reconcile methane emission estimates from UOGD operations hint at the complexities involved with estimating emissions and concentrations of other UOGD-related compounds. For example, the work on identifying the influence of super-emitters on regional methane emissions suggests that the temporal variability in emissions can explain much of the difference between bottom-up and top-down estimates (Allen et al. 2017; Vaughn et al. 2017).

Using methane emission estimates to quantify non-methane VOC emissions is complicated by the widely varying ratios of methane and non-methane compound concentrations within and across basins and during various UOGD processes (e.g., Allen et al. 2017). Further, methane emission estimates would reflect processes dominated by methane releases, so relying on methane emissions would miss a wide variety of other sources of non-methane emissions (e.g., VOCs related to internal combustion engines, NO_x, PM, and dust).

4.2.2.2 Atmospheric Transport

UOGD emissions disperse and can react in the atmosphere, leading to widely varying concentrations from local to regional scales. Dispersion is highly dependent on meteorological conditions (e.g., reduced air mixing that can occur at night and during winter), and topography (e.g., valleys trapping pollutants or hills blocking noise). Some emissions are largely unreactive (e.g., black carbon) whereas others undergo chemical transformation on the order of hours (e.g., formaldehyde). Like dispersion of emissions, chemical transformation also depends on meteorological conditions and topography and, under some conditions, the presence of other compounds. Destruction rates of directly emitted chemicals will vary from virtually unreactive species (black carbon) to species that have reaction times on the order of hours (e.g., formaldehyde), and the rates of destruction will depend on time and atmospheric conditions (including the presence of other compounds).

4.2.2.3 Linking UOGD Sources to Air Concentrations

Investigators employed various methods to link chemical concentrations and emissions with specific UOGD-related sources.

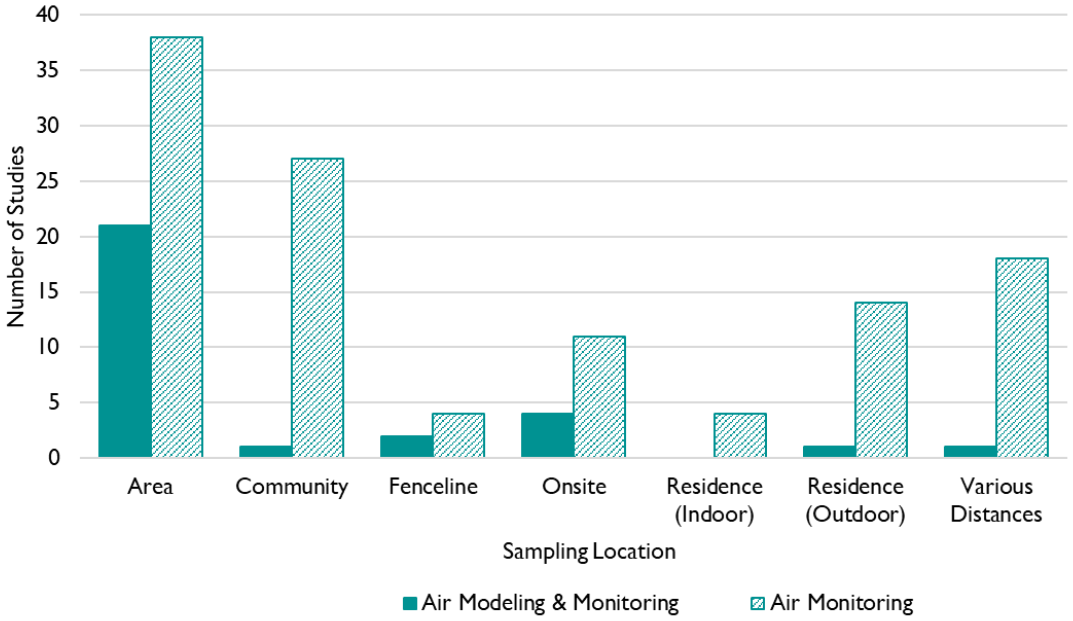
Sampling location. In an effort to quantify chemical concentrations in air that were attributable to UOGD, investigators have placed air samplers in a variety of locations proximate to UOGD operations (Figure 4-6).

The ability to link concentrations with UOGD was strongest in studies where investigators linked specific UOGD operations at high temporal resolution to measured concentrations at locations in proximity to UOGD (Allshouse et al. 2019; Collett et al. 2016a; Eisele et al. 2016; McCawley 2013; Williams et al. 2018). Investigators can also establish a link between UOGD and air quality in studies where samplers were positioned on UOGD sites (Collett et al. 2016a, 2016b; Hildenbrand et al. 2016c; Williams et al. 2018) and, to a lesser extent, along the fence line of UOGD operations, at varying distances from well pads, or in rural areas with few other possible sources (e.g., Paulik et al. 2018; Warneke et al. 2014).

Studies in which investigators positioned air samplers between well pads and residential communities (Colorado Department of Public Health and Environment 2012, 2017a, 2017b, 2017c; Eastern Research Group and Sage Environmental Consulting 2011; Macey et al. 2014; McMullin et al. 2017), in close proximity to and downwind of UOGD activity (Eisele et al. 2016; Frazier 2009; McCawley 2013; Pekney et al. 2014), and in general areas of UOGD operations (Bien and Helmig 2018; Oltmans et al. 2014; Schade and Roest 2016) would need to, at a minimum, account for other sources to demonstrate a link between the measured concentrations and UOGD.

The West Virginia–based Marcellus Shale Energy and Environment Laboratory, a multi-disciplinary research program for which data are collected to analyze emission trends and profiles unique to different phases of UOGD, measures emissions at different distances from the well pad and includes collection of detailed operational time–activity data to allow for source attribution (Pekney et al. 2018; Williams et al. 2018).

Figure 4-6. Sampler placement in air monitoring studies (Appendix A includes the list of publications).



Area= non-specific sampling location in proximity to UOGD operations; ***fence line=*** sampling on or next to the fence surrounding a well pad or UOGD-related facility; ***onsite***= on a well pad or the site of other UOGD-related equipment; ***residence (indoors)=*** sampling inside a residence; ***residence (outdoors)=*** sampling outside of a residence on homeowner property; ***residential area=*** sampling in a neighborhood but not on private property; ***various distances to well pad=*** a deliberate sampling campaign in which samples are taken at various pre-determined distances from the suspected source.

Tracers, signatures, or ratios. To differentiate the contribution of UOGD from other sources of air quality impacts, some investigators used ambient chemical concentrations as source signatures, such as methane, hexane, ethylene, or acetylene (Benedict et al. 2018; Cardoso Saldana et al. 2019; Garcia-Gonzales et al. 2019a; Goetz et al. 2015; Helmig et al. 2015; Koss et al. 2017; Nathan and Lary 2019; Prenni et al. 2016; Swarthout et al. 2015), source tracers to calculate emissions rates (Collett et al. 2016a, 2016b), methane or isomer ratios (Halliday et al. 2016; Marrero et al. 2016; Pétron et al. 2012; Rossabi and Helmig 2018; Swarthout et al. 2015; Vinciguerra et al. 2015), or a combination of approaches (Bari and Kindzierski 2018; Evanoski-Cole et al. 2017; Garcia-Gonzales et al. 2019a; Gebhart et al. 2018; Halliday et al. 2016; Lindaas et al. 2019). For example, Prenni et al. (2016) used the ratio of pentane isomers (*i*-pentane:*n*-pentane ratio) to indicate UOGD emissions, and estimated air mass age for measurements at one of the

sampling locations. The investigators performed additional analyses to assess whether concentrations of VOCs, NO_x, and black carbon had collocated sources. Nathan and Lary (2019) used dispersion modeling to predict regional VOC concentrations across the Barnett Shale region and machine learning techniques to identify whether unique source signature groups of hydrocarbons appear in areas downwind of UOG facilities, which can be used in future studies to identify UOGD and for monitoring contribution of UOGD to regional VOC concentrations.

Reference conditions. A limited number of studies compared concentrations measured in areas of high UOGD activity with conditions in the same area before development (Colborn et al. 2012; Majid et al. 2017; Maskrey et al. 2016; Vinciguerra et al. 2015; Williams et al. 2018) or at reference locations (Agency for Toxic Substances and Disease Registry 2016; Eastern Research Group and Sage Environmental Consulting 2011; Garcia-Gonzales et al. 2019a; Penningroth et al. 2013; Rich and Orimoloye 2016; Thompson et al. 2014). Investigators designated reference locations in a number of ways; a drawback associated with their use, as noted by many investigators, is the presence of other sources.

Satellites and aircraft. Some studies, conducted primarily in Colorado and North Dakota, have employed aircraft monitoring (Bahreini et al. 2018; Cheadle et al. 2017; Ethridge et al. 2015; Gvakharia et al. 2017; Halliday et al. 2016; Koss et al. 2017; Majid et al. 2017; McDuffie et al. 2016; Peischl et al. 2018; Prenni et al. 2016). The most effective aircraft monitoring studies coupled aircraft measurements with ground-based sampling of emissions sources (e.g., Ethridge et al. 2015). Although aircraft monitoring avoids the challenges associated with attempting to sample close to or directly on a well pad, it is more difficult to attribute measured concentrations to UOGD. This approach is therefore more effective in areas with few emission sources other than UOGD.

In addition, investigators are starting to take advantage of remote sensing technology placed on satellites to identify sources of UOGD emissions (Franklin et al. 2019) and to characterize air quality impacts of UOGD (Chang et al. 2016; Franco et al. 2016; Majid et al. 2017). The increased availability of satellite data may be a useful source for future UOGD air quality studies (e.g., see https://airquality.gsfc.nasa.gov/).

Modeling. Studies of both local and regional air quality have incorporated chemical transport modeling to quantitatively link chemical concentrations in air with specific UOGD sources (e.g., flaring and compressor station emissions) and to distinguish UOGD from other sources. The models typically combined measured emissions and concentrations with meteorological data (Ahmadov et al. 2015; Eastern Research Group and Sage Environmental Consulting 2011; Evanoski-Cole et al. 2017; Frazier 2009; Olaguer et al. 2014; Pekney et al. 2018; Pfister et al. 2017; Roohani et al. 2017). Many studies use chemical transport models such as AERMOD (Khalaj and Sattler 2019; Zavala-Araiza et al. 2014), which have also been used in previous air pollution literature (e.g., https://www.epa.gov/scram/air-quality-dispersion-modeling-preferred-and-recommended-models). Other studies used source apportionment modeling or other statistical techniques to disentangle UOGD activity from other sources (e.g., Ahmadov et al. 2015; Bari and Kindzierski 2018; McDuffie et al. 2016; Nathan and Lary 2019; Rutter et al. 2015; Schade and Roest 2016).

Collett et al. (2016a, 2016b) convened a multi-disciplinary team to quantify emissions from four UOGD phases (drilling, hydraulic fracturing, flowback, and production) across two oil and gas regions in Colorado. They used their estimated emission rates to model VOC concentrations in air and compared model predictions with field measurements. In this way, the investigators were able to directly connect UOGD emissions with air quality at two Colorado locations. In general, they observed that emission rates

varied across UOGD processes, with the highest VOC emission rates during flowback operations. They also reported no difference in air concentrations among seasons.

Distinguishing UOGD from conventional oil and gas development. Many studies attempted to distinguish UOGD sources from other industrial and urban sources (e.g., Lim et al. 2019), but frequently did not differentiate between UOGD and conventional oil and gas development. Emissions may be similar, with many of the tracers used for UOGD also indicative of conventional resource development (Gilman et al. 2013). Some studies attempted to differentiate chemical concentrations in air between the two types of development by measuring emissions from conventional sources (Marrero et al. 2016), by correlating trends in concentrations with UOGD production rates over time (Swarthout et al. 2015), and sampling near both active unconventional and conventional wells and examining differences in concentrations (Vinciguerra et al. 2015). Other studies attempted to link their results to UOGD by comparing concentrations over a period representing change in UOGD activity or by placing samplers in areas dominated by UOGD rather than conventional development.

4.2.3 Potentially Exposed Populations – Air Exposure Pathway

Some studies provided valuable information for understanding the likelihood, frequency, duration, and magnitude of potential exposures that people might experience.

4.2.3.1 Relevance of Information for Quantifying Exposure

Likelihood and Magnitude of Exposure. Modeling studies, especially those informed by monitoring data, can be valuable for predicting the likelihood of exposure under various conditions (e.g., Benedict et al. 2018; Eastern Research Group and Sage Environmental Consulting 2011; Fann et al. 2018; Khalaj and Sattler 2019). Bloomdahl et al. (2014) strengthened the utility of their models for quantifying exposure by pairing air quality data with the location, time–activity patterns, and protective measures in place for potentially exposed populations. In this study, investigators used models to assess the likelihood and magnitude of occupational exposure to VOCs in air.

Many of the air quality modeling studies employed methods that helped to elucidate the factors driving elevated concentrations and thus the likelihood of humans experiencing those concentrations. For example, some ozone-modeling studies combined information about meteorological conditions and UOGD operations (such as those that associated with reactive VOC emissions) to identify the conditions (e.g., meteorology and energy demand) under which elevated ozone concentrations occur (e.g., Bien and Helmig 2018; Evans and Helmig 2017; Lindaas et al. 2019; Nsanzineza et al. 2019; Olaguer et al. 2014; Oltmans et al. 2014, 2019; Pfister et al. 2017). Other models demonstrated the likelihood and magnitude of chemical formation that occurs during specific UOGD phases and activities (Bean et al. 2018). Models of regional concentrations, such as those modeling UOGD contribution to regional ozone concentrations, did not have sufficient spatial resolution to assess likelihood or magnitude of exposure (e.g., Majid et al. 2017).

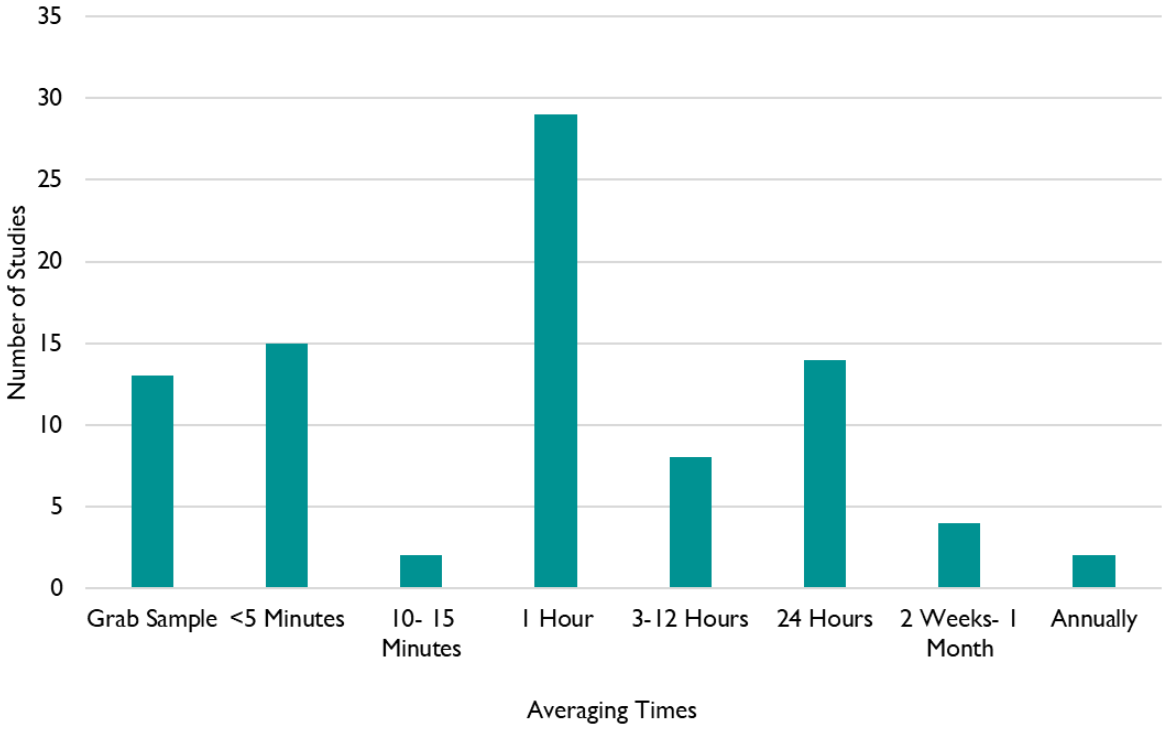
Chemical concentration data can give a sense of exposure magnitude to the extent that investigators place samplers in or use data from areas where humans might be exposed. For example, one study measured personal exposures for oil and gas workers to diesel particulates from UOGD, finding higher than recommended concentrations of elemental carbon from diesel particulates (Esswein et al. 2018). The extent to which these occupational exposures reflect the likelihood or magnitude of exposure of people living near UOGD is not known.

Temporal Representativeness (Frequency and Duration). Studies in North Dakota (Evanoski-Cole et al. 2017), Texas (Zavala-Araiza et al. 2014) and Pennsylvania (Swarthout et al. 2015) are notable with their

collection of data representing substantial temporal (and spatial) variability in VOC or $PM_{2.5}$ concentrations using at least two types of sampling campaigns and combining the resulting data with models that incorporate local meteorological data to assess the contribution of UOGD to chemical concentrations in air. This type of approach can help in understanding the temporal representativeness of study findings.

In other studies, the frequency and duration of sampling programs varied (e.g., Goetz et al. 2015; Koss et al. 2017; Paulik et al. 2016). One important consideration is the time over which individual samples are collected. For example, a sample might be collected over an 8-hour period, and this period would be referred to as the averaging time for the sample. Air sample averaging times varied across studies (Figure 4-7).

Figure 4-7. Air sample averaging times (Appendix A includes the list of publications).



Notes: This figure does not include studies that either did not report an averaging time or measured continuously and presented concentrations in time-series format.

The greatest number of studies averaged samples over one hour, an averaging time that can be useful for identifying peak, or acute, exposures. Grab samples (i.e., single samples taken at one point in time) can also be useful for this purpose. Samples averaged over 24 hours are useful for capturing daily variation but may mask peak exposures that occur over shorter periods. Given their brief averaging times, such samples have limited utility individually for understanding the frequency, duration, magnitude, and likelihood of exposure.

A brief exposure to a high chemical concentration can harm health in a way that is different from a longer exposure to a lower chemical concentration. Being able to evaluate both of these possibilities depends on an appropriate sampling plan as already discussed. In addition, the period over which individual air samples are averaged (i.e., the sample averaging time) should be selected carefully to be representative of a likely exposure, including potential peak exposures and longer exposures that might occur over weeks,

months, or longer. A good sampling program would represent the full period of exposure, either with continuous monitoring or multiple sampling campaigns.

The studies of greatest utility for assessing temporal variability of exposure were those that included measurements of concentrations over multiple sampling campaigns representing a variety of UOGD activities, meteorological conditions, seasons, and times of day (e.g., Allshouse et al. 2019; Evanoski-Cole et al. 2017; Pekney et al. 2018). For example, Evanoski-Cole et al. (2017) measured concentrations of $PM_{2.5}$ and its components over two sampling campaigns during winter. The investigators summarized results at daily, 48-hour, and weekly time intervals, information which is useful for understanding acute and sub-chronic exposures during winter. Bunch et al. (2014) used hourly concentration data collected over a ten-year period to provide 1-hour, 24-hour, and annual average concentrations. Pekney et al. (2018) outfitted a mobile lab with a range of instrumentation to collect data continuously, thus allowing for longitudinal assessment of concentrations over different phases of UOGD.

Spatial Representativeness (variation within the study area). Whether a given sample represents air that is both impacted by UOGD and breathed by potentially exposed populations depends on sampler placement, whether and what type of UOGD operations occurred at the time of sampling, and what non-UOGD sources exist nearby. Some studies collected air samples near residences with the objective of capturing samples representative of human exposure to chemicals in air (Lewis et al. 2016; Macey et al. 2014; Maskrey et al. 2016; McCawley 2013; McKenzie et al. 2012; Paulik et al. 2016, 2018; Pennsylvania Department of Environmental Protection 2010; Steinzor et al. 2013). While addressing the end of the exposure conceptual model, it is unclear what proportion of the reported concentrations are attributable to UOGD operations and other sources.

Sampling campaigns in some studies quantified spatial variability at the local level using systematic mobile or stationary monitoring (Eisele et al. 2016; Field et al. 2015; Halliday et al. 2016; Pennsylvania Department of Environmental Protection 2018; Williams et al. 2018), but it is not clear how well study results are relevant to human exposures. Data provided in these studies could be useful for characterizing exposures if combined with information about meteorology, UOGD activity, population proximity, and behavior.

Studies at the regional scale provide valuable information about spatial variability over large areas, but do not always provide data at spatial resolutions fine enough to quantify variability in human exposure, particularly involving point sources (e.g., Ahmadi and John 2015; Bahreini et al. 2018; Katzenstein et al. 2003). For example, Fann et al. (2018) used a national-scale, photochemical air quality model to estimate the health damages associated with UOGD emissions. However, they did not examine exposure levels near the UOGD emission sources, identify UOGD process-specific impacts on air quality, or assess how well the model described the effect of UOGD emissions on air quality. There are several notable exceptions. Cheadle et al. (2017), a study of regional ozone concentrations measured using both mobile and stationary monitoring, provided information on localized peak concentrations attributable to UOGD, which may represent human exposure conditions if proximate to residential areas or population centers. Hildenbrand et al. (2016c) collected mobile air quality measurements at multiple well pads over a 13-county area and combined the data with records of well pad activities to model concentration intensity over the region at high spatial and temporal resolution. The investigators attributed peak BTEX concentrations to flaring stations, condensate tanks, and compressor units on some well pads.

To characterize variability in air quality over a given region, investigators have combined and reviewed multiple sources of air quality data related to UOGD (Box 4-1).

Box 4-1. Reviews of existing air quality data

Investigators have reviewed existing air quality data (e.g., publicly available data, published peer-reviewed articles, reports) to summarize what is known about air quality in several UOGD regions of the United States and, in some cases, to assess the potential for adversely affecting human health.

Long et al. (2019) compiled and summarized air quality data from over 30 datasets representing approximately 200 sampling locations in the Marcellus region of Pennsylvania. The Colorado Department of Public Health and Environment compiled and summarized air quality data from 47 datasets representing 34 locations in Colorado (McMullin et al. 2018). Both sets of investigators compared chemical concentrations in air to health-based benchmarks to assess the health risk for exposed individuals. Garcia-Gonzales et al. (2019c) reviewed air quality data from 37 peer-reviewed articles investigating hazardous air pollutant concentrations near oil and gas development, and Garcia-Gonzales et al. (2019b) compiled and analyzed the data from these articles to identify the oil and gas operations that contributed most to hazardous air pollutant concentrations.

The authors noted several limitations in the data that they reviewed and opportunities to remedy them in future research, such as the use of source apportionment techniques to distinguish between the contributions of UOGD and other sources to air quality impacts, air monitoring campaigns with shorter averaging times to capture episodic peak exposures, and coupling air monitoring with biomonitoring and personal monitoring of the potentially exposed population.

Generalizability. Investigators provided minimal information about the generalizability of study results to other populations, locations, and UOGD operating conditions. Studies that measured air emissions or concentrations during specific UOGD processes provide useful information that is potentially generalizable to areas experiencing the same type and scale of UOGD processes (e.g., Roohani et al. 2017). Similarly, studies that linked concentrations measured over time with UOGD production activities may inform how concentrations vary temporally with changing meteorological conditions or with changing regulation (Ghosh 2018; Islam et al. 2016; Kort et al. 2016; McLeod et al. 2014; Pacsi et al. 2013).

Some modeling studies incorporated methods such as trajectory analysis and chemical age analysis that can be applied to other regions (e.g., Evanoski-Cole et al. 2017; Katzenstein et al. 2003; Khalaj and Sattler 2019; Nathan and Lary 2019; Pekney et al. 2018). Studies that used accurate emission measurements as model inputs could also apply their results to other areas with similar operational practices and equipment (e.g., Pétron et al. 2012). A notable example is Khalaj and Sattler (2019), who used chemical dispersion modeling, combined with emissions data and information about equipment locations and topography to determine whether 1-hour concentrations exceeded National Ambient Air Quality Standards at various distances from well pads. The modeling approaches used in this study can be useful for predicting exposures in other locations and populations experiencing similar operations. Further, many of the modeling studies can simulate secondary pollution formation in other regions with similar conditions (Edwards et al. 2014; Field et al. 2015; Oltmans et al. 2014; Pfister et al. 2017). Nevertheless, application of modeling results to other conditions should be done with caution due to variability in UOGD operational practices, meteorology, terrain, and the composition of oil and natural gas resources across plays.

4.2.3.2 Characteristics of Potentially Exposed Populations

Several air monitoring and modeling studies aimed to quantify potential exposures of people living near UOGD. Some identified the specific populations they intended to study but did not report whether sensitive sub-populations might be disproportionately affected by UOGD emissions. Studies that identified the potentially exposed population were those involving sampler placement inside or on residential properties (Frazier 2009; Lewis et al. 2016; Maskrey et al. 2016; Paulik et al. 2016, 2018;

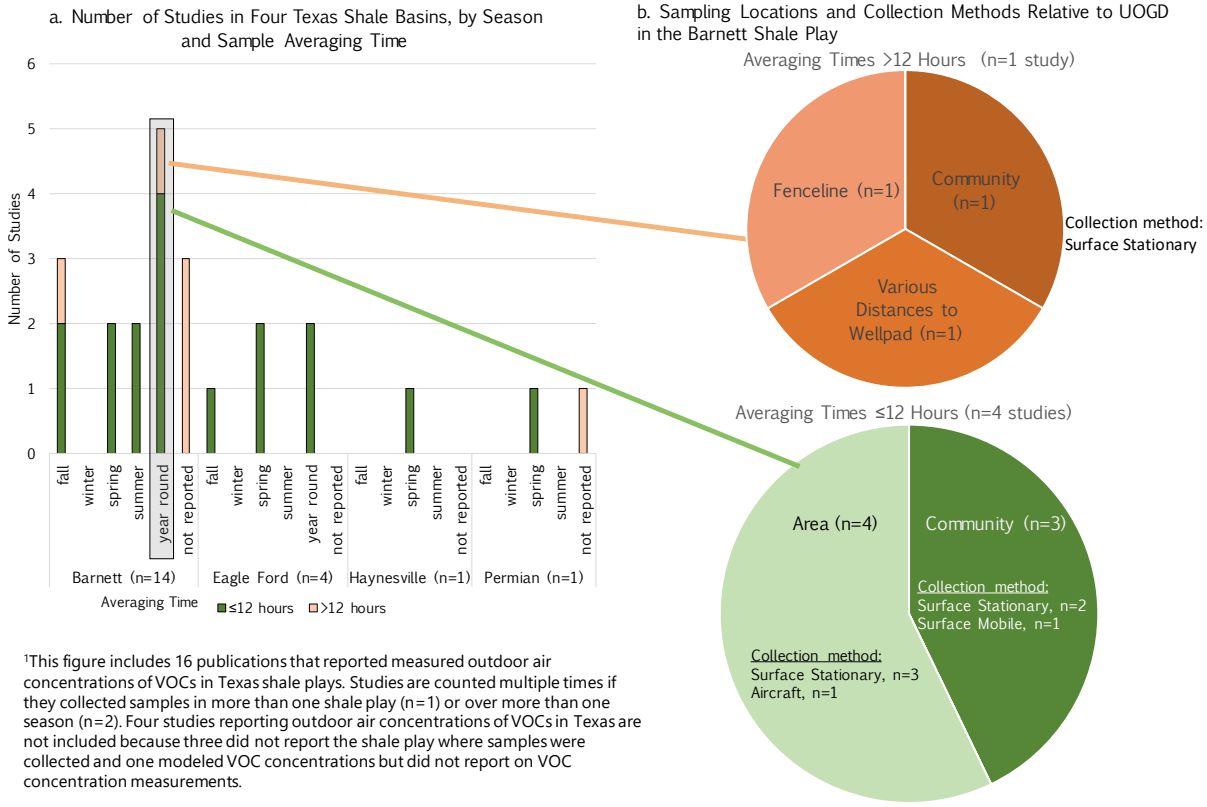
Steinzor et al. 2013) or in residential communities (Agency for Toxic Substances and Disease Registry 2010; Colorado Department of Public Health and Environment 2012, 2017c; Crowe et al. 2016; Frazier 2009; Macey et al. 2014; Pennsylvania Department of Environmental Protection 2010, 2018; Swarthout et al. 2015; Thompson et al. 2014; Walther 2011). Some of these studies accounted for wind direction relative to UOGD operations to connect residential or community concentrations with UOGD. Health assessments (e.g., Agency for Toxic Substances and Disease Registry 2010) provided information on the sociodemographic characteristics of the potentially exposed population. Three studies (Haynes et al. 2019; Macey et al. 2014; Steinzor et al. 2013) involved local community members in sampling design and collection.

4.2.4 Concluding Remarks – Air Exposure Pathway

Despite the size, breadth, and, in many cases, quality of the literature, it collectively falls short of providing an understanding of the extent of temporal and spatial variability of potential exposures across major U.S. oil and gas regions.

By way of illustration, consider the 16 air quality studies conducted in major oil- and gas-producing regions of Texas (Figure 4-8). Most studies were conducted in the Barnett Shale where UOGD began, with only one in each of the Haynesville and Permian shale plays. Investigators primarily collected data year-round with averaging times of ≤12 hours. These short averaging times can be useful for estimating acute exposures but have less utility for estimating chronic exposures. Other studies present seasonal average concentrations, which can be useful for estimating chronic exposure. Focusing on the Barnett Shale where most studies occurred, investigators collected data at a range of different locations and with different sample averaging times (as shown in the pies in Figure 4-8). Although the Barnett Shale studies provided useful information for understanding air quality in the region and the potential for human exposure, they provided a limited amount of information to assess human exposures at any particular location over time (Figure 4-8). This is especially true for Texas shale plays outside of the Barnett region.

Figure 4-8. Number of outdoor air quality studies in four Texas shale basins, by sampling location, time of year, and sample averaging time (Appendix A includes the list of publications).



[1]This figure includes 16 publications that reported measured outdoor air concentrations of VOCs in Texas shale plays. Studies are counted multiple times if they collected samples in more than one shale play (n=1) or over more than one season (n=2). Four studies reporting outdoor air concentrations of VOCs in Texas are not included because three did not report the shale play where samples were collected and one modeled VOC concentrations but did not report on VOC concentration measurements.

Capturing all elements of the conceptual model of exposure in a single study has not been achieved, even in the most comprehensive undertakings. Although some investigators attempted to measure or model regional and local air quality impacts of UOGD, they had varying success in linking measured concentrations with UOGD and were not always aiming to quantify human exposure. Some studies of note have employed exemplary methods for use in an exposure study (Boxes 4-2 and 4-3).

Box 4-2. Examples of studies that employed useful methods for quantifying a complete air exposure pathway from a UOGD source to a population: *Local community exposure to chemical concentrations in air*

Background
Characterizing exposure to UOGD-related atmospheric emissions is complex due to the high spatial and temporal variability in emissions, combined with complex atmospheric transport across scales. Further, not all of the important emissions will occur on-site, as mobile emissions, including those from heavy trucks that transport material off and on the well pad. Few studies have documented short- and long-term variability in concentrations, while documenting a complete exposure pathway and connecting concentrations of agents at the source to concentrations in communities where people might be exposed. Zielinska et al. (2014) endeavors to do so in a pilot study.

Study Summary
Zielinska et al. (2014), studied the Barnett Shale play to quantify air quality changes from UOGD. The two-phase study began with mobile survey sampling to identify emission sources of interest (Phase 1), followed by Phase 2 using saturation monitoring in a community. Phase 1 concentrated on shorter term sampling of gases to determine source profiles. Phase 2 included PM, VOC, and NO_x measurements throughout a community and at various distances to a residence. They used the source profiles to conduct source apportionment using a chemical mass balance method. Phase 2 focused on longer term samples that short-term peaks would not be capture. Based on their modeling and acknowledging important sources of uncertainty, they reported that the dominant source of ambient non-methane VOCs was motor vehicles, followed by natural gas and condensate tank emissions.

Notable Features
The two-phase sampling method allowed investigators to identify emission sources and measure air quality in residential communities as a result of the identified sources. The study design provided a nice balance between short-term and longer-term integrated sampling, which are applicable to assessing human exposures. The measurements also capture releases from both stationary and mobile sources. The investigators examined the source contribution to several different chemical concentrations and assessed the rate of degradation of chemical concentrations at various distances from the well pad, thus contributing to an understanding of whether a complete exposure pathway existed between the UOGD sources and residential areas.

Missing Elements
As a pilot, the study was limited to a small community and a short period of time (a month). Therefore, the measurements do not capture variations in chemical concentrations as a function of seasons, meteorology, phases of development, operator practice, and geographic region. The study results are limited in their generalizability.

Box 4-3. Examples of studies that employed useful methods for quantifying a complete air exposure pathway from a UOGD source to a population: *Regional exposure to chemical concentrations in air*

Background
Few studies assessed exposures on a regional scale (hundreds to thousands of kilometers). Ideally, studies would combine air quality monitoring data with emission rate data and use modeling to predict concentrations in areas where people are exposed to air pollution, incorporating methods to identify the source contributions. Zavala-Araiza et al. (2014) exemplifies a study that combines emission and monitoring data to model the contribution of UOGD to concentrations of primary pollutants.

Summary
Zavala-Araiza et al. (2014) used existing hourly VOC concentrations data collected over a 20-month period at three sampling sites representing high UOGD density, an urban area, and background conditions in the Barnett Shale region. Investigators also used publicly available emission rate data for UOGD sources of VOCs to predict UOGD contributions to regional VOC concentrations. They reported low temporal variability in VOC emissions during the production phase, that pneumatic devices dominated VOC emissions, and that meteorology, rather than episodic emission events, primarily explained variability in VOC concentrations.

Notable Features
The study design allowed investigators to capture relatively high temporal resolution (hourly) concentrations over a large geographic area, and to capture seasonal and operational variability over the 20-month sampling campaign. Additionally, sampler placement in areas representing different conditions allowed for correction for background concentrations. The availability of an emissions inventory of over 8000 sites provided information on both regional and source type (e.g., separator, vent, and flare) variability across the region. The investigators took full advantage of the emissions dataset by simulating concentrations from specific operational events, and by parameterizing a predictive model with information about topography and meteorology. Such a model, with fine enough resolution and ground-based data, can be useful to predict human exposures under different exposure conditions. Notably, the investigators performed sensitivity analysis on modified emissions factors, which have been cited as under-estimating leaks (Allen et al. 2013).

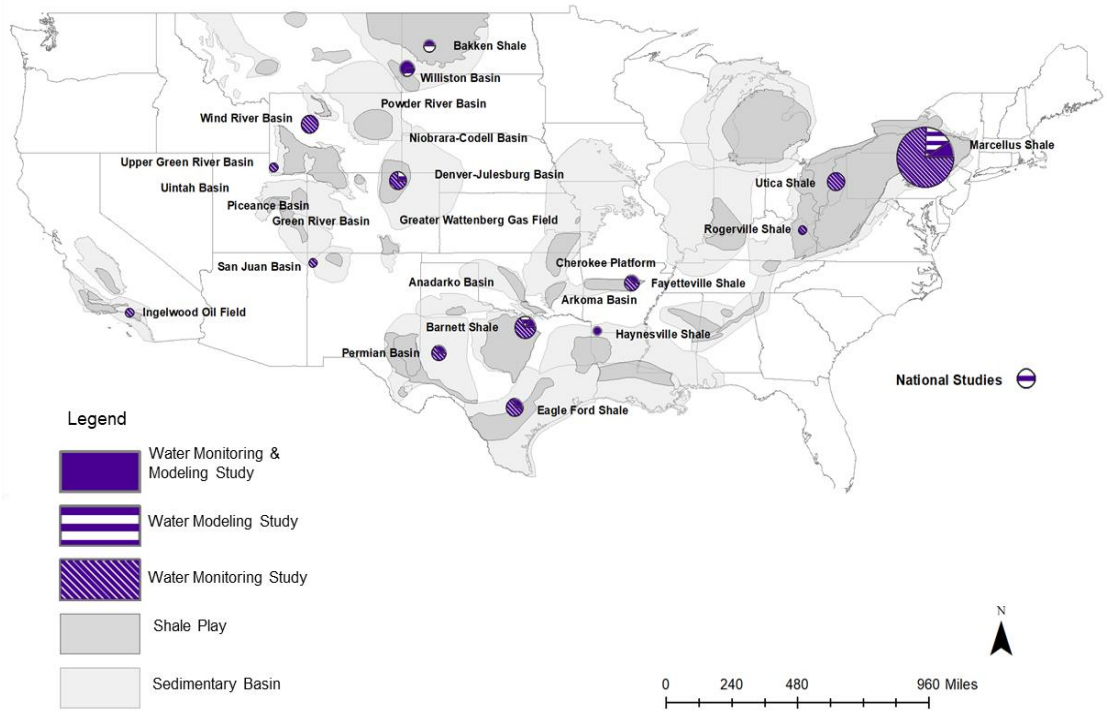
Missing Elements
Because the investigators did not focus their analysis on human populations, they did not provide information about the potentially exposed populations or the levels at which they could be exposed. Therefore, this study does not cover a full exposure pathway. The study sampling methods will not characterize near-source, peak exposures (e.g., due to a super-emitter) nor exposure to NO_x and PM emissions from combustion and mobile sources.

4.3 WATER EXPOSURE PATHWAYS

4.3.1 Summary of Studies – Water Exposure Pathway

Studies with water quality monitoring data (n=282), modeling predictions (n=15), or both (n=10) have been conducted in the major oil- and natural-gas-producing regions of the United States (Figure 4-9), with the majority of studies occurring in the Marcellus Shale region. Studies included measurements of chemical agents in groundwater (n=39), surface water (n=28), or produced water (n=9) to understand the potential water quality impacts of UOGD (Figure 4-9). Additionally, a subset of studies included assessments of sediment quality (discussed in Section 4.4). The summary of water studies builds on the U.S. EPA's review of potential water quality impacts of UOGD (U. S. EPA 2016a; Box 4-4).

Figure 4-9. Water monitoring or modeling study locations (Appendix A includes the list of publications).



Notes:

- The size of each pie chart is proportional to the total number of studies in each shale play.
- The largest pie chart on the map represents 37 studies.

Studies involved measurement or modeling of flowback and produced water indicator species, including chloride/bromide ratios (Barth-Naftilan et al. 2018; Hildenbrand et al. 2016b; Llewellyn et al. 2015; Reilly et al. 2015; Woda et al. 2018), beryllium (Burton et al. 2016), barium (Fontenot et al. 2013), strontium (Chapman et al. 2012; Fontenot et al. 2013; Woda et al. 2018) and chloride (Darrah et al. 2014; Post van der Burg and Tangen 2015; Preston et al. 2014). Investigators also studied microbial species that may serve as indicators of water quality variability in groundwater (Santos et al. 2018) and surface water (Fahrenfeld et al. 2017; Trexler et al. 2014).

Several studies involved collection of samples from municipal water supplies or residential water wells, some by community volunteers (Alawattegama et al. 2015; Boyer et al. 2012; Fontenot et al. 2013;

Haynes et al. 2019; Hildenbrand et al. 2015, 2016a; McMahon et al. 2017; Nelson et al. 2015; Steinzor et al. 2013) (Figure 4-10). Other studies leveraged existing data to assess water quality. Maloney et al. (2017) made use of existing data on crude oil, drilling water, hydraulic fracturing solution, and wastewater spills collected between 2005 and 2014 in Pennsylvania, Colorado, North Dakota, and New Mexico to compare the distance between spills and surface water. They noted that Pennsylvania spills occurred more frequently near watersheds of high relative importance to drinking water than spills in the other states.

Box 4-4. U.S. EPA Review: *Fracturing for Oil and Gas: Impacts from the Hydraulic Fracturing Water Cycle on Drinking Water Resources in the United States*

Purpose of the Report
The largest review to date on potential UOGD impacts on water in the United States was published by U.S. EPA Office of Research and Development in 2016 (U. S. EPA 2016a). The aim of the report was to assess the likelihood and magnitude of impacts to underground sources of drinking water from the hydraulic fracturing water cycle.

U.S. EPA's Findings
It identified 1,606 chemicals associated with hydraulic fracturing, including 1,084 chemicals used in hydraulic fracturing fluid and 599 chemicals detected in produced water. The report describes the following activities as "more likely than others to result in more frequent or more severe impacts":

- Water acquisition that entails water withdrawals in areas with limited water resources;
- Spills of hydraulic fracturing fluids, chemicals, or produced water;
- Injection of hydraulic fracturing fluid directly into groundwater resources or into wells with inadequate integrity that allow for gas or liquid to enter groundwater resources;
- Discharge of inadequately treated wastewater directly to surface water resources; and,
- Use of unlined pits for wastewater storage or disposal.

For each activity, the review identified several practices that may reduce the frequency and severity of UOGD impacts on drinking water quality and quantity. U.S. EPA concluded that several important data gaps in its assessment of impacts on drinking water prevented its estimation of the frequency and severity of impacts on drinking water resources across the country.

Data Gaps Identified in the Report
U.S. EPA noted several data gaps, including (1) limited information on the location of hydraulic fracturing–related activities relative to drinking water resources, (2) insufficient pre-drilling data, (3) difficulty discerning the potential effects of UOGD from other potential sources in the area (e.g., conventional oil and gas operations, other industries, and natural sources) and complexities involved in understanding subsurface migration of contaminants, and (4) lack of information on the identity of unknown chemicals in fracturing fluid and the toxicity reference values of known chemicals in fracturing fluid.

4.3.2 UOGD Sources and Potential Release Mechanisms – Water Exposure Pathway

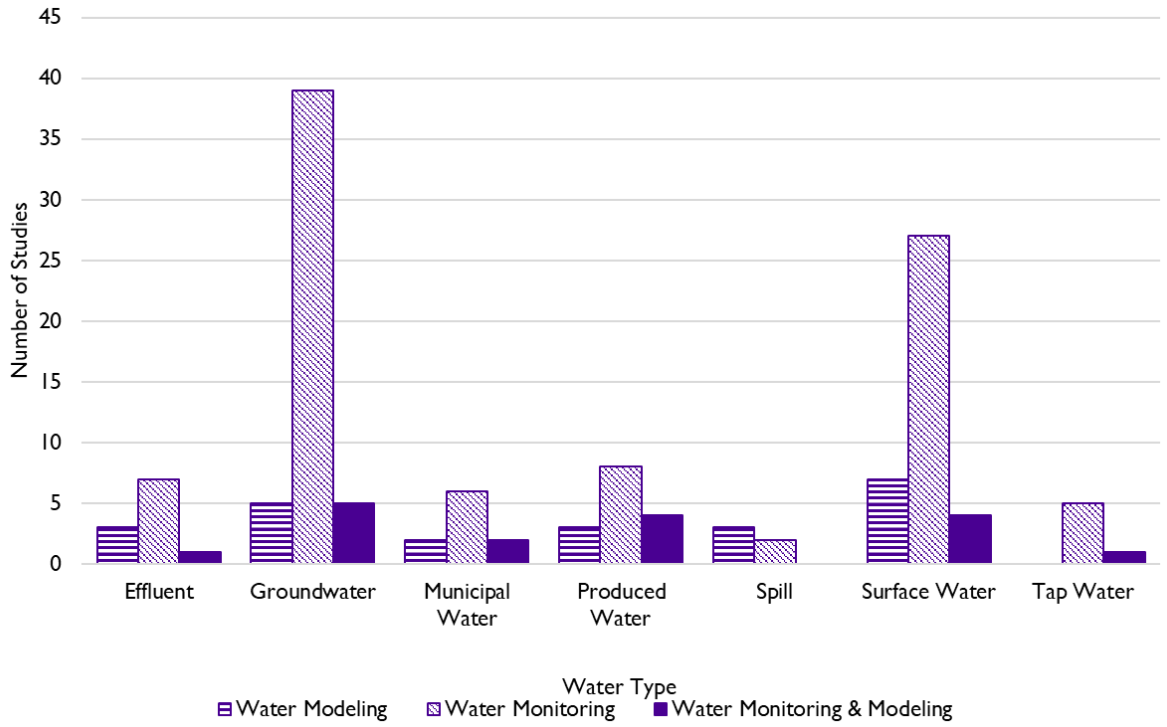
4.3.2.1 UOGD Releases to Water

UOGD releases to surface water and groundwater can occur as a result of permitted discharges and also under a variety of accidental conditions (SL Brantley et al. 2014; U.S. Environmental Protection Agency 2016a). To date, the scientific literature has been focused primarily on possible accidental releases to water. However, there is growing need for research about the impact to groundwater and surface water from permitted discharge of treated UOGD wastewater effluent to surface water. There is additional need for research on use of produced water that meets required quality criteria for applications outside the oil

and gas production site (e.g., irrigation of crops, watering of cattle, and de-dusting or de-icing roads)(Ground Water Protection Council 2019).

The potential for UOGD contamination of groundwater has been investigated in a number of locations, including Dimock, Pennsylvania (Agency for Toxic Substances and Disease Registry 2016; Hammond 2015; U.S. Environmental Protection Agency 2019a), Pavillion, Wyoming (American Petroleum Institute 2013; DiGiulio and Jackson 2016; Ling and Heglie 2016; U.S. Environmental Protection Agency 2011a; Wright et al. 2012), and Parker County, Texas (Larson et al. 2018; Veil 2012). Surface water contamination attributed to UOGD accidental releases and waste management and disposal has also been studied (e.g., Cozzarelli et al. 2017).

Figure 4-10. Number of studies by type of water sample (Appendix A includes the list of publications).



Kuwayama et al. (2016) reviewed the literature on water contamination risk associated with storage of produced water in impoundments (often referred to as pits) versus storage tanks. Produced water impoundments are typically lined to reduce the possibility of leaching into the subsurface, but the potential for leaks remains. In addition, impoundments are open to the atmosphere. The potential for volatilization has received limited attention in the literature (Bean et al. 2018). Because UOGD flowback has been exposed to high pressure and temperatures in the drilled bore of the well (downhole), the formation of unknown compounds is possible (Butkovskyi et al. 2017; Luek and Gonsior 2017). Shih et al. (2015) characterized chemical composition of flowback, produced water, and drilling waste samples collected in Pennsylvania from 2009 to 2011, finding high levels of chloride and sodium ions, as well as metals (e.g., barium, strontium).

4.3.2.2 Subsurface Mobility of UOGD-Related Contamination

The possibility that contaminants from UOGD activities might enter groundwater aquifers and be transported to drinking water wells is a consideration in evaluating the risk of potential exposure.

Contaminants of concern include (1) chemicals used in hydraulic fracturing fluids that return up the borehole casing once the fracturing work has been completed (flowback and produced fluids), (2) constituents in the water that occur naturally in the shale or other source rock, such as barium and radium, and that flow from the well along with hydrocarbons (produced water) (e.g., Orem et al. 2014; Phan et al. 2015; Renock et al. 2016), and (3) the hydrocarbons themselves, which are the target of the well development. The mobility of a particular contaminant depends on its chemical and physical characteristics, particularly on how the constituent interacts with the mineral grains of the aquifer or with materials such as casing cement before the fluid reaches an aquifer (Cai et al. 2018).

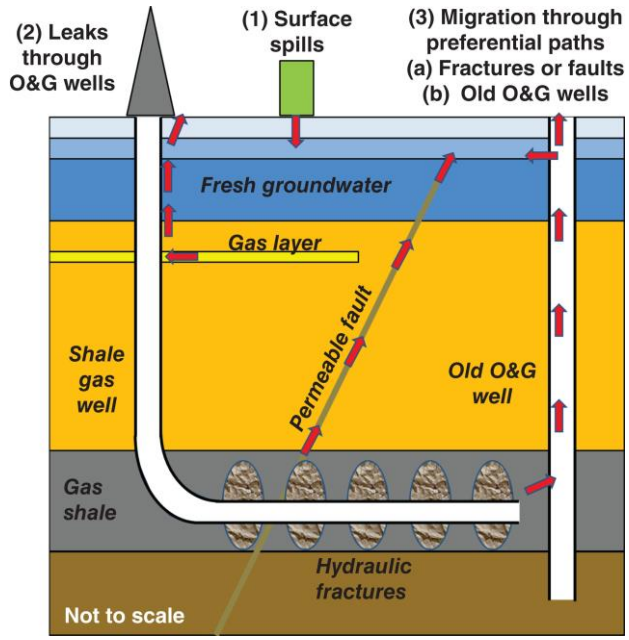


Figure 4-11. Potential groundwater contamination mechanisms related to shale gas production. (Source: Lefebvre 2016; © 2016 Wiley Periodicals, Inc. Used by permission.)

Three scenarios could lead to groundwater contamination (Figure 4-11). The first scenario is an association with the hydraulic fracturing process itself; that is, the fractures in the source rock may propagate upward from depth leading to a release of hydraulic fracturing fluids and water contained in the source rock upward into overlying aquifers. Direct hydraulic fracture growth into overlying aquifers has been shown to be implausible (Fisher and Warpinski 2012). Propagation of fractures is more likely if there is an abandoned well or a natural fracture or fault for the hydraulic fracture to intersect that leads to a pathway upward to an aquifer. Even so, the likelihood of an occurrence is considered to be low, especially relative to the other types of cause for a contamination event (Shanafield et al. 2018).

A second cause of an accidental release of a contaminant is through a well casing failure. Contamination of groundwater due to well casing failure is reportedly rare (Wen et al. 2018). Reported incidents have noted that stray gas (methane) has migrated in groundwater to drinking water wells (Darrah et al. 2014; McMahon et al. 2018). Although to date only methane has been linked to impacts of well casing failure, concerns remain about how groundwater contamination with drilling fluids or produced fluids may appear in the future (Lefebvre 2016). To avoid future releases of contaminants into groundwater, precautions in well construction such as intermediate casing strings have come into widespread use.

Spills of chemicals, return flows, and produced waters on and near well pads provide the most likely source of contaminants to shallow groundwater (Lefebvre 2016; Shanafield et al. 2018; Soeder and Kent 2018). Thousands of spills related to UOGD have been documented (Maloney et al. 2017). Contaminants linked with surface operations have been detected in groundwater (Drollette et al. 2015; Llewellyn et al. 2015). Such observed subsurface contamination of water due to UOGD is most likely from surface spills (Shanafield et al. 2018).

4.3.2.3 Linking UOGD Sources to Water Concentrations

Quantifying the impact of UOGD on water quality is challenging. The literature reports that multiple sources have the potential to contribute to chemical concentrations, including UOGD, conventional oil and gas development, other anthropogenic sources, and naturally occurring conditions. There is also complexity and uncertainty in understanding subsurface conditions as they relate to potential migration of UOGD-related contaminants. Investigators employed several methods to isolate the influence of UOGD on water quality.

Sampling location. Most studies measured chemical concentrations in private drinking water (i.e., groundwater) wells or surface water used as a drinking water source. Investigators typically sampled drinking water wells at residences located near UOGD wells (Alawattegama et al. 2015; Boyer et al. 2012; Darrah et al. 2014; Elliott et al. 2018; Fontenot et al. 2013; Harkness et al. 2017; Hildenbrand et al. 2015, 2016a, 2016b; Jackson et al. 2013; LeDoux et al. 2016; Ling and Heglie 2016; Llewellyn et al. 2015; McMahon et al. 2019; Nelson et al. 2015; Reilly et al. 2015; Steinzor et al. 2013; Warner et al. 2013b; Zhu et al. 2017), assessing the relationship between water quality and proximity to UOGD, or reporting chemical concentrations of samples collected from wells tapping aquifers located near UOGD, without conducting source attribution (Molofsky et al. 2013; Osborn et al. 2011a, 2011b; Saba and Orzechowski 2011). Many surface water monitoring studies assessed the impact of UOGD wastewater effluent by sampling upstream and downstream of wastewater treatment facilities (Akob et al. 2016; Ferrar et al. 2013b; Hladik et al. 2014; Landis et al. 2016; Warner et al. 2013a).

Tracers, signatures, or ratios. A number of water studies used tracers, markers, or ratios to isolate contaminants specific to UOGD in surface water and groundwater. For example, studies used geochemical tracers such as hydrocarbon isotopes to determine chemical sources, and used ratios, tracers, and ion geochemistry as measures of groundwater age and origin (e.g., Darrah et al. 2014; Grieve et al. 2018; Hammack et al. 2014; Jackson et al. 2013; LeDoux et al. 2016; Llewellyn et al. 2015; McMahon et al. 2017, 2019; Sherwood et al. 2016; Woda et al. 2018). Some studies distinguished natural methane from anthropogenic methane in groundwater to aid in identifying sources (e.g., Christian et al. 2016; Darrah et al. 2014; Grieve et al. 2018; Harkness et al. 2017; Li and Carlson 2014; McMahon et al. 2019). Llewellyn et al. (2015) identified a common constituent of hydraulic fracturing fluid, 2-*n*-butoxyethanol, in drinking water wells and concluded that UOGD might be the source of contamination (see Box 4-6). Darrah et al. (2014) identified noble gas isotopic signatures in drinking water wells, which the investigators linked to specific events that might lead to contamination, including failure of wellbore annulus cement, faulty production casing, and underground gas well failure.

Reference conditions. Some investigators have attempted to isolate UOGD impacts by documenting conditions before, during, and after drilling. Nelson et al. (2015) evaluated radionuclide concentrations in three private drinking water wells at residences less than 2000 meters from UOGD before and approximately one year after hydraulic fracturing activities. The investigators reported no significant difference in concentrations between the two sampling periods.

At the National Energy Technology Laboratory's Hydraulic Fracturing Test Site, Eisenlord et al. (2018) collected air quality and groundwater quality data in the Permian Basin in Texas before operations began, during UOGD fracturing and flowback phases, and during production. They reported a moderate increase in BTEX concentrations in air 1000 feet during flowback and no impact to the local aquifer.

Barth-Naftilan et al. (2018) collected monthly bedrock aquifer samples in a 25-km^2 area in the Marcellus Shale region over a two-year period during which UOGD well drilling, hydraulic fracturing, and production occurred. They reported large variability in methane concentrations across the study area but minimal variation over time.

Harkness et al. (2017) measured inorganic geochemistry parameters (e.g., Cl^-, SO_4^{2-}, Br^-), isotopes of selected inorganic constituents (strontium [87Sr/86Sr], boron [d11B], lithium [d7Li], and carbon [d13C-DIC]), and selected hydrocarbon molecular and isotopic tracers in drinking water wells to evaluate groundwater quality differences before, during, and after hydraulic fracturing and before and after well installation in West Virginia. The investigators attributed changes in water quality after hydraulic fracturing to migration of naturally occurring methane and reported no changes in water quality after well installation. They also reported surface water contamination, which they attributed to a nearby wastewater spill using isotope ratio markers.

Groundwater studies have also utilized pre-drill datasets collected by oil and gas companies or government agencies (Gross et al. 2013; Li and Carlson 2014; Sherwood et al. 2016; Wen et al. 2018, 2019; Wilson and VanBriesen 2012). Alawattegama et al. (2015) compared pre- and post-drill private water well samples from 2 of 33 residential wells in their study for which existing pre-drill data from industry and Pennsylvania Department of Environmental Protection were available. They reported increased metal concentrations during UOGD activities, with a subsequent decrease in concentrations in samples collected after drilling. The investigators also mapped elevation, nearby coal mining, and abandoned well data, noting the potential influence of those factors on chemical concentrations. These data sources have limitations that make it difficult for investigators to contextualize their results and that may lead to potential over- or under-estimation of the effects of UOGD on water quality (Betanzo et al. 2016).

Some studies collected data at reference locations, such as surface water upstream of wastewater treatment facilities (Hladik et al. 2014) or at some distance from UOGD operations (Pelak and Sharma 2014; Walters et al. 2019). Although the use of reference locations and sampling before, during, and after UOGD operations provides useful information about trends over time, these methods may not consider other factors affecting water quality (e.g., earlier oil and gas operations, coal mines, biodegradation of organic material, agriculture, and natural methane). Some investigators acknowledged the lack of baseline or reference data as a limitation of their studies (Hildenbrand et al. 2016a; LeDoux et al. 2016; Steinzor et al. 2013).

Modeling. Investigators employed diverse modeling approaches to provide quantitative linkages between UOGD sources and potential human exposure via the water pathway (Burton et al. 2016; Hill and Ma 2017; Landis et al. 2016; Olmstead et al. 2013; Preston and Chesley-Preston 2015; Shanafield et al. 2018; Shores et al. 2017; Torres et al. 2017; Weaver et al. 2015). Investigators collected their own data to parameterize models (Bean et al. 2018; Drollette et al. 2015; Larson et al. 2018; McMahon et al. 2017; Post van der Burg and Tangen 2015; Preston et al. 2014) or relied on data curated by a state or federal regulatory agency, other investigators, or commercial sources (Burton et al. 2016; DiGiulio and Jackson 2016; Hill and Ma 2017; Olmstead et al. 2013; Preston and Chesley-Preston 2015; Shores et al. 2017; Shores and Laituri 2018; Torres et al. 2017, 2018; Weaver et al. 2015).

The aim of most water modeling was to estimate the impact of increasing UOGD prevalence on groundwater or surface water quality (e.g., Hill and Ma 2017; Olmstead et al. 2013; Shanafield et al. 2018). For example, Burton et al. (2016) created a geospatial model using information about the wellbore, fluid velocity, and reservoir pressure to assess whether changes in groundwater quality were associated with UOGD. They reported that well density and formation pressures, but not proximity of samples to gas wells within 1000 feet, were associated with groundwater quality. Results also indicated the potential for groundwater contamination due to chemical migration from the annular spaces in the wellbore. Several human health risk assessments incorporated modeling approaches to assess risk to human health from exposure to water contaminated by UOGD (Abualfaraj et al. 2018; Durant et al. 2016; Gradient Corporation 2013; Regli et al. 2015; Rish and Pfau 2018; Torres et al. 2018).

Distinguishing UOGD from conventional oil and gas development. Most studies collected water samples in Pennsylvania, Colorado, Texas, and Wyoming — states that have a long history of conventional oil and natural gas development. Some studies have investigated the impact of abandoned conventional wells on water quality (e.g., McIntosh and Ferguson 2019), but it remains difficult to distinguish between the contributions of collocated conventional and unconventional development to changes in water quality.

4.3.3 Potentially Exposed Populations – Water Exposure Pathway

4.3.3.1 Relevance of Information for Quantifying Exposure

Temporal and spatial representativeness. The water quality studies related to UOGD are temporally and spatially limited. Use of water quality data from short-term sampling campaigns to quantify longer-term human exposures can result in under- or over-estimates. Ideally, data to inform human exposure would be collected across seasons and over a period of months or years. Few studies sampled in more than one shale play — two in the Marcellus and Utica shales (Osborn et al. 2011a; Penningroth et al. 2013), one in the Eagle Ford, Fayetteville, and Haynesville shales (McMahon et al. 2017), and one in the Barnett and Marcellus shales (Darrah et al. 2014). Studies that reported data from samples in one shale play generally did not discuss whether results were generalizable to other regions.

Some studies reported data for samples of tap water that residents use (e.g., Boyer et al. 2012; Elliott et al. 2018; Steinzor et al. 2013; Yan et al. 2017) and, therefore, identified the exposed population. Surface water monitoring studies provided little or no information on how people used a given surface water body (e.g., drinking, swimming, fishing, or recreational activities), making it challenging to make inferences about the representativeness of surface water quality data to a given population's exposure.

Generalizability. Surface water studies involving collection of samples from upstream and downstream of commercial wastewater treatment facilities may be somewhat generalizable to facilities with similar operating practices. The water modeling studies provided a useful template for extrapolating results from one set of conditions to another; however, they were parameterized with data from one shale play, with the exception of McMahon et al. (2017).

4.3.3.2 Characteristics of Potentially Exposed Populations

Some studies characterized potentially exposed populations through well water samples and information about the people using those sources for drinking water. Elliott et al. (2018) sampled household drinking water and collected information about participant demographics, their primary sources of water for drinking and for other uses, and drinking water treatment systems. Steinzor et al. (2013) collected data on health symptoms, occupational history, and past toxic exposures from study participants whose water supplies were tested. Steinzor et al. (2013) also sampled air quality at residences in the study population. Water samples were collected in some studies to address complaints about the smell, taste, color, or odor of drinking water (Boyer et al. 2012; Ling and Heglie 2016; Llewellyn et al. 2015; U.S. Environmental Protection Agency 2011a). For the most part, investigators of these studies did not use methods (aside from distance-based metrics) to link concentrations measured in drinking wells to UOGD processes.

4.3.4 Concluding Remarks – Water Exposure Pathway

Although potential UOGD impacts on water quality have been a subject of much concern and numerous complaints have been submitted to state regulatory authorities, few studies to date have demonstrated a complete exposure pathway. Drollette et al. (2015) (Box 4-5) and Llewelyn et al. (2015) (Box 4-6) are among those that come closest to doing so. It is important to note that many of the studies discussed in

this review did not set out specifically to assess exposure. Instead, most aimed to measure or model chemical concentrations, noting that these measurements could potentially be used to assess exposure in future studies. Findings from U.S. EPA (2016a) remain relevant; there are limited data to describe the likelihood, magnitude, frequency, or duration of exposure to water potentially contaminated by UOGD, or whether improved regulation and operational practices have decreased the likelihood of releases that affect water quality. More studies are needed with the objective of quantifying potential human exposure to water contamination from UOGD processes.

Box 4-5. Examples of studies that employed useful methods for quantifying a complete water exposure pathway from a UOGD source to a population: *Exposure to UOGD wastewater from surface spills*

Background
Flowback and produced waters from UOGD are a main concern with regard to potential exposures to both introduced chemicals in the hydraulic fracturing process and naturally occurring chemicals in the brines that are produced along with oil and gas. Only a small fraction of these waters are treated and released to the environment (National Academies of Sciences, Engineering, and Medicine 2017) or reused within the oil and gas industry or other applications (U.S. Environmental Protection Agency 2019b). Therefore spills (accidental releases including leaks from pits and tanks) are the most likely release mechanism for wastewater-related contamination of ground or surface water. Although spills occur not infrequently (Maloney et al. 2017), except for rare cases involving major accidental releases (e.g., Cozzarelli et al. 2017), there have been only a few studies that specifically focus on spills. One such report is a paper by Drollette et al. (2015).

Study Summary
Drollette et al. (2015) sampled 64 private residential groundwater wells between 2012 and 2014 in northeastern Pennsylvania and in southern New York to look for organic compounds that potentially originated from UOGD. They reported trace levels of VOCs in 6 samples (10%), and low levels of gasoline range (9 of 59 samples) and diesel range (23 of 41 samples) organic compounds. Analyses of inorganic elements, including isotopic ratios, were used as indicators of upward migration of fluids, potential leakage from compromised well casings, or leaks from pits or tanks for storing flowback and produced water. None of these indicators were co-observed with the organics, making subsurface releases or releases from surface storage highly unlikely as explanations for the observed water well contaminants. Bis(2-ethylhexyl) phthalate, a known ingredient of fracturing fluids, was detected in the two well water samples having the highest concentrations of diesel range organic compounds. Based on the evidence presented, the authors concluded that the "*data are consistent with a surface-derived source of organic compounds in the study area, possibly from releases of hydraulic fracturing materials near drill sites*."

Notable Features
Drollette et al. (2015) is "*the first study of its kind to evaluate, on a regional scale, different possible mechanistic sources of organic compounds detected in drinking water wells in the Marcellus region using complementary inorganic chemical analyses.*" The authors explored several alternative hypotheses about the potential origin of the chemicals measured in the samples from the drinking water wells.

Missing Elements
Drollette et al. (2015) illustrates many of the difficulties of assessing exposures from UOGD waste waters. In this study, the measured contaminants did not identify UOGD as the unique source, so authors used correlations with proximity to UOGD well pads and roadways to develop a "weight-of-evidence" argument for identifying the source. Release via spills of hydraulic fracturing materials near drill sites was inferred because other plausible releases were not easily seen to be consistent with the data. Specifying how material might be transported from UOGD well pads to drinking-water wells is problematic in essentially all hydrogeological settings, but certainly in an area where migration is through fractured rocks. Transport times from spill sites to wells sampled are long according to standard hydrogeological estimates so the only thing that can be said about the measurement of bis(2-ethylhexyl) phthalate in two drinking water wells is that migration "*would have to occur via some enhanced transport or solubilization process*" (Drollette et al. 2019). Finally, quantifying the routes of exposure and the exposed population would require an even more extensive effort than Drollette et al. (2015) conducted to elaborate on the characteristics of water use by the potentially exposed population as well as to estimate the magnitude, frequency, and timing of exposures.

Box 4-6. Examples of studies that employed useful methods for quantifying a complete water exposure pathway from a UOGD source to a population: *Exposure to UOGD wastewater from well-bore releases to an aquifer*

Background

A potential release mechanism for hydraulic fracturing fluids, flowback water, and produced water is through a compromised (or absent) casing, creating a pathway between a UOGD well and a freshwater aquifer. A several percent frequency of barrier failure in UOGD wells (Davies et al. 2014) implies potential problems in a large number of UOGD wells given that tens of thousands have been constructed. Although stray gas has been detected in the vicinity of wells that have had issues with well integrity (Darrah et al. 2014), only a small number of documented cases of non-methane contamination have been reported in the scientific literature. For example, there have been fewer than 10 cases for the Marcellus Shale through 2017 (Brantley et al. 2018). Consequently, exposure assessments for this release scenario are rare.

Study Summary

Llewellyn et al. (2015) reported a case study in which stray natural gas and a foaming agent were reported to have contaminated several domestic groundwater wells in Pennsylvania following the development of five UOGD wells 1–2 km away. The authors used sophisticated analytical techniques (two-dimensional gas chromatography coupled to time-of-flight mass spectrometry) to detect the presence of organic unresolved complex mixtures at very low detection levels (nanograms per liter) in samples from the affected wells. Low levels of unresolved complex mixtures and the surfactant, 2-*n*-butoxyethanol (known to be used in hydraulic fracturing fluid) were detected in water well samples. Surface casing was installed in the UOGD wells to about 300 meters depth and production casing was used in the Marcellus Shale at depths between 2,100 and 2,300 meters, but at intermediate depths no casing was installed. Hydrogeological patterns indicate that bedding planes, which can facilitate fluid migration, are near the surface at the domestic water wells and dip downward and intersect the UOGD wells between about 180 and 580 meters in depth, that is, in the uncased intermediate section of the UOG wells. The authors indicate that multiple lines of evidence "*implicate fluids flowing vertically along gas well boreholes and through intersecting shallow to intermediate flow paths via bedrock fractures*" as responsible for the contaminant transport.

Notable Features

The study by Llewellyn et al. (2015) addresses the first parts of the conceptual model of exposure (Figure 4-1). Although samples of the drilling fluids and flowback water for the implicated gas wells were not available, the measurements were consistent with flowback and production waters from other similar unconventional gas wells in Pennsylvania, therefore the source identification is reliable. Release due to pressurization in the borehole is documented. Also, the hydrogeological setting is reasonably well characterized so the identified transport pathway — "*stray natural gas and drilling or HF compounds were driven ~1–3 km along shallow to intermediate depth fractures to the aquifer used as a potable water source*" — is supported by evidence.

Missing Elements

This study demonstrates a need for representative source data from fluid or mud samples from wells and other data that could strengthen conclusions about potential sources of contamination. Additionally, the full exposure pathway for a broad population cannot be covered by a single case study, especially one subject to limited available data to connect a specific source to the affected wells. Given that more than 10,000 UOGD wells have been drilled in Pennsylvania over the past ~15 years, there is a need for systematic documentation of contamination events such as that explored by Llewellyn et al. (2015) and of levels of contamination in drinking water supplies that may result. For example, Wen et al. (2018) analyzed a large methane data set for one region in Pennsylvania and concluded that slightly elevated concentrations occur near 7 out of the 1,385 shale-gas wells in the region studied. Such analyses might form the basis for more detailed work to investigate whether the elevated methane concentrations are indicators of contamination by wastewater from UOGD and thus are candidates for future research to understand possible water-related exposure pathways.

4.4 SOIL AND SEDIMENT EXPOSURE PATHWAYS

4.4.1 Summary of Studies – Soil and Sediment Exposure Pathways

Few studies have investigated potential UOGD impacts on the quality of soil and sediment that could lead to human exposure. Studies aimed to improve understanding of the mobility and impacts of UOGD-related chemicals in soil (Lyman et al. 2017; Oetjen et al. 2018), measure soil quality impacts from use of produced water to treat roads (Tasker et al. 2018), or quantify sediment quality impacts from discharge of treated produced water to surface water (Skalak et al. 2013; Van Sice et al. 2018). A small body of literature has focused on the potential impacts on food; Bamberger and Oswald (2012, 2014, 2015) interviewed owners of animal farms that are near UOGD about the health of their herds and flocks.

4.4.2 UOGD Sources and Potential Release Mechanisms – Soil and Sediment Exposure Pathways

Soil and sediment contamination from UOGD operations can occur through accidental spills on the well pad or during fluid transport and unauthorized disposal off the well pad (Konkel 2016; Pichtel 2016). Contamination may also occur via casing failure in the wellbore or pipelines, leaks from impoundments, or from produced water reuse for crop irrigate or road de-salting if not properly treated (Al-Ghouti et al. 2019; Shonkoff et al. 2016).

Migration from Soil to Other Media. Contamination in soil can migrate to other media, such as groundwater, surface water, or air, such that exposure occurs via these other media. Two studies examined the mobility of UOGD-related chemicals in soil using lab-based (Oetjen et al. 2018) and field-based methods (Lyman et al. 2017). Oetjen et al. (2018) used bench-scale soil columns to simulate a spill of hydraulic fracturing wastewater from a well in Greeley, Colorado onto agricultural soil under environmental conditions relevant to the region. Investigators reported that copper, lead, magnesium, and iron were mobilized. No surfactants or their transformation products were detected in leachate samples from the experiment, suggesting that they do not travel far from the initial spill location under the experimental conditions.

Lyman et al. 2017 compared fluxes of methane, non-methane VOCs, and carbon dioxide from soil on gas well pads with production, storage, and shut-in equipment with fluxes from soil located in areas without UOGD in the Uinta Basin of Utah. The investigators reported that hydrocarbon fluxes exhibited spatial variability within a single well pad, but the majority of the time the fluxes were higher than the average flux from undisturbed soils. Hydrocarbon fluxes within 2.5 meters of the wellhead were lowest at producing wells and highest at shut-in wells. They concluded that the majority of emission fluxes were likely attributable to raw gas migrating from the subsurface to the atmosphere, with the rest resulting from spilled liquid hydrocarbons.

Reuse of UOGD wastewater. Individual states are considering options for produced water reuse, especially in water-stressed regions of the United States, such as New Mexico and Oklahoma (State of New Mexico and U. S. Environmental Protection Agency 2018; U.S. Environmental Protection Agency 2019c). Produced water represents a complex chemical mixture (Danforth et al. 2020), and its reuse can potentially impact soil or sediment quality or reach other media such as groundwater or nearby surface water bodies, thereby providing multiple possible exposure pathways. The U.S. EPA (2019c) is currently conducting a study to summarize options for wastewater management from both conventional and unconventional oil and gas development and to gather the perspectives of different stakeholders (e.g., oil and gas industry, environmental nongovernmental organizations, academics, and state regulators) about current practices and potential regulatory changes to expand wastewater management options. Because reuse and recycling of produced water from UOGD outside of oil and gas production sites (e.g., road

treatment and crop irrigation) is not prevalent nationally, opportunities to collect data or analyze existing data are sparse.

Tasker et al. (2018) analyzed state-level regulation about wastewater reuse and analyzed the chemical composition of samples of wastewater from 14 Pennsylvania townships that was intended to be spread on roads. Oil and gas road-spreading data revealed that 35 million and 5 million liters per year of wastewater was spread on Pennsylvania and Ohio roads, respectively, primarily from conventional wells. Using these data, the investigators simulated multiple road spreading and runoff events in lab experiments focused on radium retention in the road material. They reported increases in radium concentrations in soils around roads following simulated spreading and rain events that did not exceed regulatory standards but that were higher than concentrations from wastewater treatment facilities and spills. Skalak et al. (2013) investigated soil impacts from road spreading, reporting that areas that used brines from conventional oil and gas wells for road deicing saw an accumulation of radium-226, as well as extractable strontium, calcium, and sodium in sediment near the roads.

Sediment quality and surface water discharges. Skalak et al. (2013) evaluated the potential for accumulation of alkali-earth elements in the sediment of streams used for surface disposal of produced waters following treatment. The investigators collected surface sediment grab samples upstream and downstream of five publicly owned treatment works (POTWs). The investigators reported no increase in concentrations of total radium (radium-226) and extractable barium, calcium, sodium, or strontium in downstream sediments.

Van Sice et al. (2018) leveraged a 2011 request from the Pennsylvania Department of Environmental Protection that operators recycle rather than treat and discharge UOGD wastewater from centralized waste treatment facilities to determine whether the radium loading to streams decreased. The investigators reported that the voluntary request coincided with a decrease in radium loading to the study stream by approximately 95% between 2011 and 2017.

4.4.3 Potentially Exposed Populations – Soil and Sediment Exposure Pathways

4.4.3.1 Relevance of Information for Quantifying Exposure

Studies of potential UOGD impacts on the quality of soil and sediment did not endeavor to establish a connection between UOGD and a specific population.

4.4.3.2 Characteristics of Potentially Exposed Populations

Studies of potential UOGD impacts on soil and sediment quality did not identify characteristics of populations potentially exposed to chemicals released from UOGD via the soil and sediment pathway.

4.4.4 Concluding Remarks – Soil and Sediment Exposure Pathways

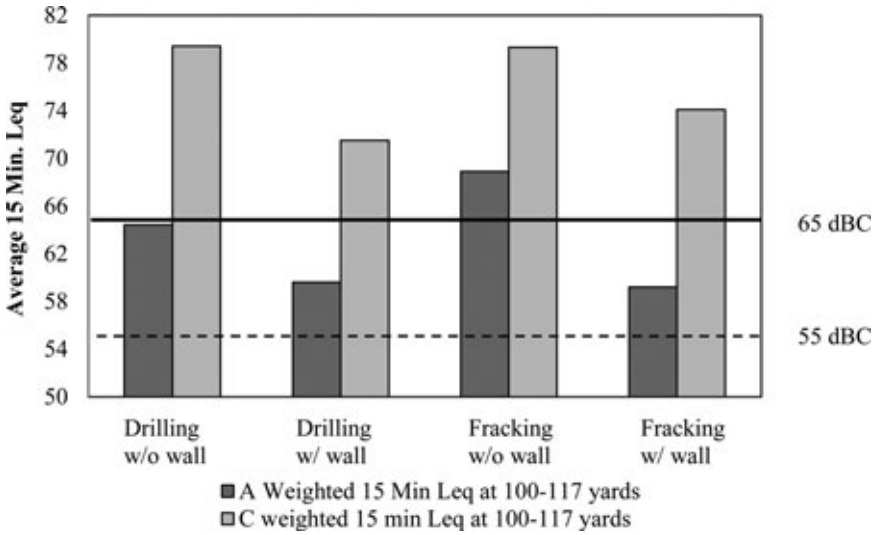
The literature describes how contamination of soil, sediment, and agricultural products might arise. Studies evaluating soil and sediment quality impacts focus on specific incidents or conditions and were not broadly generalizable to other locations and operational conditions. In addition, studies did not include information about potentially exposed populations. Investigators of the studies recommended further research to understand factors that influence chemical mobility in soil (Echchelh et al. 2018; Shariq 2013), particularly as more options of produced water reuse are explored (U.S. EPA 2019c).

4.5 UOGD Noise, Light, and Odor

4.5.1 Summary of Studies – Sensory Exposure Pathway

Several studies have included measurements of exposure to sensory agents[1] from UOGD processes. Five involved noise monitoring (Blair et al. 2018b; Boyle et al. 2017; Lorig 2016; Radtke et al. 2017; Richburg and Slagley 2018), one involved noise and light monitoring (McCawley 2013), and one involved noise, traffic count, and air quality monitoring (Allshouse et al. 2019). All were conducted in either the Denver-Julesburg basin (Allshouse et al. 2019; Blair et al. 2018b; Radtke et al. 2017) or the Marcellus region (Boyle et al. 2017; Lorig 2016; McCawley 2013; Richburg and Slagley 2018). Sampling was conducted at various distances from the well pad (McCawley 2013; Radtke et al. 2017), using area monitoring (Lorig 2016) outdoors on residential property (Blair et al. 2018b) both indoors and outdoors at residences (Boyle et al. 2017), or at a combination of residential and area sampling (Richburg and Slagley 2018). Three studies (Blair et al. 2018b; Boyle et al. 2017; Richburg and Slagley 2018) used samples collected during the day and night, capturing diurnal variation in noise levels.

Figure 4-12. Measured sound levels at drilling and hydraulic fracturing sites with and without sounds walls. (Source: Radtke et al. 2017. © American Industrial Hygiene Association and American Conference of Governmental Industrial Hygienists. Used by permission of Taylor & Francis Ltd. on their behalf.)



Notes:
- Leq: continuous sound pressure level
- dBC: c-weighted decibel level

Radtke et al. (2017) conducted noise monitoring at 23 oil and gas sites in Northern Colorado at various distances from drilling, hydraulic fracturing, and completion sites that varied in their use of noise barriers. Investigators found that noise barriers were effective in dampening noise within 350 feet (Figure 4-12); however, the measured reduction was not sufficient to reduce noise levels below the residential permissible noise standard in Colorado (55 A-weighted decibels [dBA]).

Two studies included measurements of multiple types of exposure. Allshouse et al. (2019) measured 1-minute average A-weighted noise levels (audible to the human ear) and C-weighted noise levels (low frequency sound pressure). These investigators also measured concentrations of $PM_{2.5}$ and black carbon in air (see Section 4.2) at four Colorado residences located northeast, south, northwest, and east (between 217.9 and 392.6 meters) of the sound wall surrounding a 22-well pad. Traffic counts were also measured near one of the sampling locations. Sampling occurred over a one-year period (2017–2018) at two of the residences during drilling, hydraulic fracturing, flowback, and production phases. Sound levels varied

[1] Sensory agents include noise, vibration, light, and odor. Odors arise from chemicals in the air, but for the purposes of this report, we discuss this exposure separately.

depending on sampling location and time of day. Continuous A-weighted noise levels exceeded 50 dBA (World Health Organization's community noise guidelines) during hydraulic fracturing, flowback, and production phases and C-weighted noise levels exceeded 65 C-weighted decibels (dbC) over all phases. Investigators also found that noise exceedances occurred during higher traffic counts, which occurred during hydraulic fracturing (average 8.9 and 8.5 heavy trucks/hour during the day and night, respectively) and flowback (average 13.5 and 6.6 non-heavy trucks/hour during the day and night, respectively). McCawley et al. (2013) measured both light and noise at six residential and non-residential sites near wells reflecting different operating conditions and obstructions to residential exposure (e.g., residences in a valley and with or without foliage).

Boyle et al. (2017) and Blair et al. (2018b) measured noise levels in West Virginia and Colorado residences, respectively. Boyle et al. (2017) compared 24-hour indoor and outdoor measures of noise in eight homes within 750 meters of the nearest compressor station, and three control homes more than 1000 meters from the nearest compressor station. Geometric mean outdoor and indoor noise levels were higher in the exposed homes than the control homes. The differences between indoor noise levels in exposed versus control homes were 13.1 dBA during the day and 9.4 dBA at night. Blair et al. (2018b) measured noise at four Colorado residences between 320 and 550 meters from a multi-well site permitted for 22 wells. Monitoring was conducted during construction and drilling over three months. The authors noted that, overall, 41.1% of daytime and 23.6% of nighttime dBA 1-min equivalent continuous noise measures exceeded 50 dBA.

Richburg and Slagley (2018) measured noise at a residence and a community near a well pad and in a community near a compressor station. Dosimeters were used to record day–night levels of 53.5–69.4 dBA outside and 37.5–50.1 dBA inside, which the investigators noted exceeds U.S. EPA guidelines.

Lorig (2016) is the only noise modeling study to date. Investigators used pre-existing noise measurements taken near compressor stations to model noise across the Pennsylvania state forests in the Marcellus region. Modeling allowed the investigators to understand how noise from compressor stations disperses under different conditions and to identify natural barriers (e.g., basins or valleys) that dampen noise.

4.5.2 UOGD Sources and Potential Release Mechanisms – Sensory Exposure Pathway

Noise is present on the well pad during the development phase, beginning with site preparation. Noise — along with light — continues after site preparation, occurring from 24 hours a day, 7 days a week to intermittently, during the drilling and hydraulic fracturing phases, depending on local requirements and operator practices. Flaring is another source of noise, along with on-pad truck traffic, diesel and natural gas engines powering generators, drill rigs, pumps required for hydraulic fracturing, and other machinery. According to a study conducted by the New York State Department of Environmental Conservation (NYSDEC) artificial lighting from operations can intrude into homes and may be especially intense during flaring operations (New York State Department of Environmental Conservation 2015). Malodorous compounds, such as H_2S and some VOCs, can be emitted during the development phase (Colorado Department of Public Health and Environment 2016; McCawley 2013; New York State Department of Health 2014; Pennsylvania Department of Environmental Protection 2010).

Light, noise, and odor can continue on the well pad during the production phase. Flaring also produces noise and light. Compressors can produce continuous noise that in some instances has exceeded state maximum allowable noise limits at fence line distances (Maryland Institute for Applied Environmental Health 2014). Similarly, malodorous compounds (e.g., H_2S) have been measured near well pads during the production phase (Eapi et al. 2014; Pennsylvania Department of Environmental Protection 2010).

Like chemical measurements, sensory agents have sources other than UOGD, such as conventional oil and gas operations and local construction projects. Hays et al. (2016) discussed temporal factors (e.g., length of activity phases) that can help distinguish noise derived from conventional oil and gas development and UOGD. However, the studies using measurements of noise did not discuss whether the noise measurements were unique to UOGD activities.

4.5.3 Potentially Exposed Populations – Sensory Exposure Pathway

4.5.3.1 Utility of Information for Quantifying Exposure

The studies conducted to date involved sample sizes consistent with pilot studies. Studies with larger samples across a variety of landscapes would be helpful to assess temporal and spatial variability of these exposures for specific populations, with Allshouse et al. (2019) providing a useful example with noise, $PM_{2.5,}$ and black carbon monitoring during multiple well development phases at varying directions from the pad. Although the noise studies are a relatively small body of literature, they included measurements of concentrations in outdoor air of communities and indoor air of residences, reflecting conditions where people are exposed. Some investigators also designed their studies to compare noise levels among different mitigation techniques, which is helpful to understand how noise exposure varies as a function of these techniques.

4.5.3.2 Characteristics of Potentially Exposed Populations

Two of the studies included samples taken from inside residences, but did not report on characteristics of the residents, particularly their sensitivity to noise (Boyle et al. 2017; Richburg and Slagley 2018). Richburg and Slagley (2018) interviewed residents about their sleep quality and perception of the impact noise was having on their health but did not conduct any quantitative analyses to understand relationships between noise and reported health concerns.

4.5.4 Concluding Remarks – Sensory Exposure Pathway

The current body of literature on sensory exposure potentially attributable to UOGD is spatially and temporally limited. Some work is underway to monitor noise and odor complaints in communities, which may be of value to future research (e.g., Colorado Department of Public Health and Environment Oil and Gas Information Response Program). However, in general, the available studies provide evidence that noise levels can exceed maximum permissible levels for residential areas and that sound wall barriers do not effectively block all forms of noise. In addition, some states allow a higher maximum permissible noise level during some activities, such as pipeline or gas facility installation or maintenance, drilling, and hydraulic fracturing. It is not clear how well these few studies reflect the reality of sensory exposures experienced across regions, with or without mitigation measures. The available literature does not address factors related to in-home mitigation techniques, sensitivity of residents to sensory exposure, and the presence of vulnerable populations in residences experiencing sensory exposure attributable to UOGD. In a review of the noise literature, Hays et al. (2016) noted the relative paucity of the research, the diversity of noise types (e.g., intermittent versus continuous, levels of intensity, and high versus low frequency), and the importance of considering subpopulations of individuals with noise sensitivity.

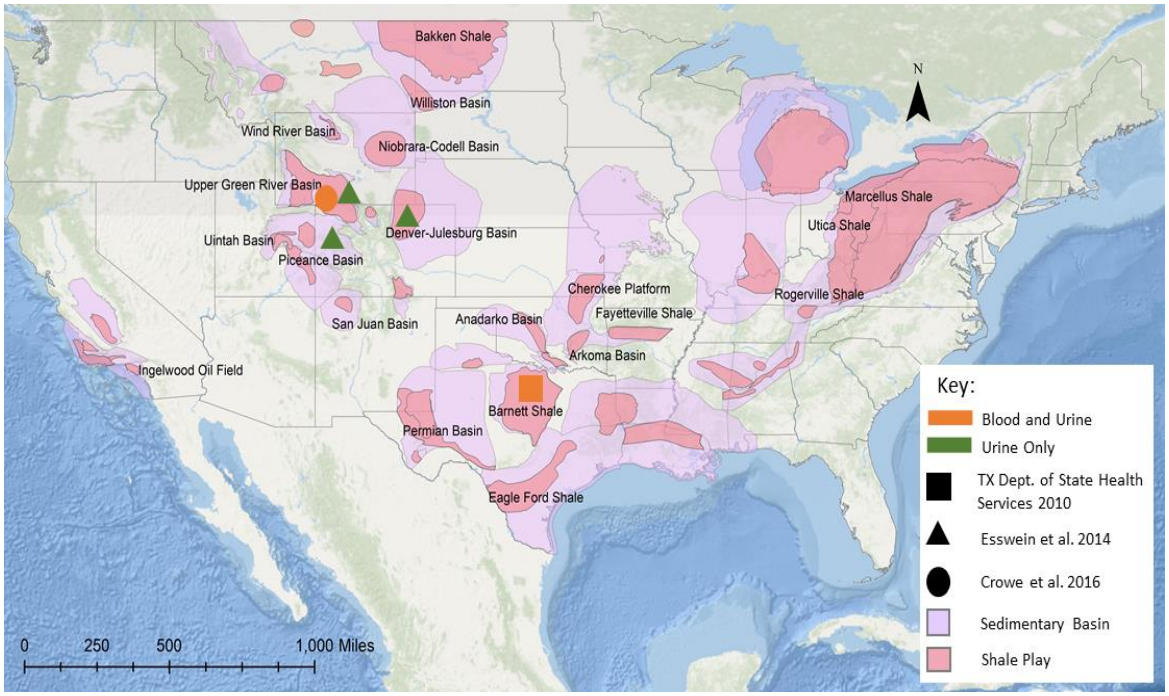
4.6 EXPOSURE BIOMONITORING

4.6.1 Summary of Studies

Five studies reported biomonitoring results for human exposure to VOCs as measured in blood, urine, or hair (Figure 4-13; Caron-Beaudoin et al. 2018, 2019; Crowe et al. 2016; Esswein et al. 2014; Texas Department of State Health Services 2010). A summary description of biomonitoring is provided in Box 4-7.

In Caron-Beaudoin et al. (2018), participants collected five urine samples over a 5-day period, but no information was provided on time of day or participant activities prior to the time of sampling. Therefore, it is not known whether the sample concentrations were impacted by activities such as smoking, workplace exposures, driving, pumping gas, etc. The same research group performed a second study in which they measured trace metals in five spot urine (pooled for analysis) and hair samples collected from 29 Indigenous and non-Indigenous pregnant women living in Canada in proximity to UOGD (Caron-Beaudoin et al. 2019). Investigators collected additional information on lifestyle factors (e.g., smoking habits) and sociodemographic information and compared concentrations between the study population to the general Canadian population.

Figure 4-13. Number of biomonitoring studies.



Note: Two additional biomonitoring studies, Caron-Beaudoin et al. 2018 and Caron-Beaudoin et al. 2019, collected urine samples in Canada in communities proximate to UOGD operations. These studies are not depicted on this map.

In response to citizen concerns, the Texas Department of State Health Services (Texas Department of State Health Services 2010) collected urine, blood, and tap water samples from 28 residents of DISH, Texas during a one-time sampling event to determine whether VOC concentrations were in the fifth percentile of U.S. population (using National Health and Nutrition Examination Survey data) values. Investigators also collected field observations of odor, noise, and presence of nearby well pads, storage equipment, and compressor stations. Additionally, the study included staff who provided blood and urine samples before visiting residences located near compressor stations and gas wells (at the Austin

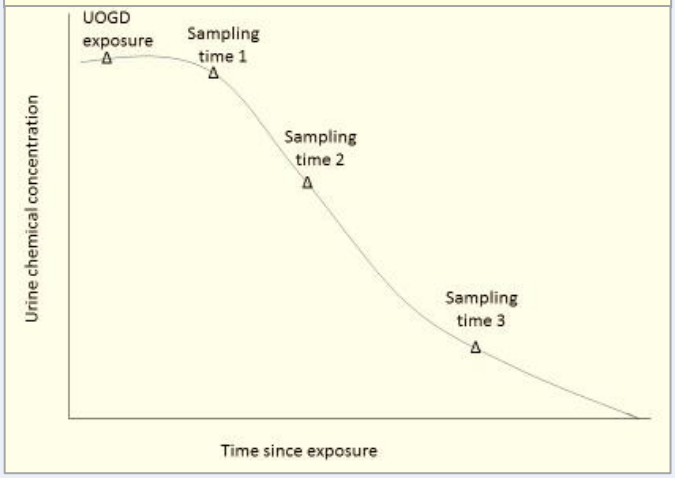
headquarters where there is no exposure to UOGD) and then again after spending 2 to 3 days in DISH, Texas (where UOGD is widespread). This longitudinal approach could potentially be useful for identifying populations exposed to oil- and gas-related chemicals; the study, however, found no difference in VOC levels before and after the site visit.

Box 4-7. Brief Explanation of Biomonitoring

As evidenced by this review, the body of literature examining human exposures to UOGD-related chemicals is extensive and includes models and measurements for estimating intake of chemicals via inhalation and ingestion (with limited studies involving the dermal route of exposure among UOGD workers). To estimate exposure using chemical concentrations in environmental media (e.g., air, water, and soil), these data can be evaluated alone or in combination with intake rates (e.g., volume of air breathed per day, liters of water consumed per day); this is referred to as external exposure. Another approach that is used by scientists to estimate human exposures is biomonitoring, defined as a "…method for assessing human exposure to chemicals by measuring the chemicals or their metabolites in human tissues or specimens, such as blood and urine" (National Research Council 2006). Thus, biomonitoring is an internal measure of exposure.

Biomonitoring is a powerful method for quantifying exposure, but it is worth noting a few important and well-known issues that must be considered when designing and evaluating studies based on biomonitoring (LaKind et al. 2014). First, biomonitoring provides an estimate of internal dose, and therefore it integrates all routes of exposure. Although the incorporation of all routes of exposure is advantageous, a related disadvantage is that this approach does not allow one to distinguish among routes of exposure and so one cannot determine whether, for example, chemical exposure via inhalation or ingestion predominates. Similarly, biomonitoring cannot distinguish among sources of chemical exposure unless the chemical and its metabolites are unique to one source.

Hypothetical decline in urinary concentration with time as the body metabolizes and excretes a chemical. *Graphic by Judy LaKind.*



Second, many UOGD-related chemicals (e.g., VOCs) have short-physiological half-lives; that is, they remain in the body for short periods of time (perhaps hours to days) before they are metabolized and excreted, generally in urine. Therefore, the chemical concentration measured in a sample of urine may not reflect actual exposures to UOGD-related chemicals. This is illustrated in the hypothetical decline curve below. In this case, the blue curve represents the urinary concentration of a UOGD-related chemical over time; as the body metabolizes and excretes the chemical, the concentration decreases. It is clear, then, that as the time between exposure and urine sampling increases, biomonitoring will capture a smaller fraction of the actual exposure.

Third, chemicals measured in human media such as urine are often metabolites — or break-down products of the compound — to which the person was exposed (the parent compound). For example, the body metabolizes benzene (parent compound) to phenol, trans,trans-muconic acid (t,t-ma), and other metabolites. Because different parent compounds can break down to similar metabolites, it can be difficult or impossible to identify the specific parent compound.

Fourth, in a typical population, the metabolism or rate of metabolism of some chemicals may vary widely depending on genetic variation between individuals or the up- or down-regulation of genes induced by medication, certain nutrients, and other factors. Methods for accounting and adjusting for such variation remain limited.

In Crowe et al. (2016), investigators collected 27 blood and urine samples from 11 participants over a 7-day period and measured for VOCs. An advantage of this study is the simultaneous collection of stationary air samples at various locations including downwind from the well pads and personal air monitoring of people living downwind from UOGD operations. Biomonitoring samples were collected approximately 4 hours after air samples were collected to identify potential sources. Although participants were asked to avoid activities that might expose them to VOCs from sources other than oil and gas development, information on compliance with this request was not provided.

Esswein et al. (2014) collected urine samples from UOGD workers at six completion sites in Colorado and Wyoming during flowback operations. The investigators noted the participants' job at each site (e.g., flowback lead, flowback tech, production watch lead, production watch technician, and water management operator) in order to investigate how worker exposure varied among different aspects of the completion process. Personal breathing zone sampling was also conducted for workers who participated in the biomonitoring portion of the study. Like other biomonitoring studies in this body of literature, Esswein et al. (2014) did not correct the results of the analysis for smoking or other non-occupational exposures to BTEX.

4.6.2 Distinguishing UOGD Sources in Biomonitoring Studies

The importance of understanding the quantitative linkages between exposure, dose, and biomarker levels has been described (LaKind et al. 2014). However, for many VOCs, including some of those included in the publications reviewed here, these linkages are subject to many uncertainties. For example, there is research indicating inter-individual variability in the rate at which people metabolize benzene to trans,trans-muconic acid (t,t-MA), which is one of the urinary compounds measured as part of two of the studies), which can affect its utility as an exposure metric for benzene (Gobba et al. 1997). Thus, t,t-MA may not be a reliable marker for benzene exposure (Jalai et al. 2017). Similarly, urinary hippuric acid (measured in the Crowe et al. study) may overestimate toluene exposure as other factors such as coffee, tea, fruit, and vegetable intake influence urinary hippuric acid levels (Munaka et al. 2009; Penczynski et al. 2017). Future studies will need to include biomarkers that can accurately describe exposures to parent compounds.

Although VOCs are important components of UOGD-related chemicals, many other important sources of VOCs exist, such as conventional oil and gas activities, traffic exhaust, smoking, fires, personal care products (such as nail polish), occupational exposures, and — in the case of Caron-Beaudoin et al. (2018) — a gas plant. This issue was clearly acknowledged in the report by the Texas Department of State Health Services (Texas Department of State Health Services 2010), which found higher levels of cigarette-related VOCs in the blood and urine of smokers and which also describes various non–oil and gas sources of VOC exposures.

Three of the studies (Caron-Beaudoin et al. 2018, 2019; Crowe et al. 2016) were not designed to distinguish between UOGD and various additional sources of VOCs, including conventional development. Similarly, Esswein et al. (2014) did not attempt to distinguish between other UOGD occupational sources of VOC exposure on the well pad (trucks, compressors, etc.). The study by the Texas Department of State Health Services included questionnaire-derived information on participant activities that may impact internal VOC levels. Further, samples were collected over a short time period (days) and did not capture meteorological, diurnal, or seasonal variability in exposure, nor changes in UOGD operations.

4.6.3 Potentially Exposed Populations – Biomonitoring Studies

Utility of Information for Quantifying Exposure – Biomonitoring Studies. Biomonitoring studies will not be able to distinguish between a population that may be exposed from different exposure pathways unless a chemical is specific to one or the other of those media. In order to assess specific exposure pathways of concern, a biomonitoring approach would need to be paired with environmental measures or models. Three studies — Crowe et al. (2016), Esswein et al. (2014), and Texas Department of State Health Services (2010) — did collect air or water samples in parallel with biological samples. The collection of breathing zone samples from personal monitors attached to study participants in Esswein et al. (2014) allowed the investigators to compare biological sampling results to human-specific exposure via the inhalation pathway.

For the four studies under review, it is important to note that in order to understand exposures fully, information is needed on many factors including work and non-work activities, personal proximity to UOGD activities, as well as diet and other possible influences on VOC exposures. The studies addressed this data gap as a limitation of their analyses. Further, because concentrations of non-persistent chemicals generally vary widely from day to day, the generalizability of a measurement from a single sample (in other words, whether the measurement from a single person represents exposures to a larger population) is unknown.

Potentially Exposed Populations. Given the ubiquitous nature of many of the chemicals measured (e.g., benzene, toluene), it is difficult to distinguish between populations exposed to UOGD chemicals and the general population. If a chemical specific to UOGD is identified that could be measured in human media such as blood or urine, it might be a useful marker for UOGD-related exposure.

4.6.4 Concluding Remarks

Although biomonitoring research is a promising avenue for exploring internal exposure, there are many challenges associated with biomonitoring studies that make them technically and financially difficult to execute, especially in the context of UOGD exposure. The limited body of biomonitoring literature related to UOGD exposure indicates that future biomonitoring studies should focus on finding and testing markers specific to UOGD exposure if they exist.

4.7 SUMMARY OF THE LITERATURE

The Committee searched for literature to address its survey question, *What is known about potential UOGD-related human exposures?* As implicated by the survey question, the Committee's goal was to survey the literature to identify the state of the science of understanding human exposures to UOGD-related chemical and non-chemical agents.

4.7.1 Conceptual Framework for the Literature Survey

Understanding human exposures to UOGD-related chemicals and other agents represents a complex undertaking (see Box 1-2). UOGD processes involve a multitude of agents (e.g., chemicals, light, and noise) released to the environment in a variable manner over time and location. The releases may impact levels of the agents in multiple media (i.e., air, water, or soil), with varying impacts observed at the site of emissions over space within a region, and among regions. Impacts vary due to differences in shale plays, level of operations, and operator practices among other factors. Furthermore, variation in time–activity-location patterns (e.g., time spent at residential versus work locations and indoor versus outdoor locations) among potentially exposed populations complicates quantifying human exposures to agents originating from UOGD. The Committee conducted their survey of the literature within a conceptual framework of exposure, identifying exposure pathways leading from UOGD sources to populations (Figure 3-2).

4.7.2 Strengths of the Literature in Assessing Human Exposure to UOGD

The literature search returned hundreds of studies that have been conducted to understand the environmental impacts associated with UOGD. The majority of publications focused on levels of agents in air, with studies conducted across major shale play regions. Many publications also focused on levels of agents in water (mostly in the Marcellus region), and fewer characterized other environmental media (e.g., soil) or sensory agents.

Overall, the studies contained useful information for understanding human exposures, including those conducted without this specific goal. The studies helped to characterize UOGD-related human exposures by contributing to our understanding of atmospheric and hydrological conditions that affect fate and transport of UOGD agents through the environment, the relationship between operations and types or levels of emissions, and pathways of potential exposures. In addition, some investigators were resourceful in their use of previously published data, such as air quality data collected as part of state monitoring programs.

Investigators used a wide array of methods to assess potential environmental impacts and human exposures associated with UOGD. Some investigators used methods that were useful for isolating UOGD sources. Some measured emissions on well pads and used the data, along with meteorological and topographical data, to analyze air quality changes over space and time. Studies sometimes involved the use of various tracers or markers to estimate the levels of agents in air or water that were attributable to UOGD. Other investigators assessed the chemical concentrations before, during, and after UOGD activities, enabling an evaluation of potential impacts specific to those activities.

Studies of greatest utility for addressing the Committee's guiding question were those that shed light on spatial variability of agent concentrations (e.g., by sampling at various distances from a well pad) and temporal variability (e.g., by sampling over multiple sampling periods during a variety of UOGD activities, meteorological conditions, seasons, and times of day).

A subset of studies was conducted with the aim of characterizing human exposure to chemicals, noise, and light. To do so, investigators collected samples in areas where people spend much of their time, including air sampling in residential communities and water sampling of drinking-water wells. Some studies involved affected communities through discourse and participation, thereby providing results to the affected communities and benefiting from local knowledge. In addition, some state agencies conducted air sampling in response to community concerns.

4.7.3 Knowledge Gaps about Human Exposure to UOGD

The quantity of data on levels of UOGD-related agents in the environment continues to increase along with efforts to use the data to quantify human exposure. Nevertheless, important gaps remain in our understanding of who might be exposed, how exposures might arise, how exposures vary over time and across regions, and the likelihood of exposure.

Few studies provided the information necessary for linking environmental concentrations of agents to specific UOGD-related sources (e.g., diesel-powered equipment) or to distinguish between contributions from UOGD and other sources, such as conventional oil and gas development. In addition, the generalizability of study results to UOGD operations, geographic areas, and populations beyond those investigated in the studies is not clear.

Given the current state of knowledge on UOGD and potential exposures, the Committee recommends further investigation to improve understanding of human exposures to UOGD. The research should be

designed to support decision-making by community members, public health officials, regulators, oil and gas operators, and others about how to protect human health.

4.7.4 Opportunities for Future Reviews

This literature survey serves as a planning document to inform the Energy Research Committee's development of a research solicitation to fill knowledge gaps about potential community exposures and health impacts from UOGD. Many opportunities exist to build on this review. For example, there are opportunities to review baseline water quality and air quality monitoring data collected by the oil and gas industry, but which are not publicly available and would have not turned up in the electronic search employed for this review. There is an additional need for reviews that focus on literature covering specific regions, agents of concern, or time periods. Future reviews would additionally benefit from detailed quality assessments of measurement and modeling studies.

5.0 PLANNING FOR EXPOSURE RESEARCH

This section summarizes the Committee's early planning for research to address knowledge gaps about potential UOGD-related human exposures, and the principles that will guide its preparation of a Research Solicitation and review of proposals submitted in response.

5.1 KNOWLEDGE GAPS FRAMED AS RESEARCH QUESTIONS

The Committee identified gaps in knowledge about UOGD exposures (Table 5-1), framed within a conceptual model of exposure that links a UOGD source to a potentially exposed population. These knowledge gaps derived from the review of literature, supplemented by input from a range of stakeholders from communities, government, industry, nongovernmental organizations, and academia. Stakeholder consultations were important given that UOGD practices and regulation continue to evolve as do concerns in response to these changes, and much of this information is not in the scientific literature.

In defining the research questions, the Committee also looked at a variety of ways to identify research valued by local communities (Brasier et al. 2011; Korfmacher et al. 2014; Krupnick and Siikamäki 2014; Perry 2013; Schafft et al. 2014). The goal was to define research that, when implemented, would provide the knowledge needed to answer the most important questions about potential UOGD exposures.

The Committee recognizes that the research questions are not necessarily of equal importance nor do they fully encompass all worthy research topics. Although the questions individually represent different components of the conceptual model, an ideal future research project would document the elements of an exposure pathway to determine whether a specific UOGD agent reaches a specific population.

Table 5-1. Knowledge gaps framed as example research questions

UOGD SOURCES
1. How do the characteristics (i.e., the likelihood, composition, magnitude, frequency, and duration) of potential environmental releases from UOGD vary over space and time as a function of differences in the geological formations, meteorology, and variable practices among operators, across phases of development, or in response to technological innovation, changing regulations and guidance, and community concerns?
2. **a.** What is the relative contribution of operational, accidental, and unauthorized releases to environmental concentrations of UOGD agents[1] in air? How might they contribute disproportionately to total emissions? How can emissions from individual UOGD processes be best quantified? Can measurements of the release of methane or other chemicals be used to help inform estimating non-methane emissions associated with UOGD operations? How can we use longer term observations (e.g., routine ground-based and satellite, including flares) observations to estimate historical trends in emissions? **b.** What is the relative contribution of operational, accidental, and unauthorized releases to environmental concentrations of UOGD agents in surface water and groundwater?
RELEASE MECHANISMS AND TRANSPORT PATHWAYS
3. **a.** How does variation in regional conditions (e.g., meteorology and topography) affect the levels of UOGD agents in air over various temporal scales (e.g., hourly, diurnally, and seasonally) as a result of chemical transformation and transport? What methods are available to characterize the fate and transport of UOGD releases to the air? **b.** How does variation in regional conditions (e.g., topography, geochemistry, geophysics, and hydrology) affect the levels of UOGD agents in water over various temporal scales (e.g., hourly, diurnally, and seasonally) as a result of chemical transformation and transport? What methods are available to characterize the fate and transport of UOGD releases to water? **c.** To what extent does UOGD contribute to increased levels of noise, light, and vibration within and across regions and operations?

Table 5-1. Knowledge gaps framed as example research questions

4.	**a.** How can levels of UOGD agents in air be distinguished from levels contributed by other natural and anthropogenic sources? What is the relative contribution of air emissions from UOGD to local and regional concentrations? **b.** How can levels of UOGD agents in water be distinguished from levels contributed by other natural and anthropogenic sources? What is the relative contribution of water releases from UOGD to local and regional concentrations?
POPULATIONS	
5.	What are the characteristics[2] of populations potentially exposed to UOGD agents at local and regional scales?
6.	Which population behaviors (e.g., time–activity patterns) influence the potential for exposure to UOGD agents? To what extent do exposures to UOGD agents differ among individuals within and among exposed populations?
7.	How can exposure monitoring methods (e.g., study design, instrumentation, and other technologies) accurately characterize total personal and population-wide exposures to UOGD over time and space?

[1]UOGD agents might be released to the environment as:
- Operational releases: In accordance with applicable regulations (e.g., permitted discharges to surface water, equipment emissions to ambient air, and vehicle emissions),
- Accidental releases: As a result of poor practices (e.g., improper waste disposal, accidental releases, and explosions), or
- Unauthorized releases: As a result of illegal activities (e.g., unapproved disposal of waste materials).

[2]Population characteristics include numerous factors, such as age, sex, race, ethnicity, socioeconomic status, health status, size of the population, activity patterns, and other factors.

The following series of tables elaborates on each of the research questions in Table 5-1. Each box includes one of the research questions, background information that briefly explains its importance, and example research activities to address the question. The examples are provided to illustrate how the research question might be addressed but are not intended to limit the scope of research.

5.1.1 UOGD Sources

Topic:	Source – Characterization
Question:	**1. How do the characteristics (i.e., the likelihood, composition, magnitude, frequency, and duration) of potential environmental releases from UOGD vary over space and time as a function of differences in the geological formations, climate, and variable practices among operators, across phases of development, or in response to technological innovation, changing regulations and guidance, and community concerns?**

Background: Much effort has been directed toward understanding the chemical and non-chemical agents that might be released to the environment from UOGD operations. Examples include the characterization of drilling fluid, hydraulic fracturing fluid, flowback, produced water, and solid waste composition; emissions and air quality impacts; releases to water and water quality impacts, and sensory impacts. Although the identity and toxicity of some chemicals used in and released during UOGD operations are known, some reporting of chemicals remains proprietary, leaving gaps in knowledge about the composition and toxicity of chemical releases to the environment and their transformation under high temperature and pressure. There is also limited understanding of the spatial and temporal variability in the magnitude and composition of releases across oil and gas-producing regions of the United States. This information is important for understanding the significance of human exposures that might occur.

Numerous spatial and temporal considerations exist in the types of chemicals used and released during UOGD operations (Section 2). Variation among state regulations regarding all aspects of UOGD may exist (Zirogiannis et al. 2016) and should be considered in designing exposure studies. Operator and service company approaches during drilling and completion operations and a company's ability to effectively monitor and respond to releases when they occur might influence the potential releases to the environment. For example, air-related exposures are subject to many variables; one example is how operators manage gas associated with oil production (e.g., by using it in on-site equipment or flaring to the atmosphere). The same is true for water-related exposures. With the exception of those required by regulation, most trends in UOGD operations are adopted over a period of time as new practices gain acceptance by operators, and they are not necessarily documented. The UOGD industry has changed practices over time in response to new understanding of health, safety, and environmental practices; regulatory changes; and technological changes. An understanding of these changes over time and differences among regions is important to understanding how and where exposures might arise.

The increasing use of produced water in hydraulic fracturing is an example. Water recycling and reuse differs among the shale plays, in part, because the quality of produced water varies and because of varying regulations, requiring different levels of freshwater dilution and other treatment before reuse (Lipus et al. 2017; Vikram et al. 2014). Such differences impact the composition of potential releases. Also, important operational trends over time and across regions might influence the potential for exposure. For example, across many shale plays, there is a trend toward drilling longer laterals, with increasing numbers of hydraulic fracturing stages and, consequently, use of more fracturing fluid and proppant. This trend may increase the likelihood of releases of fracturing materials, flowback water, or produced water to the environment. Trends in energy production and use during boom and bust cycles also impact emissions and must be considered in predicting the magnitude and likelihood of exposures (Nsanzineza et al. 2019).

Research Goal and Examples of Research Activities: The goal of this research would be to characterize the chemicals used and produced during UOGD operations and to improve understanding of factors that influence whether people might be exposed to them. Many details regarding UOGD practices influence whether exposures occur and, if they do, how and where. For example, Jackson and Dusseault (2014) studied gas release mechanisms from wellbores and illustrated that the cemented annulus between the production casing and formation often exhibits sustained annulus pressure (SAP). At present, there is no generally accepted way of quantifying how SAP translates into the probability of gas being released to groundwater. Understanding operational practices used to manage SAP would be helpful in assessing the likelihood of UOGD releases. This type of UOGD operational information is central to understanding human exposures but is typically not published. Investigators would need to consult operators, regulators, and other knowledgeable entities, and perhaps conduct preliminary research to identify UOGD operational variables most affecting exposures before proceeding to full-scale research.

Topic:	Source – Releases to Air
Question:	**2a. What is the relative contribution of operational, accidental, and unauthorized releases to environmental concentrations of UOGD agents in air? How might they contribute disproportionately to total emissions? How can emissions from individual UOGD processes be best quantified? Can measurements of the release of methane or other chemicals be used to help inform estimating non-methane emissions associated with UOGD operations? How can we use longer term observations (e.g., routine ground-based and satellite, including flares) observations to estimate historical trends in emissions?**

Background: One of the primary potential exposures of concern is inhalation of air pollutants emitted from UOGD-related operations, as well as known and unknown products of chemical reactions involving emitted compounds. The known compounds emitted during UOGD are discussed for each UOGD phase in Section 2.3 and more generally in Section 4.2.2. Temporally, emissions vary due to operational variations (both planned and unplanned) and may be authorized, accidental, or unauthorized. Some short-term processes and specific sites (e.g., super-emitters) are found to dominate emissions. A number of direct and indirect methods have been used to quantify process-specific, site-specific, and regional emissions from UOGD operations. Much of the UOGD health literature reported associations between proximity to wells and adverse health outcomes, so characterizing local-level emissions is important.

Research Goals and Examples of Research Activities: A foundation to understanding inhalation exposures to UOGD operations is to characterize emission rates and composition over time. Such information can then be used to better estimate compound-specific exposure levels (e.g., through some type of modeling), with a particular emphasis on variability. The goal of this research would be to characterize the composition and rates of release of compounds of concern (e.g., air toxics, PM, NO_x, ozone precursors) at the site and regional levels. Such research could entail development or application of new or existing methods to characterize (quantity and composition) emissions at the process or site level; development of distributions of emissions at the process, facility, or well pad level; collection of or use of pre-existing (or concurrent) basin-level observations (likely using ground-based observations and, potentially, drone, aircraft, or satellite observations) of air pollutants for analysis of site-level emissions estimates as well as regional exposures, and analyses of methane and non-methane species emission studies.

Reconciling emissions estimates developed from aggregating process and site-level measurements and regional observations may involve integration of measurements and modeling. Research would require collection of detailed process flow and instrumentation information from operators to understand the specific processes influencing variability in releases. Future research should consider better characterizing both known air toxics as well as a more complete understanding of the range of compounds emitted from each process. Specific attention should be focused on linking emissions to specific processes that may be highly variable temporally and on characterizing the variability in emissions between locations. Research opportunities may present themselves through the use of past studies characterizing three-dimensional pollutant concentrations in UOGD-abundant areas, as well as from routine networks.

Topic:	Source – Releases to Water
Question:	2b. What is the relative contribution of operational, accidental, and unauthorized releases to environmental concentrations of UOGD agents in surface water and groundwater?

Background: The sources for potential contamination of surface waters and groundwaters due to UOGD activities are discussed by each UOGD phase in Section 2.3 and more generally in Section 4.3.2. The most common operational release of UOGD-related water is as produced water, which can be disposed of in deep injection wells or re-used in fracturing of new wells or other purposes. Some produced water is treated and then released to surface waters (Akob et al. 2016; Ferrar et al. 2013b; Hladik et al. 2014; States et al. 2013; Warner et al. 2013a) and, in some cases, is used for ice and dust control on roads (Allison and Mandler 2018). Currently the U.S. EPA prohibits discharge of produced water from UOGD through publicly owned treatment works (U.S. Environmental Protection Agency 2016a). However, uncertainties remain about exposures from produced water disposal due to the variability in produced water constituents and the produced water disposal and reuse regulations that vary among states (Ground Water Protection Council, 2019). Another possible operational release results from failure of wellbores, which has been linked to release of methane ("stray gas") to groundwater aquifers (Soeder 2018). Also, accidental spills of UOGD chemicals and produced water can occur on well pads and during transportation (Clancy et al. 2018). As described in U.S. EPA (2016a), there is a lack of understanding of the location of hydraulic fracturing–related activities relative to drinking water resources. There is also limited information about the frequency and likelihood of unintentional and unauthorized releases to water.

Research Goal and Examples of Research Activities: The goal of research would be to quantify the contribution of UOGD releases to the concentrations of a range of pollutants in surface waters and groundwaters. This would require integration of measurement and modeling approaches, use of existing data, and collection of original data. Although many measurements of groundwater quality have been made in shale plays in the United States, the attribution of contamination to UOGD operations has been noted in the scientific literature in only a few cases (e.g., Cozzarelli et al. 2017; Llewellyn et al. 2015). While efforts are underway to quantify potential releases to air and groundwater at UOGD site created specifically for research purposes, the generalizability of this research is unknown.

Baseline characterization of water quality prior to UOGD operations is essential. State regulations require some operators to collect pre-drill data. However, only some states (e.g., Pennsylvania, Colorado, and Ohio) require pre-drill water quality data to be submitted to the state, and much of these data are not publicly available. Future research would benefit from access to industry-collected baseline data. In addition, investigators should take a targeted approach to sampling where contamination is suspected and should focus on the use of tracers that can identify UOGD as a source of contamination (McIntosh et al. 2018). Spills of chemicals, whether unintentional or by unauthorized dumping, are by their nature difficult to quantify broadly. Investigators have compiled available spills data to understand the potential impacts to drinking water (Gross et al. 2013; Maloney et al. 2017). Research opportunities may present themselves by building on previous work and through identification of sites where spills have been recorded with subsequent design of a measurement and modeling program that could contribute to a risk analysis to inform measures protective of human health and the environment.

5.1.2 Release Mechanisms and Transport Pathways

Topic:	Release Mechanisms and Transport Pathways in Air
Question:	**3a. How does variation in regional conditions (e.g., meteorology and topography) affect the levels of UOGD agents in air over various temporal scales (e.g., hourly, diurnally, and seasonally) as a result of chemical transformation and transport? What methods are available to characterize the fate and transport of UOGD releases to the air?**

Background: After release into the air, UOGD-related emissions are dispersed and can react in the atmosphere, leading to widely varying atmospheric concentrations, and potential exposures, from local to regional scales. A discussion of atmospheric transport as it relates to UOGD emissions is found in Section 4.2.2. Understanding the complexities of atmospheric transport and chemistry of UOGD emissions will be key to quantifying exposures to emissions from the variety of UOGD operations across spatial and temporal scales.

Research Goals and Examples of Research Activities: The goal of this research would be to develop and apply methods that can quantify how releases from UOGD sites impact air quality at different scales (near-site to regional) for use in individual and population-based exposure analyses and to characterize how spatially and temporally varying chemical and transport processes affect concentrations.

One potential area of research would be the development and application of methods to conduct the direct measurements of UOGD compounds on and near sites and associated concentrations downwind and at the regional level, as well as the investigation of how those concentrations vary in response to atmospheric conditions and topography. Use of sensitive instruments and of novel approaches, including the use of inexpensive sensors and satellite observations, may be of interest, with satellite-based observations potentially helping to characterize historic exposures during both periods of heavy and light activity. Such observations, which are relatively complete temporally and spatially, can provide a means to extend detailed ground-based observations to periods of different activity levels, though the coarseness of many of the retrievals may limit their ability for use in near-field exposure assessment. The blending of inexpensive sensors, routine measurements, and satellite observations could lead to a multiscale modeling framework to capture both near-field and regional exposures in a consistent fashion. This would likely be combined with atmospheric modeling to identify appropriate methods to relate emissions from unmonitored sites to surrounding concentrations for use in broader scale exposure modeling. A particular interest would be in demonstrating the ability to capture the temporally and spatially varying concentrations of compounds of concern (e.g., air toxics, NO_2, and PM) over a range of atmospheric conditions and topographies.

At the regional scale, the formation of secondary species via chemical reactions may be an important component of exposure, and the development or application of methods to quantify how UOGD emissions impact secondary air pollutants is of interest. There is also an extensive amount of historical data from both routine monitoring networks and satellites that may be useful for quantifying historical chemical concentrations at various spatial and temporal scales. Ultimately, development and evaluation of accurate approaches to relate compound-specific emissions at UOGD sites to concentrations that vary spatially and temporally is desired. Estimates of uncertainty in their application would be important for their later use in exposure estimation.

Topic:	Release Mechanisms and Transport Pathways in Water
Question:	**3b. How does variation in regional conditions (e.g., topography, geochemistry, geophysics, and hydrology) affect the levels of UOGD agents in water over various temporal scales (e.g., hourly, diurnally, and seasonally) as a result of chemical transformation and transport? What methods are available to characterize the fate and transport of UOGD releases to water?**

Background: There are many complexities that limit our ability to determine how UOGD may affect regional surface water or groundwater quality (Soeder 2015). A discussion of potential UOGD releases to water is found in Section 4.3.2. Any effect must be discerned against a background of spatial and temporal chemical variations due to natural causes (e.g., storm runoff or seasonal groundwater recharge); to historical extraction of oil, gas, or coal in the region; and to a multitude of other activities (e.g., application of many chemicals in agriculture, spraying roads for dust control or deicing, and discharge of industrial wastes either intentionally or unintentionally). Well-casing failures, which occur during hydraulic fracturing, are typically more readily detected than fluid movement behind pipe. Identifying groundwater contamination from leaking wells is particularly challenging. While spills are more readily detected, they are difficult to generalize. Furthermore, geological features determine when pathways exist that can transport chemicals to shallow aquifers that are used for water supply and also determine how and where elevated concentrations of shale-related chemicals occur due to natural causes (e.g., Kreuzer et al. 2018; Nicot et al. 2017). Upward migration of contaminants through fractures to shallow groundwater sources is unlikely (Flewelling and Sharma 2013; Llewellyn et al. 2015; Soeder et al. 2014). However, drilling in areas with geological features that allow for migration increases the chance of contact with interconnected fractures that can provide pathways for contaminants to migrate into shallow groundwater (Woda et al. 2018).

Research Goal and Examples of Research Activities: The goal of the research would be to determine to what extent chemicals associated with UOGD have migrated to water supplies leading to potential exposures to humans, how these chemicals have migrated (pathways), and what geochemical changes have been induced during transport. These questions need to be answered in a representative region where UOGD operations are taking place, given regional variability. Research could take a retrospective or a prospective approach. Either approach would use data analysis along with modeling to interpret results in the appropriate geological (physical and chemical) context.

Retrospective activities would consider how existing data can illuminate the answers to research questions despite serious limitations on the use of readily available data for this purpose (Betanzo et al. 2016; Bowen et al. 2015). Use of a large data set with interpretation based on the geological context can provide a basis to isolate likely areas where UOGD contaminants may be present in water supplies (Wen et al. 2018). Exploration of large data sets may provide some evidence for contamination potential. Detailed analysis of existing or newly collected data in areas identified as geologically prone to contaminant migration can provide additional evidence (Woda et al. 2018). If access to data from industry and regulators can be obtained, statistically valid tests of changes in regional water quality are possible (Betanzo et al. 2016; Wen et al. 2019).

A prospective approach would involve a research design to monitor water quality before, during, and after UOGD is initiated in a region. Such activities could cover a relatively broad area (Montcoudiol et al. 2017) or could focus more narrowly on a particular operation (Barth-Naftilan et al. 2018).

Topic:	Release Mechanisms and Transport Pathways for Noise, Light, and Vibration
Question:	3c. To what extent does UOGD contribute to increased levels of noise, light, and vibration within and across regions and operations?

Background: Research on sensory impacts associated with UOGD provide evidence of noise levels that exceed the maximum permissible levels for residential areas. UOGD operations have the potential to contribute to noise, light, and odor disturbances at varying magnitudes and durations (see Section 4.5). It is not clear how well the few studies investigating sensory impacts, with relatively small sample sizes, reflect the reality of noise exposure experienced across regions and over time, including levels under peak noise and light conditions and under different mitigation scenarios.

Research Goal and Examples of Research Activities: To better quantify exposure to sensory factors, future investigators should consider studying well pads with varying numbers of wells undergoing development, and large samples of participants with diverse residence structures. They should consider the impact of noise-reduction techniques, sample across regions with different topographies, and conduct sampling that represents multiple seasons, times of day, and phases of development.

Topic:	Release Mechanisms and Transport Pathways for Air
Question:	4a. How can levels of UOGD agents in air be distinguished from levels contributed by other natural and anthropogenic sources? What is the relative contribution of air emissions from UOGD to local and regional concentrations?

Background. UOGD emissions are released into an already complex mixture of compounds in the atmosphere, and many of the UOGD compounds are also released from other natural and anthropogenic sources. Secondary pollutants impacted by UOGD emissions are also formed from other sources, with which UOGD emissions may also interact. A number of methods have been applied to help tease out the contribution of UOGD operations on atmospheric concentrations, though their application has been limited (see Section 4.2.2.3 for a discussion on the strengths and limitations of these methods). UOGD exposure analyses will depend upon differentiating among the sources affecting air quality.

Research Goals and Examples of Research Activities: The goals of research related to these questions would include the development of new methods to quantify the fraction of chemical concentrations in air that come from UOGD operations versus other sources (both natural and anthropogenic), application of one or more methods to atmospheric observations to quantify the contributions of UOGD emissions on concentrations at various temporal scales, and characterization of the uncertainty in various methods.

If successful, such research would provide one or more approaches that could be used to relate atmospheric observations and knowledge of emissions to local to regional-scale concentrations of chemicals in air on a compound-by-compound basis. Preferably, the methods would further provide information on the impact of individual UOGD processes and activities on chemical species concentrations. The methods may use or be applied to longer-term, routine observations to provide historical contributions of UOGD operations on local and regional air quality.

Topic:	Release Mechanisms and Transport Pathways for Water
Question:	4b. How can levels of UOGD agents in water be distinguished from levels contributed by other natural and anthropogenic sources? What is the relative contribution of water releases from UOGD to local and regional concentrations?

Background: Chemical agents that potentially can be released from UOGD activities can also be associated with a host of other activities, including legacy conventional oil and gas development, coal mining, industrial operations, and traffic. The inability to definitively attribute measured contaminants in groundwater and surface water to UOGD specifically has led to controversy about impact assessment. For example, determining whether methane detected in groundwater wells is due to UOGD activities, to legacy oil or coal development, or to natural seepage is a difficult problem (Vidic et al. 2013). The confounded issue of attribution of measured chemicals in natural waters in UOGD areas is one reason why the importance of securing water samples prior to UOGD has been stressed (HEI Special Scientific Committee on Unconventional Oil and Gas Development in the Appalachian Basin 2015).

Research Goal and Examples of Research Activities: The goal of the research would be to employ existing techniques, and to develop new techniques as necessary, to identify UOGD sources of contamination as part of an exposure study related to groundwater and surface water exposure pathways. New sensor technologies may be applicable to gain needed temporal resolution of changes in groundwater chemical composition as well as to gather pertinent baseline information (Son et al. 2018). A variety of tracers, such as stable isotopes, have been used to identify gasses, brines, and flowback fluids from hydraulic fracturing (e.g., Dorman et al. 2018; Warner et al. 2014). In some cases, it may be possible to inject unique tracers as part of the fracturing fluids and then to monitor natural groundwater and surface water for signs of contamination (Hammack et al. 2013). In all cases it is imperative that local geological controls that might allow preferential flow of fluids from deep unconventional source rocks be evaluated as part of any study to identify contamination resulting from UOGD activities (Talma et al. 2018; Woda et al. 2018).

5.1.3 Potentially Exposed Populations

Topic:	**Populations**
Question:	**5. What are the characteristics of populations potentially exposed to UOGD agents at local and regional scales?**

Background: The majority of UOGD epidemiology studies have considered proximity-based metrics for assigning exposures, thus implicitly acknowledging the potential exposure impacts of living near UOGD. Little research is available describing the populations residing close to UOGD operations, nor the potential differences in population characteristics of those living near versus far from the operations (Ish et al. 2019; Konkel 2019). Some of the uncertainty about characteristics of populations relates to lack of knowledge about the full geographic extent of potential exposures. For example, over what area do UOGD emissions to air disperse and under what conditions and distances do they decline? Over what area are noise, light, and vibration perceived? Some investigators have attempted to answer these questions by studying chemical dispersion gradients at various distances to UOGD operations (e.g., Garcia-Gonzales et al. 2019b)

Because of likely differences in infrastructure (e.g., rural vs. urban), housing (e.g., costs, quality, and type), and employment opportunities present in locations near and far from UOGD operations, these populations may also differ in susceptibility factors (e.g., age, co-exposures, underlying health conditions, and socioeconomic factors).

Together, the environmental contributions of UOGD releases and population characteristics that affect exposure and susceptibility from UOGD operations contribute to complex exposure pathways that are likely to result in differential UOGD health risk. In order to assess generalizability of epidemiologic results and better predict potential health outcomes, characterization of populations potentially exposed to UOGD agents is needed, including whether and how population characteristics vary at local to regional scales within and between shale play regions.

Research Goal and Examples of Research Activities: The goal of the research would be to characterize populations at local and regional scales with respect to UOGD operations. The research should be designed to provide an enhanced understanding of populations residing near UOGD operations and to assess and compare whether populations differ within and between shale play regions over time. The research should also characterize populations living further from UOGD operations (i.e., within regions anticipated to be impacted by UOGD releases) and to assess and compare how populations differ at local and regional scales within these regions. The research would require: (a) defining and justifying the local and regional scales of interest; (b) identifying and justifying population characterization metrics (e.g., targeting population exposure and susceptibility factors such as age, sex, race/ethnicity, income, and health status); and (c) determining data sources and quality (advantages and limitations) for these metrics. The research would likely rely on existing data sources (e.g., census-based sociodemographic data), supplemented with survey or other primary data collection to enhance population characterization. Ultimately, the data should be used to describe populations within and between shale play regions and to identify potential differences in population characteristics that could influence UOGD exposure and health risk at different scales. Community involvement in data collection may bring value to research design and data analysis, but it can also introduce potential bias associated with unblinded, self-report, and non-random sampling.

Topic:	Populations
Question:	**6. Which population behaviors (e.g., time–activity patterns) influence the potential for exposure to UOGD agents? To what extent do exposures to UOGD agents differ among individuals within and among exposed populations?**

Background: People living in communities near UOGD or in areas impacted by regional effects of UOGD may be exposed to a variety of UOGD-related chemical and non-chemical agents and possibly by more than one exposure pathway. Addressing an individual's total exposure is a vitally important component of health risk assessment and exposure research. To understand the potential for these stressors to adversely impact health, characterization of these exposures must be undertaken. In addition to data on chemical concentrations in various media, exposure assessment includes information on frequency and duration of exposures to chemicals in different media. Limited information has been incorporated into past studies of exposure–outcome associations.

Research Goal and Examples of Research Activities: The goal of research would be to characterize individual and population behaviors that influence frequency and duration of exposure. In addition, researchers would assess the degree to which those behaviors are unique to a given geographic area so that an understanding of the generalizability of the research results can be obtained. Future assessments should consider temporal, spatial, and individual variability. For example, individuals may spend more time outdoors in warm weather months, which would affect temporal variability and activity patterns (which can, for example, influence breathing rates and dermal exposures). Spatial variability considerations may include regional differences in population behaviors that can affect UOGD-related exposures (e.g., differences in outdoor recreational activities by region). Finally, it should be expected that individual day-to-day behaviors will vary. Methods for capturing these differences will be necessary to fully understand exposures.

Topic:	Populations
Question:	**7. How can exposure monitoring methods (e.g., study design, instrumentation, and other technologies) accurately characterize total personal and population-wide exposures to UOGD over time and space?**

Background: Whether health effects occur depends on an individual's total exposure by way of all exposure pathways. The exposure of an individual or a population can be assessed by estimating *external* exposure (e.g., mapping distances to sources, defining job exposure categories, or measuring chemical concentrations in environmental media) or estimating *internal* doses (through biomonitoring).

Assessing external exposure requires information on both media concentrations of chemicals of interest and on factors influencing the concentrations. Much of the exposure literature to date provides information on chemical concentrations in environmental media, but not in combination of factors influencing intake of those chemicals (e.g., breathing rate, soil or water ingestion rate, and dermal exposure area) specific to the potentially exposed populations.

Research Goal and Examples of Research Activities: The goal of research would be to determine sufficient time–activity information such that, combined with concentration data, personal exposures to UOGD-related stressors can be estimated. Combinations of technologies can provide paired data on both chemical concentrations and time–activity information to aid in better understanding total exposure. For example, personal air monitors combined with wearables that allow for collection of activity data may provide a better understanding of an individual's total exposure. Web-based instruments can also be considered assuming that these do not exclude segments of the population(s) of interest. In general, researchers should be open to using a combination of monitoring technologies (including novel ones) while keeping in mind the importance of using methods that have been demonstrated to provide accurate data.

Researchers should consider incorporating both established and innovative approaches. In addition, the research results should shed light on the degree to which the information is generalizable to populations outside of the study population. Research activities should consider different types of populations (e.g., age, gender, race, and susceptible populations) and include validation of proposed approaches and assessments of error in the estimates of exposure. Further, a range of approaches to collecting data may be considered including scientist-based data collection and citizen science approaches.

5.2 ANTICIPATED ATTRIBUTES OF RESEARCH

The Research Committee will prepare a Research Solicitation requesting proposals for population-level exposure studies in key representative locations.

5.2.1 Scope of Exposure Studies

In defining the scope of research, the Committee recognizes the value of a better understanding of air and water-related exposures, achieved with comprehensive, high-quality research that characterizes the range of exposure conditions across regions of the United States. Non-chemical agents of concern include noise and light. Methane is not believed to be toxic to humans at levels typically associated with UOGD unless, of course, they rise to the level of a safety hazard. Therefore, methane is not expected to be a focus of human exposure research except to the extent that it might function as a tracer of UOGD releases to the environment. In general, research needs to advance the understanding of UOGD agents, the mechanisms by which human exposures to them might arise, and be generalizable to different sets of regional conditions, operational practices, and population characteristics. Details about the scope of research, including environmental media of focus, budget, and research design are found in the Research Solicitation.

5.2.2 Study Quality and Scientific Value

The Committee is charged with overseeing selection and implementation of all research and ensuring its quality and utility. In preparing its Research Solicitation and reviewing proposals submitted in response, the Committee seeks research that possesses the characteristics in Table 5-2. The characteristics will be used to make a qualitative rather than quantitative assessment of research topics and proposals.

As reflected in Table 5-2, Committee members will prioritize research that recognizes practical considerations such as efficiency and utility for decision-making and planning.

In its Research Solicitation, the Committee will specify that several key components are required for a research program to be selected, including study of agents of potential concern for health, relevant geographic areas, necessary technical and community engagement expertise on the investigator team, a detailed quality assurance project plan, and an a priori study interpretation and communication plan, among other general components of a high-quality study.

5.3 LOOKING AHEAD TO HEI-ENERGY'S RESEARCH SOLICITATION

The Committee will prepare a Research Solicitation for population-level research based on its review of the literature, input provided during the two public workshops, and comments received on the draft version of this report.

5.3.1 Expected Utility of Research

With UOGD projected to continue, HEI-Energy's research program is designed to be the source of high-quality, impartial science needed to support decisions about how best to ensure protection of public health in the oversight and implementation of this development. The overarching goal of the program is to identify the spatial and temporal range of human exposures arising from UOGD operations across the United States, the conditions under which they occur, and the likelihood of occurrence.

Table 5-2. Characteristics of appropriate research identified by HEI-Energy Research Committee (in alphabetical order)

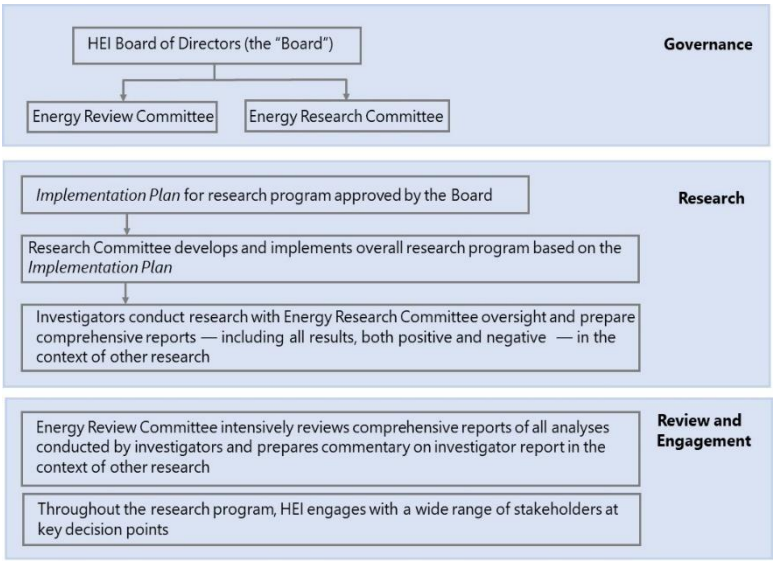
Criterion	Description
Brings value to and informs decision-making	Is useful to communities in study areas, government officials, industry, and other stakeholders. Ideal study designs will be informed by successful engagement with the communities in study areas and other stakeholders.
Broadly generalizable	Designed to be broadly generalizable across geographic regions, UOGD operating conditions, or communities over time, including periods of low and high UOGD activity, without sacrificing validity.
Determines whether an exposure pathway links a UOGD process with a community	Links one or more chemical or non-chemical agents directly released to the environment from a UOGD process to a potentially exposed community. The research allows for the detection of possible causal links between one or more UOGD processes (e.g., specific equipment, activity, or phase of development) and resulting human exposures. The study is designed to distinguish between agents released from UOGD and non-UOGD sources.
Expands understanding of temporal and spatial variability of exposure	Selected study locations and designs will substantially fill important gaps in understanding of variability in exposure conditions over temporal and spatial scales relevant for decision-making by communities, regulators, industry, and other stakeholders.
Optimizes use of the research budget by maximizing efficiency	Ensures that the research budget is spent on gathering data and information that is not already available (e.g., by incorporating or complementing existing data and information) and that prioritization and sequencing of data collection maintains a focus on exposures of possible concern.
Useful for assessing health risk	Collects data or analyzes existing data (or establishes practical exposure assessment methodologies) that is useful for assessing the potential for human health effects at resolutions relevant for application in an epidemiology study or risk assessment.

5.3.2 The Model for Providing Impartial Science

The new research program is modeled after HEI's existing successful model for providing high quality, impartial scientific information about air quality (Figure 5-1). Key components include:

- *Independent governance* of the research program with leadership by an independent board of directors not affiliated with sponsors
- *Balanced funding* from the oil and gas industry, governmental agencies, and foundations
- *High-quality science* with research oversight by the Energy Research Committee, which consists of knowledgeable scientists that have been vetted for bias and conflict of interest
- *Extensive peer review* of science by an Energy Review Committee, which works independently of the Energy Research Committee to provide peer review and commentary on research
- *Open and extensive engagement with stakeholders*, including local community members and officials in study locations
- *Communication* of all results, including both positive and negative findings, in the context of other relevant research
- *Provides impartial science* for better informed decisions without advocating policy positions

Figure 5-1. Overview of HEI-Energy model for providing impartial scientific research, which is selected, implemented, and reviewed independently of the program's sponsors.



5.3.3 Assessment of Research Solicitation Applications

The Research Solicitations will be distributed widely among the scientific community. HEI-Energy will be seeking multi-disciplinary teams with the skill and capacity to mobilize exposure studies at locations across the major regions of the country. Applications will be evaluated and scored by External Review Panels specifically identified as having relevant expertise. The Research Committee will then evaluate the proposals with consideration of the External Review Panels' evaluation and scores and the characteristics listed in Table 5-2 to determine whether the proposed research will (1) improve the understanding of the specific problem under investigation, (2) contribute to HEI-Energy's overall research program, keeping in mind available resources, and (3) advance the goal of building a coordinated program of related studies designed to answer key questions, and not just completing a collection of independent studies. The Research Committee makes final recommendations regarding funding of studies to the HEI-Energy Board, which makes the final funding decision.

Before research begins, HEI-Energy will negotiate detailed contractual agreements with the research team and, as needed, with owners of facilities, operations, or equipment where some of the research may take place. The agreements will address a number of questions, including data quality assessment, management of confidential business information, data access and dissemination, stakeholder engagement planning, cost management, insurance requirements, and other factors important for successful implementation of research.

Throughout the selection, implementation, and review of research projects, HEI-Energy and the Research Committee provide oversight to ensure its quality and effective communication with stakeholders about research progress. HEI-Energy regards effective communication as equally important to the research.

HEI-Energy will fund research that informs decisions about how best to protect public health in the oversight of UOGD. HEI-Energy expects that results will be used by federal, state, and local regulators, communities, the oil and natural gas industry, environmental organizations, public health experts, and other stakeholders to inform policy development in this important area.

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MATERIALS AVAILABLE ON THE HEI-ENERGY WEBSITE

Appendices A through D contain supplemental material and are available separately at *www.hei-energy.org*.

Appendix A: References for Executive Summary and Section 4 Figures
Appendix B: Research Priorities and Study Design Elements Recommended by Workshop Participants
Appendix C: Glossary
Appendix D: Biographies of the Energy Research Committee Members

HEI-ENERGY BOARD, RESEARCH COMMITTEE, AND STAFF