

The diagram illustrates the hydraulic fracturing water cycle through five circular panels arranged in a semi-circle. From left to right: 1. Water trucks (labeled H<sub>2</sub>O) transport water to a wellhead. 2. Water is pumped down the wellbore into the reservoir. 3. Water is pumped back up to the surface, carrying oil and gas. 4. Water is treated in a facility. 5. Treated water is recycled back into the system. The background features a stylized globe with a white arc.

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





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

Office of Research and Development  
U.S. Environmental Protection Agency  
Washington, DC 20460

---

This page is intentionally left blank.

---



---

## Disclaimer

This document has been reviewed in accordance with U.S. Environmental Protection Agency policy and approved for publication. Mention of trade names or commercial products does not constitute endorsement or recommendation for use.

**Preferred citation:** U.S. EPA (U.S. Environmental Protection Agency). 2016. Hydraulic Fracturing for Oil and Gas: Impacts from the Hydraulic Fracturing Water Cycle on Drinking Water Resources in the United States. Office of Research and Development, Washington, DC. EPA/600/R-16/236Fa.

---

## Contents

<b>List of Tables .....</b>	<b>ix</b>
<b>List of Figures.....</b>	<b>xii</b>
<b>List of Text Boxes.....</b>	<b>xvii</b>
<b>List of Acronyms/Abbreviations .....</b>	<b>xix</b>
<b>Preface.....</b>	<b>xxiv</b>
<b>Authors, Contributors, and Reviewers.....</b>	<b>xxv</b>
<b>Acknowledgements.....</b>	<b>xxxix</b>
<b>Executive Summary .....</b>	<b>ES-1</b>
Drinking Water Resources in the United States.....	ES-4
Hydraulic Fracturing for Oil and Gas in the United States.....	ES-5
Approach: The Hydraulic Fracturing Water Cycle .....	ES-9
Water Acquisition.....	ES-12
Water Acquisition Conclusions .....	ES-18
Chemical Mixing.....	ES-18
Chemical Mixing Conclusions.....	ES-26
Well Injection .....	ES-26
Well Injection Conclusions.....	ES-32
Produced Water Handling .....	ES-33
Produced Water Handling Conclusions.....	ES-37
Wastewater Disposal and Reuse.....	ES-38
Wastewater Disposal and Reuse Conclusions .....	ES-42
Chemicals in the Hydraulic Fracturing Water Cycle.....	ES-42
Chemicals in the Hydraulic Fracturing Water Cycle Conclusions .....	ES-44
Data Gaps and Uncertainties.....	ES-44
Report Conclusions.....	ES-46
<b>Chapter 1. Introduction .....</b>	<b>1-1</b>
1.1 Background .....	1-3
1.2 Goals .....	1-4
1.3 Scope .....	1-4
1.4 Approach .....	1-9
1.4.1 EPA Hydraulic Fracturing Study Publications.....	1-9
1.4.2 Literature and Data Search Strategy.....	1-10
1.4.3 Literature and Data Evaluation Strategy .....	1-11
1.4.4 Quality Assurance and Peer Review .....	1-11
1.5 Organization.....	1-12
1.6 Intended Use .....	1-13

---

<b>Chapter 2. Drinking Water Resources in the United States.....</b>	<b>2-1</b>
Abstract.....	2-1
2.1 Introduction.....	2-3
2.2 Ground and Surface Water Resources.....	2-3
2.2.1 Groundwater Resources.....	2-5
2.2.2 Surface Water Resources.....	2-7
2.3 Current Drinking Water Sources.....	2-9
2.3.1 Factors Affecting How Water Becomes a Drinking Water Source.....	2-11
2.4 Future Drinking Water Sources.....	2-13
2.5 Proximity of Drinking Water Resources to Hydraulic Fracturing Operations.....	2-14
2.5.1 Lateral Distance between Public Water System Sources and Hydraulic Fracturing.....	2-14
2.5.2 Vertical Distance between Drinking Water Resources and Hydraulic Fracturing.....	2-16
2.6 Conclusions.....	2-18
<b>Chapter 3. Hydraulic Fracturing for Oil and Gas in the United States.....</b>	<b>3-1</b>
Abstract.....	3-1
3.1 Introduction.....	3-3
3.2 What is Hydraulic Fracturing?.....	3-3
3.3 Hydraulic Fracturing and the Life of a Well.....	3-11
3.3.1 Site Preparation and Well Construction.....	3-12
3.3.2 Hydraulic Fracturing.....	3-18
3.3.3 Fluid Recovery, Handling, and Disposal or Reuse.....	3-23
3.3.4 Oil and Gas Production.....	3-24
3.3.5 Site and Well Closure.....	3-25
3.4 How Widespread is Hydraulic Fracturing?.....	3-25
3.4.1 Number of Wells Fractured per Year.....	3-29
3.4.2 Hydraulic Fracturing Rates.....	3-31
3.5 Trends and Outlook for the Future.....	3-32
3.5.1 Natural Gas.....	3-33
3.5.2 Oil.....	3-36
3.6 Conclusions.....	3-38
<b>Chapter 4. Water Acquisition.....</b>	<b>4-1</b>
Abstract.....	4-1
4.1 Introduction.....	4-3
4.2 Types of Water Used.....	4-5
4.2.1 Source.....	4-5
4.2.2 Quality.....	4-8
4.2.3 Provisioning.....	4-10
4.3 Water Use Per Well.....	4-10
4.3.1 Hydraulic Fracturing Water Use in the Life Cycle of Oil and Gas.....	4-10
4.3.2 National Estimates and Variability in Water Use Per Well for Hydraulic Fracturing.....	4-11

---

---

4.4	Hydraulic Fracturing Water Use and Consumption at the National, State, and County Scale.....	4-13
4.4.1	National and State Scale .....	4-13
4.4.2	County Scale .....	4-15
4.5	Potential for Impacts by Location.....	4-21
4.5.1	Texas.....	4-21
4.5.2	Colorado and Wyoming.....	4-31
4.5.3	Pennsylvania, West Virginia, and Ohio .....	4-35
4.5.4	North Dakota and Montana .....	4-40
4.5.5	Arkansas and Louisiana .....	4-42
4.6	Chapter Synthesis .....	4-45
4.6.1	Major Findings .....	4-45
4.6.2	Factors Affecting Frequency or Severity of Impacts .....	4-47
4.6.3	Uncertainties.....	4-49
4.6.4	Conclusions.....	4-50
<b>Chapter 5.</b>	<b>Chemical Mixing.....</b>	<b>5-1</b>
	Abstract.....	5-1
5.1	Introduction .....	5-3
5.2	Chemical Mixing Process .....	5-4
5.3	Overview of Hydraulic Fracturing Fluids .....	5-8
5.3.1	Water-Based Fracturing Fluids.....	5-12
5.3.2	Alternative Fracturing Fluids.....	5-13
5.3.3	Tracers.....	5-14
5.3.4	Proppants .....	5-16
5.3.5	Example Hydraulic Fracturing Fluids .....	5-16
5.4	Frequency and Volume of Hydraulic Fracturing Chemical Use .....	5-17
5.4.1	National Frequency of Use of Hydraulic Fracturing Chemicals .....	5-20
5.4.2	Nationwide Oil versus Gas .....	5-24
5.4.3	State-by-State Frequency of Use of Hydraulic Fracturing Chemicals.....	5-25
5.4.4	Volume of Chemical Use.....	5-26
5.4.5	Chemical Composition of Hydraulic Fracturing Fluids and Additives .....	5-28
5.5	Chemical Management and Spill Potential.....	5-31
5.5.1	Storage.....	5-33
5.5.2	Hoses and Lines .....	5-37
5.5.3	Blender .....	5-38
5.5.4	Manifold .....	5-39
5.5.5	High-Pressure Fracturing Pumps.....	5-39
5.5.6	Surface Wellhead for Fracture Stimulation .....	5-39
5.6	Overview of Chemical Spills Data .....	5-41
5.6.1	EPA Analysis of Spills Associated with Hydraulic Fracturing.....	5-41
5.6.2	Estimated Spill Rate and Other Spill Reports and Data .....	5-45
5.7	Spill Prevention, Containment, and Mitigation .....	5-46

---

---

5.8	Fate and Transport of Spilled Chemicals .....	5-47
5.8.1	Potential Paths .....	5-49
5.8.2	Physicochemical Properties of Organic Hydraulic Fracturing Chemicals .....	5-50
5.8.3	Mobility of Organic Hydraulic Fracturing Chemicals .....	5-52
5.8.4	Transformation Processes .....	5-56
5.8.5	Fate and Transport of Chemical Mixtures .....	5-57
5.8.6	Site and Environmental Conditions .....	5-58
5.8.7	Peer-Reviewed Literature on the Fate and Transport of Hydraulic Fracturing Fluid Spills.....	5-58
5.8.8	Potential and Documented Fate and Transport of Documented Spills.....	5-59
5.8.9	Challenges with Unmonitored and Undetected Chemicals.....	5-62
5.9	Trends in the Use of Hydraulic Fracturing Chemicals .....	5-63
5.10	Synthesis.....	5-64
5.10.1	Summary of Findings .....	5-64
5.10.2	Factors Affecting the Frequency or Severity of Impacts.....	5-66
5.10.3	Uncertainties.....	5-67
5.10.4	Conclusions.....	5-69
<b>Chapter 6.</b>	<b>Well Injection.....</b>	<b>6-1</b>
	Abstract.....	6-1
6.1	Introduction .....	6-3
6.2	Fluid Migration Pathways Within and Along the Production Well .....	6-5
6.2.1	Overview of Well Construction .....	6-5
6.2.2	Factors that can Affect Fluid Movement to Drinking Water Resources .....	6-16
6.3	Fluid Migration Associated with Induced Fractures within Subsurface Formations.....	6-38
6.3.1	Overview of Subsurface Fracture Growth.....	6-40
6.3.2	Migration of Fluids through Pathways Related to Fractures/Formations.....	6-44
6.4	Synthesis.....	6-69
6.4.1	Summary of Findings .....	6-70
6.4.2	Factors Affecting Frequency or Severity of Impacts .....	6-73
6.4.3	Uncertainties.....	6-75
6.4.4	Conclusions.....	6-77
<b>Chapter 7.</b>	<b>Produced Water Handling.....</b>	<b>7-1</b>
	Abstract.....	7-1
7.1	Introduction .....	7-3
7.1.1	Definitions.....	7-4
7.2	Volume of Hydraulic Fracturing Flowback and Produced Water .....	7-5
7.2.1	Flowback of Injected Hydraulic Fracturing Fluid .....	7-6
7.2.2	Produced Water Volumes.....	7-8
7.3	Chemical Composition of Produced Water .....	7-11
7.3.1	Determination of Produced Water Composition.....	7-11
7.3.2	Factors Influencing Produced Water Composition .....	7-12
7.3.3	Produced Water Composition During the Flowback Period .....	7-12

---

---

7.3.4	Produced Water Composition .....	7-16
7.3.5	Spatial Trends in Produced Water Composition .....	7-24
7.4	Spill and Release Impacts on Drinking Water Resources.....	7-25
7.4.1	Produced Water Handling and Spill Potential.....	7-25
7.4.2	Spills of Produced Water .....	7-26
7.5	Roadway Transport of Produced Water .....	7-40
7.6	Synthesis.....	7-41
7.6.1	Summary of Findings .....	7-41
7.6.2	Factors Affecting the Frequency or Severity of Impacts.....	7-43
7.6.3	Uncertainties.....	7-43
7.6.4	Conclusions.....	7-44
<b>Chapter 8.</b>	<b>Wastewater Disposal and Reuse.....</b>	<b>8-1</b>
	Abstract.....	8-1
8.1	Introduction.....	8-3
8.2	Volumes of Hydraulic Fracturing Wastewater.....	8-4
8.2.1	National Level Estimate .....	8-6
8.2.2	Regional/State Level Estimates.....	8-6
8.2.3	Estimation Methodologies and Challenges.....	8-8
8.3	Wastewater Characteristics .....	8-11
8.3.1	Wastewater.....	8-11
8.3.2	Constituents in Residuals .....	8-13
8.4	Wastewater Management Practices and Their Potential Impacts on Drinking Water Resources.....	8-14
8.4.1	Underground Injection .....	8-23
8.4.2	Publicly Owned Treatment Works .....	8-27
8.4.3	Centralized Waste Treatment Facilities.....	8-28
8.4.4	Wastewater Reuse for Hydraulic Fracturing .....	8-35
8.4.5	Storage and Disposal Pits and Impoundments .....	8-39
8.4.6	Other Management Practices and Issues.....	8-46
8.4.7	Management of Solid and Liquid Residuals.....	8-51
8.5	Potential Impacts of Hydraulic Fracturing Wastewater Constituents on Drinking Water Resources.....	8-54
8.5.1	Bromide, Iodide, and Chloride.....	8-54
8.5.2	Radionuclides .....	8-58
8.5.3	Metals .....	8-64
8.5.4	Volatile Organic Compounds.....	8-65
8.5.5	Semi-Volatile Organic Compounds.....	8-65
8.5.6	Oil and Grease.....	8-66
8.6	Synthesis.....	8-66
8.6.1	Summary of Findings .....	8-66
8.6.2	Factors Affecting the Frequency or Severity of Impacts.....	8-70
8.6.3	Uncertainties.....	8-73

---



---

8.6.4	Conclusions.....	8-75
<b>Chapter 9. Identification and Hazard Evaluation of Chemicals across the Hydraulic Fracturing Water Cycle..... 9-1</b>		
	Abstract.....	9-1
9.1	Introduction.....	9-3
9.2	Overview: Hydraulic Fracturing and Potential Impacts on Human Health .....	9-5
9.3	Identification of Chemicals Associated with the Hydraulic Fracturing Water Cycle .....	9-8
9.3.1	Chemicals Used in Hydraulic Fracturing Fluids.....	9-9
9.3.2	Chemicals Detected in Produced Water.....	9-11
9.4	Toxicological and Physicochemical Properties of Hydraulic Fracturing Chemicals .....	9-11
9.4.1	Reference Values (RfVs), Oral Slope Factors (OSFs), and Qualitative Cancer Classifications.....	9-13
9.4.2	Estimating Toxicity Using Quantitative Structure Activity Relationship (QSAR) Modeling.....	9-17
9.4.3	Chemical Data Available from EPA's Aggregated Computations Toxicology Resource (ACToR) Database.....	9-19
9.4.4	Additional Tools for Hazard Evaluation.....	9-20
9.4.5	Physicochemical Properties .....	9-21
9.4.6	Summary of Available Toxicological and Physicochemical Information for Hydraulic Fracturing Chemicals.....	9-21
9.5	Hazard Identification of Hydraulic Fracturing Chemicals.....	9-22
9.5.1	Chemicals Used in Hydraulic Fracturing Fluids.....	9-23
9.5.2	Organic Chemicals in Produced Water .....	9-30
9.5.3	Inorganic Chemicals and TENORM in Produced Water .....	9-38
9.5.4	Organochlorine Pesticides and Polychlorinated Biphenyls (PCBs) in Produced Water.....	9-44
9.5.5	Methane in Stray Gas.....	9-46
9.5.6	Disinfection Byproducts (DBPs) Formed from Wastewater Constituents.....	9-47
9.5.7	Chemicals Detected in Multiple Stages of the Hydraulic Fracturing Water Cycle.....	9-48
9.6	Hazard Evaluation of Selected Subsets of Hydraulic Fracturing Chemicals Using Multi-Criteria Decision Analysis (MCDA): Integrating Toxicity, Occurrence, and Physicochemical Data.....	9-51
9.6.1	Overview of the MCDA Framework for Hazard Evaluation.....	9-53
9.6.2	Selection of Chemicals for Hazard Evaluation in the MCDA Framework.....	9-53
9.6.3	Calculation of MCDA Scores.....	9-57
9.6.4	Total Hazard Potential Score .....	9-58
9.6.5	MCDA Results .....	9-59
9.6.6	Limitations and Uncertainty of the MCDA Framework.....	9-77
9.6.7	Application of the MCDA Framework for Preliminary Hazard Evaluation.....	9-78
9.7	Synthesis.....	9-79
9.7.1	Summary of Findings .....	9-79
9.7.2	Factors Affecting the Frequency or Severity of Impacts.....	9-81
9.7.3	Uncertainties.....	9-82
9.7.4	Conclusions.....	9-83

---

---

9.8	Annex .....	9-84
9.8.1	Calculation of Physicochemical Property Scores (MCDA Hazard Evaluation) .....	9-84
9.8.2	Example of MCDA Score Calculation.....	9-85
<b>Chapter 10.</b>	<b>Synthesis .....</b>	<b>10-1</b>
	Introduction.....	10-3
10.1	Factors Affecting the Frequency or Severity of Impacts.....	10-4
10.1.1	Water Acquisition.....	10-4
10.1.2	Chemical Mixing and Produced Water Handling.....	10-8
10.1.3	Well Injection.....	10-13
10.1.4	Wastewater Disposal and Reuse .....	10-21
10.1.5	Summary.....	10-23
10.2	Uncertainties and Data Gaps.....	10-24
10.3	Use of this Assessment .....	10-28
<b>Chapter 11.</b>	<b>References .....</b>	<b>11-1</b>

---

## List of Tables

Table ES-1. Water use per hydraulically fractured well between January 2011 and February 2013.....	ES-13
Table ES-2. Chemicals reported in 10% or more of disclosures in FracFocus 1.0.....	ES-20
Table ES-3. Available chronic oral reference values for hydraulic fracturing chemicals reported in 10% or more of disclosures in FracFocus 1.0.....	ES-43
Table 1-1. The five factors and accompanying criteria used to evaluate literature and data cited in this assessment.....	1-11
Table 2-1. Summary of drinking water sources in the United States in 2010.....	2-10
Table 3-1. Estimated number of new wells hydraulically fractured nationally by year from various sources.....	3-29
Table 4-1. Estimated proportions of hydraulic fracturing source water from surface water and groundwater.....	4-6
Table 4-2. Percentage of injected water volume that comes from reused hydraulic fracturing wastewater in various states, basins, and plays.....	4-7
Table 4-3. Average annual hydraulic fracturing water use and consumption in 2011 and 2012 compared to total annual water use and consumption in 2010, by county.....	4-16
Table 4-4. Estimated brackish water use as a percentage of total hydraulic fracturing water use in the main hydraulic fracturing areas of Texas, 2011.....	4-23
Table 5-1. Examples of common additives, their function, and the most frequently used chemicals reported to FracFocus for these additives.....	5-11
Table 5-2. Classes and specifically identified examples of tracers used in hydraulic fracturing fluids.....	5-14
Table 5-3. Chemicals identified in the EPA FracFocus 1.0 project database in 10% or more disclosures, with the percent of disclosures for which each chemical is reported as an ingredient in an additive and the top four reported additives for which the chemical is used.....	5-21
Table 5-4. Example list of chemicals and chemical volumes used in hydraulic fracturing.....	5-26
Table 5-5. Fluid and additive composition by maximum mass percent.....	5-29
Table 5-6. Examples of typical hydraulic fracturing equipment and its function.....	5-32
Table 5-7. The 20 chemicals reported most frequently nationwide for hydraulic fracturing based on the EPA FracFocus 1.0 project database, with EPI Suite™ physicochemical parameters where available, and estimated mean and median volumes of those chemicals where density was available.....	5-54
Table 6-1. Failure rates of vertical wells in the Wattenberg field, Colorado.....	6-20
Table 6-2. Results of studies of PA DEP violation data that examined mechanical integrity failure rates.....	6-30
Table 6-3. Comparing the approximate depth and thickness of selected U.S. shale gas plays and coalbed methane basins.....	6-46
Table 6-4. Modeling parameters and scenarios investigated by Reagan et al. (2015).....	6-57
Table 7-1. Data from one company's operations indicating approximate total water use and approximate produced water volumes within 10 days after completion of wells.....	7-6

---

Table 7-2. Additional short-, medium-, and long-term produced water estimates. ....	7-7
Table 7-3. Flowback water characteristics for wells in unconventional reservoirs.....	7-8
Table 7-4. Long-term produced water generation rates (gal/day per well) for wells in unconventional reservoirs. ....	7-9
Table 7-5. Compiled minimum and maximum concentrations for various geochemical constituents in produced water from shale gas, tight gas, and CBM produced water.....	7-17
Table 7-6. Examples of compounds identified in produced water that can be components of hydraulic fracturing fluid. ....	7-22
Table 7-7. Summary of produced water release volumes.....	7-37
Table 8-1. Estimated volumes (millions of gal) of wastewater based on state data for selected years and numbers of wells producing fluid. ....	8-9
Table 8-2. Estimated percentages of wastewater managed by practice and by state. ....	8-16
Table 8-3. Management practices for wastewater from unconventional oil and gas resources.....	8-17
Table 8-4. Distribution of active Class IID wells across the United States.....	8-24
Table 8-5. Number, by state, of CWT facilities that have accepted or plan to accept wastewater from unconventional oil and gas activities.....	8-30
Table 8-6. Estimated percentages of reuse of hydraulic fracturing wastewater. ....	8-36
Table 9-1. Sources of selected RfVs, OSFs, and qualitative cancer classifications. ....	9-15
Table 9-2. Chemicals reported to FracFocus 1.0 from January 1, 2011 to February 28, 2013 in 10% or more disclosures, with the percent of disclosures for which each chemical is reported. Chronic oral RfVs, TOPKAT LOAEL estimates, and availability of ACToR data are shown when available.....	9-25
Table 9-3. List of OSFs and qualitative cancer classifications available for all carcinogenic chemicals reported to FracFocus 1.0 from January 1, 2011 to February 28, 2013 in 10% or more disclosures.....	9-28
Table 9-4. List of a subset of organic chemicals that have been detected in produced water, with respective chronic oral RfVs, TOPKAT LOAEL estimates, and availability of ACToR data shown when available. ....	9-32
Table 9-5. List of OSFs and qualitative cancer classifications available for a subset of organic chemicals that have been reported in produced water. ....	9-36
Table 9-6. List of inorganics and TENORM reported in produced water, and respective chronic oral RfVs and OSFs when available.....	9-39
Table 9-7. List of qualitative cancer classifications available for inorganics and NORM that were reported in produced water. ....	9-42
Table 9-8. List of organochlorine pesticides and PCBs that were reported in produced water, and their respective chronic oral RfVs, TOPKAT LOAEL estimates, and availability of data in EPA's ACToR database. ....	9-44
Table 9-9. List of OSFs and qualitative cancer classifications available for organochlorine pesticides reported in produced water.....	9-46
Table 9-10. List of 45 chemicals on EPA's list that were used in hydraulic fracturing fluids and detected in produced water and have an RfV or OSF available.....	9-48

---

---

Table 9-11. Thresholds used for developing the Toxicity Score, Occurrence Score, and Physicochemical Properties Score in this MCDA framework.....	9-59
Table 9-12. Data on the selected subset of chemicals in hydraulic fracturing fluids used for input into a noncancer MCDA.....	9-62
Table 9-13. Data on the selected subset of chemicals in hydraulic fracturing fluids used for input into a cancer MCDA.....	9-70
Table 9-14. Data on the selected subset of chemicals detected in produced water used for input into a noncancer MCDA.....	9-72
Table 9-15. Data on the selected subset of chemicals detected in produced water used for input into a cancer MCDA.....	9-76
Table 10-1. Literature estimates of mechanical integrity failure rates resulting in contamination of groundwater or failure of all well barriers, potentially exposing the groundwater. ....	10-15

---

## List of Figures

Figure ES-1. General timeline and summary of activities at a hydraulically fractured oil or gas production well. ....	ES-6
Figure ES-2. Locations of approximately 275,000 wells that were drilled and likely hydraulically fractured between 2000 and 2013. ....	ES-8
Figure ES-3. The five stages of the hydraulic fracturing water cycle. ....	ES-10
Figure ES-4. Water budgets illustrative of hydraulic fracturing water management practices in the Marcellus Shale in the Susquehanna River Basin between approximately 2008 and 2013 and the Barnett Shale in Texas between approximately 2011 and 2013. ....	ES-14
Figure ES-5. Generalized depiction of factors that influence whether spilled hydraulic fracturing fluids or additives reach drinking water resources, including spill characteristics, environmental fate and transport, and spill response activities. ....	ES-25
Figure ES-6. Potential pathways for fluid movement in a cemented well. ....	ES-29
Figure ES-7. Examples of different subsurface environments in which hydraulic fracturing takes place. ....	ES-31
Figure ES-8. Changes in wastewater management practices over time in the Marcellus Shale area of Pennsylvania. ....	ES-41
Figure 1-1. Conceptualized view of the stages of the hydraulic fracturing water cycle. ....	1-5
Figure 2-1. Geographic variability in drinking water sources for public water systems. ....	2-10
Figure 2-2. The location of public water system sources having hydraulically fractured wells within 1 mile. ....	2-15
Figure 2-3. Separation distance between drinking water resources and hydraulically fractured intervals in wells. ....	2-17
Figure 3-1. Conceptual illustration of the types of oil and gas reservoirs and production wells used in hydraulic fracturing. ....	3-6
Figure 3-2. Major shale gas and oil plays in the contiguous United States. ....	3-8
Figure 3-3. Major tight gas plays in the contiguous United States. ....	3-9
Figure 3-4. Coalbed methane fields and coal basins in the contiguous United States. ....	3-10
Figure 3-5. General timeline and summary of activities that take place during the preparation and through the operations of an oil or gas well site at which hydraulic fracturing is used. ....	3-12
Figure 3-6. Surface water being pumped for oil and gas development. ....	3-14
Figure 3-7. Illustration of well construction showing different types of casing and cement. ....	3-15
Figure 3-8. Sections of well casing ready for installation at a well site in Colorado. ....	3-16
Figure 3-9. Aerial photograph of two hydraulic fracturing well sites and a service road in Springville Township, Pennsylvania. ....	3-17
Figure 3-10. Aerial photograph of hydraulic fracturing well sites near Williston, North Dakota. ....	3-18
Figure 3-11. Well site with equipment (and pits in the background) in preparation for hydraulic fracturing in Troy, Pennsylvania. ....	3-19
Figure 3-12. Three wellheads on a multi-well pad connected to the piping used for hydraulic fracturing injection. ....	3-20



---

Figure 3-13. Water tanks (blue, foreground) lined up for hydraulic fracturing at a well site in central Arkansas. ....	3-22
Figure 3-14. A pit on the site of a hydraulic fracturing operation in central Arkansas.....	3-23
Figure 3-15. Locations of the approximately 275,000 wells drilled and hydraulically fractured between 2000 and 2013.....	3-26
Figure 3-16. Landsat photo showing hydraulic fracturing well sites near Frierson, Louisiana.....	3-27
Figure 3-17. Landsat photo showing hydraulic fracturing well sites near Pinedale, Wyoming.....	3-28
Figure 3-18. Primary U.S. energy production by source, 1950 to 2015.....	3-32
Figure 3-19. U.S. production of oil (left) and gas (right) from hydraulically fractured wells from 2000 to 2015. ....	3-33
Figure 3-20. Location of horizontal wells that began producing oil or natural gas in 2000, 2005, and 2012.....	3-34
Figure 3-21. Natural gas prices and drilling activity, United States, 1988 to 2015. ....	3-35
Figure 3-22. Historic and projected natural gas production by source (trillion cubic feet). ....	3-35
Figure 3-23. Production from U.S. shale gas plays, 2000-2014.....	3-36
Figure 3-24. Crude oil prices and drilling activity, United States, 1988 to 2015. ....	3-37
Figure 3-25. Historic and projected oil production by source (million barrels per day).....	3-37
Figure 3-26. Production from U.S. tight oil plays, 2000-2014.....	3-38
Figure 4-1. Median water volume per hydraulically fractured well nationally, expressed by well type and completion year. ....	4-12
Figure 4-2. Average annual hydraulic fracturing water use in 2011 and 2012 by county. ....	4-18
Figure 4-3. (a) Average annual hydraulic fracturing water use in 2011 and 2012 compared to total annual water use in 2010, by county, expressed as a percentage; (b) Average annual hydraulic fracturing water consumption in 2011 and 2012 compared to total annual water consumption in 2010, by county, expressed as a percentage. ....	4-19
Figure 4-4. Locations of wells in the EPA FracFocus 1.0 project database, with respect to U.S. EIA shale plays and basins. ....	4-22
Figure 4-5. Major U.S. EIA shale plays and basins for Texas.....	4-22
Figure 4-6. Average annual hydraulic fracturing water use in 2011 and 2012 compared to (a) fresh water available and (b) total water (fresh, brackish, and wastewater) available, by county, expressed as a percentage.....	4-26
Figure 4-7. (a) Estimated annual surface water runoff from the USGS; (b) Reliance on groundwater as indicated by the ratio of groundwater pumping to stream flow and pumping. ....	4-27
Figure 4-8. Percentage of weeks in drought between 2000 and 2013 by county. ....	4-29
Figure 4-9. Major U.S. EIA shale plays and basins for Colorado and Wyoming.....	4-31
Figure 4-10. Major U.S. EIA shale plays and basins for Pennsylvania, West Virginia, and Ohio.....	4-35
Figure 4-11. Major U.S. EIA shale plays and basins for North Dakota and Montana.....	4-40
Figure 4-12. Major U.S. EIA shale plays and basins for Arkansas and Louisiana. ....	4-43

---

---

Figure 5-1. Representative hydraulic fracturing site showing equipment used on-site during the chemical mixing process. ....	5-5
Figure 5-2. Overview of a chemical mixing process of the hydraulic fracturing water cycle. ....	5-6
Figure 5-3. Example hydraulic fracturing fluid decision tree for gas and oil wells. ....	5-9
Figure 5-4. Example hydraulic fracturing fluids. ....	5-17
Figure 5-5. Estimated median volumes for 74 chemicals reported in at least 100 disclosures in the FracFocus 1.0 project database for use in hydraulic fracturing from January 1, 2011 to February 28, 2013. ....	5-28
Figure 5-6. Typical hydraulic fracturing equipment layout. ....	5-33
Figure 5-7. Metal and high-density polyethylene (HDPE) additive units. ....	5-35
Figure 5-8. Hoses and lines at a site in Arkansas. ....	5-37
Figure 5-9. Multiple fracture heads. ....	5-40
Figure 5-10. Percent distribution of the causes of spills. ....	5-42
Figure 5-11. Percent distribution of the sources of spills. ....	5-43
Figure 5-12. Distribution of the number of spills for different ranges of spill volumes. ....	5-43
Figure 5-13. Total volume of fluids spilled from different sources. ....	5-44
Figure 5-14. Number of spills by environmental receptor. ....	5-45
Figure 5-15. Fate and transport schematic for a spilled hydraulic fracturing fluid. ....	5-48
Figure 5-16. Histograms of physicochemical properties of organic chemicals used in the hydraulic fracturing process. ....	5-52
Figure 5-17. Fate and Transport Spill Example: Case 1. ....	5-60
Figure 5-18. Fate and Transport Spill Example: Case 2. ....	5-61
Figure 5-19 Fate and Transport Spill Example: Case 3. ....	5-62
Figure 6-1. Schematic cross-section of general types of oil and gas resources and the orientations of production wells used in hydraulic fracturing. ....	6-6
Figure 6-2. Overview of well construction. ....	6-8
Figure 6-3. The various stresses to which the casing will be exposed. ....	6-10
Figure 6-4. Potential pathways for fluid movement in a cemented wellbore. ....	6-17
Figure 6-5. Hydraulic fracture planes (represented as ovals), with respect to the principal subsurface compressive stresses: $S_v$ (the vertical stress), $S_H$ (the maximum horizontal stress), and $S_h$ (the minimum horizontal stress). ....	6-41
Figure 6-6. Vertical distances in the subsurface separating drinking water resources and hydraulic fracturing depths. ....	6-45
Figure 6-7. Conceptualized depiction of potential pathways for fluid movement out of the production zone: (a) induced fracture overgrowth into over- or underlying formations; (b) induced fractures intersecting natural fractures; and (c) induced fractures intersecting a permeable fault. ....	6-53
Figure 6-8. Induced fractures intersecting an offset well (in a production zone, as shown, or in overlying formations into which fracture growth may have occurred). ....	6-59

---

---

Figure 6-9. Well communication (a frac hit).....	6-60
Figure 7-1. Generalized examples of produced water flow from five formations.....	7-10
Figure 7-2. Typical produced water volume for a coal bed methane well in the western United States.....	7-11
Figure 7-3. TDS concentrations measured through time for injected fluid (at 0 days), and produced water samples from four Marcellus Shale gas wells in three southwest Pennsylvania counties.....	7-13
Figure 7-4. Total radium and TDS concentrations measured through time for injected (day 0), and produced water samples Greene County, PA, Marcellus Shale gas wells.....	7-14
Figure 7-5. (a) Increasing chloride (Cl) and (b) decreasing DOC concentrations measured through time for samples from three Marcellus Shale gas wells on a single well pad in Greene County, PA.....	7-15
Figure 7-6. Data on radium 226 (open symbols) and total radium (filled symbols) for Marcellus Shale wells (leftmost three columns) and other formations (rightmost three columns). ....	7-21
Figure 7-7. Produced water spill rates (spills per active wells) for North Dakota from 2001 to 2015 (Appendix Section E.5).....	7-31
Figure 7-8. Number of produced water releases in North Dakota by cause for 2014 and 2015 (Appendix Section E.5).....	7-32
Figure 7-9. Distribution of spill causes in Oklahoma, pre-high volume hydraulic fracturing years of 1993-2003 (left) and in the EPA study of spills on production pads (right).....	7-33
Figure 7-10. Distribution of spill sources in Oklahoma, pre-high volume hydraulic fracturing years of 1993-2003 (left) and in the EPA study of spills on production pads (right).....	7-33
Figure 7-11. Volumes of 2015 North Dakota salt water releases by cause (leftmost 13 boxes in red), and all causes (last box in blue). ....	7-34
Figure 7-12. Volumes of produced water spills reported by the EPA for 2006 to 2012 by cause (the five left most boxes in red), source (the second five boxes in yellow), and all spills (blue).....	7-35
Figure 7-13. Median, mean, and maximum produced water spill volumes for North Dakota from 2001 to 2015. ....	7-36
Figure 7-14. Schematic view of transport processes occurring during releases of produced water.....	7-40
Figure 8-1. Wastewater (i.e., produced water and fracturing fluid waste) and produced gas volumes from unconventional (as defined by PA DEP) wells in Pennsylvania from January 2010 through June 2016. ....	8-5
Figure 8-2. Wastewater quantities in the western United States (billions of gal per year). ....	8-7
Figure 8-3. Schematic of wastewater management strategies. ....	8-14
Figure 8-4. Percentages of total unconventional wastewater (as defined by PA DEP) managed via various practices for the second half of 2009 through the first half of 2014. ....	8-21
Figure 8-5. Management of wastewater in Colorado in regions where hydraulic fracturing is being performed. ....	8-22
Figure 8-6. Oil and gas wastewater volumes discharged to POTWs from 2001-2011 in the Marcellus Shale. (“Conventional” is indicated by the authors as non-Marcellus wells and described as vertically drilled to shallower depths in more porous formations.) ....	8-27

---

---

Figure 8-7. Map showing Pennsylvania surface water designated as potable water supplies and upstream CWTs.....	8-32
Figure 8-8. Lined evaporation pit in the Battle Creek Field (Montana).....	8-42
Figure 9-1. Fate and transport schematic for a hydraulic fracturing-related spill or release.....	9-6
Figure 9-2. Percentage of hydraulic fracturing-related chemicals (out of 1,606 total) with at least one data point in each ACToR data class.....	9-20
Figure 9-3. Overall representation of the selected toxicological, physicochemical, and occurrence data available for the 1,606 hydraulic fracturing-related chemicals identified by the EPA. ....	9-22
Figure 9-4. Availability of toxicity data (chronic oral RfVs/OSFs, TOPKAT LOAEL estimates, and relevant data on ACToR) for subsets of chemicals used at various frequencies in hydraulic fracturing fluids, as determined based on the number of disclosures in the EPA FracFocus 1.0 project database.....	9-29
Figure 9-5. Overview of the MCDA framework for hazard evaluation.....	9-53
Figure 9-6. The subsets of chemicals selected for hazard evaluation using the noncancer MCDA framework included 42 chemicals used in hydraulic fracturing fluids and 29 chemicals detected in produced water.....	9-55
Figure 9-7. The subsets of chemicals selected for hazard evaluation using the cancer MCDA framework included 10 chemicals used in hydraulic fracturing fluids, and 7 chemicals detected in produced water.....	9-56
Figure 9-8. Noncancer MCDA results for 42 chemicals used in hydraulic fracturing fluids (national analysis), showing the Toxicity Score, Occurrence Score, and Physicochemical Properties Score for each chemical. ....	9-65
Figure 9-9. Noncancer MCDA results for 36 chemicals used in hydraulic fracturing fluids in Texas (state-specific analysis), showing the Toxicity Score, Occurrence Score, and Physicochemical Properties Score for each chemical.....	9-66
Figure 9-10. Noncancer MCDA results for 20 chemicals used in hydraulic fracturing fluids in Pennsylvania (state-specific analysis), showing the Toxicity Score, Occurrence Score, and Physicochemical Properties Score for each chemical.....	9-67
Figure 9-11. Noncancer MCDA results for 21 chemicals used in hydraulic fracturing fluids in North Dakota (state-specific analysis), showing the Toxicity Score, Occurrence Score, and Physicochemical Properties Score for each chemical.....	9-68
Figure 9-12. Cancer MCDA results for 10 chemicals used in hydraulic fracturing fluids, showing the Toxicity Score, Occurrence Score, and Physicochemical Properties Score for each chemical. ....	9-71
Figure 9-13. Noncancer MCDA results for a subset of 29 chemicals detected in produced water, showing the Toxicity Score, Occurrence Score, and Physicochemical Properties Score for each chemical.....	9-74
Figure 9-14. Cancer MCDA results for 7 chemicals detected in produced water, showing the Toxicity Score, Occurrence Score, and Physicochemical Properties Score for each chemical.....	9-77
Figure 10-1. Water budgets representative of practices in (top) the Marcellus Shale in the Susquehanna River Basin in Pennsylvania and (bottom) the Barnett Shale in Texas.....	10-7
Figure 10-2. Fate and transport schematic for a spill of chemicals, hydraulic fracturing fluid, or produced water.....	10-11
Figure 10-3. Separation in measured depth between drinking water resources and hydraulically fractured intervals in wells.....	10-20

---

---

## List of Text Boxes

Text Box ES-1. Drinking Water Resources.....	ES-5
Text Box ES-2. Hydraulically Fractured Oil and Gas Production Wells.....	ES-7
Text Box ES-3. The EPA's <i>Study of the Potential Impacts of Hydraulic Fracturing for Oil and Gas on Drinking Water Resources</i> .....	ES-11
Text Box ES-4. FracFocus Chemical Disclosure Registry.....	ES-13
Text Box ES-5. County-Level Water Use for Hydraulic Fracturing.....	ES-16
Text Box ES-6. Examples of Hydraulic Fracturing Fluids.....	ES-19
Text Box ES-7. Chemical Mixing Equipment.....	ES-23
Text Box ES-8. Fracture Growth.....	ES-28
Text Box ES-9. Produced Water from Hydraulically Fractured Oil and Gas Production Wells.....	ES-34
Text Box ES-10. On-Site Storage of Produced Water. ....	ES-36
Text Box ES-11. Hydraulic Fracturing Wastewater Management.....	ES-39
Text Box 1-1. Regulatory Protection for Drinking Water Resources.....	1-7
Text Box 2-1. The Hydrologic Cycle.....	2-4
Text Box 2-2. El Paso's Use of Higher Salinity Water for Drinking Water.....	2-11
Text Box 3-1. Hydraulic Fracturing: Not New, but Different and Still Changing.....	3-4
Text Box 3-2. "Conventional" Versus "Unconventional." .....	3-7
Text Box 4-1. Using the EPA's FracFocus 1.0 Project Database to Estimate Water Use for Hydraulic Fracturing.....	4-20
Text Box 4-2. Hydraulic Fracturing Water Use as a Percentage of Water Availability Estimates.....	4-25
Text Box 4-3. Case Study: Water Profile of the Eagle Ford Play, Texas.....	4-30
Text Box 4-4. Case Study: Impact of Water Acquisition for Hydraulic Fracturing on Local Water Availability in the Upper Colorado River Basin.....	4-34
Text Box 4-5. Case Study: Impact of Water Acquisition for Hydraulic Fracturing on Local Water Availability in the Susquehanna River Basin.....	4-38
Text Box 5-1. The FracFocus Registry and EPA FracFocus Report.....	5-18
Text Box 5-2. Confidential Business Information (CBI).....	5-20
Text Box 5-3. Spills from Storage Units.....	5-34
Text Box 5-4. Spill from Additive (Crosslinker) Storage Tote.....	5-34
Text Box 5-5. Spill of Acid from Storage Container.....	5-36
Text Box 5-6. Spill of Gel Slurry during Mixing.....	5-36
Text Box 5-7. Spill of Hydraulic Fracturing Fluid from Blender.....	5-38
Text Box 5-8. Spill of Fluid from Fracture Pump.....	5-39
Text Box 5-9. Spill from Frac Head Failure.....	5-40

---

Text Box 5-10. EPA Review of State and Industry Spill Data: Characterization of Hydraulic Fracturing-Related Spills.....	5-41
Text Box 6-1. The Well File Review.....	6-9
Text Box 6-2. Dimock, Pennsylvania.....	6-11
Text Box 6-3. Stray Gas Migration.....	6-23
Text Box 6-4. Parker County, Texas.....	6-26
Text Box 6-5. Pavillion, Wyoming.....	6-47
Text Box 6-6. Monitoring at the Greene County, Pennsylvania, Hydraulic Fracturing Test Site.....	6-54
Text Box 6-7. Well Communication at a Horizontal Well near Innisfail, Alberta, Canada.....	6-63
Text Box 8-1. Temporal Trends in Wastewater Management – Experience of Pennsylvania.....	8-19
Text Box 8-2. Regulations Affecting Wastewater Management.....	8-21
Text Box 8-3. Wastewater Treatment Processes.....	8-28
Text Box 9-1. Applying Toxicological Data for Human Health Risk Assessment.....	9-5
Text Box 9-2. The EPA’s List of Chemicals Identified in Hydraulic Fracturing Fluids and/or Produced Water.....	9-9
Text Box 9-3. Toxicity Values for Hydraulic Fracturing-Related Chemicals.....	9-12
Text Box 10-1. Hydraulic Fracturing and Groundwater Quality Monitoring in California.....	10-25
Text Box 10-2. Causal Assessment and Hydraulic Fracturing Water Cycle Activities.....	10-27



---

## List of Acronyms/Abbreviations

<b><u>Acronym</u></b>	<b><u>Definition</u></b>
<b>2BE</b>	2-butoxyethanol
<b>ACToR</b>	Aggregated Computational Toxicology Resource database
<b>AME</b>	Acton Mickelson Environmental, Inc.
<b>AMEC</b>	AMEC Environment & Infrastructure, Inc.
<b>ANRC</b>	Arkansas Natural Resources Commission
<b>AO</b>	administrative order
<b>AOGC</b>	Arkansas Oil and Gas Commission
<b>API</b>	American Petroleum Institute
<b>ATSDR</b>	Agency for Toxic Substance and Disease Registry
<b>AWWA</b>	American Water Works Association
<b>BLM</b>	Bureau of Land Management
<b>BTEX</b>	benzene, toluene, ethylbenzene, and xylenes
<b>CARES</b>	Casella Altela Regional Environmental Services
<b>CASRN</b>	chemical abstract services registration number
<b>CBI</b>	confidential business information
<b>CBM</b>	coalbed methane
<b>CCST</b>	California Council on Science and Technology
<b>CDC</b>	Centers for Disease Control and Prevention
<b>CDWR</b>	Colorado Division of Water Resources
<b>CFR</b>	Code of Federal Regulations
<b>CICAD</b>	Concise International Chemical Assessment Document
<b>CM</b>	chemical mixing
<b>CMV</b>	commercial motor vehicle
<b>COGCC</b>	Colorado Oil and Gas Conservation Commission
<b>COWDF</b>	Commercial Oil Field Waste Disposal Facilities
<b>CWA</b>	Clean Water Act
<b>CWCB</b>	Colorado Water Conservation Board
<b>CWT</b>	centralized waste treatment
<b>CWTF</b>	centralized water treatment facility
<b>DBNM</b>	dibromochloronitromethane
<b>DBP</b>	disinfection byproduct
<b>DecaBDE</b>	decabromodiphenyl ether
<b>DfE</b>	Design for the Environment
<b>DI</b>	Drilling Info, Inc.
<b>DMA</b>	dimethylamine
<b>DMR</b>	Discharge Monitoring Report
<b>DNR</b>	Department of Natural Resources
<b>DO</b>	dissolved oxygen
<b>DOC</b>	dissolved organic carbon

---

<b>DOE</b>	U.S. Department of Energy
<b>DOGGR</b>	California Department of Conservation's Division of Oil, Gas & Geothermal Resources
<b>DOI</b>	U.S. Department of the Interior
<b>DOJ</b>	U.S. Department of Justice
<b>DOT</b>	U.S. Department of Transportation
<b>DRB</b>	Delaware River Basin
<b>DRO</b>	diesel range organics
<b>DWSHA</b>	Drinking Water Standards and Health Advisories
<b>ECHA</b>	European Chemicals Agency
<b>EERC</b>	Energy and Environmental Research Center, University of North Dakota
<b>EIA</b>	U.S. Energy Information Administration
<b>EPA</b>	U.S. Environmental Protection Agency
<b>EPA OW</b>	U.S. Environmental Protection Agency, Office of Water
<b>EPI</b>	estimation programs interface
<b>EPWU</b>	El Paso Water Utility
<b>ERCB</b>	Energy Resource Conservation Board
<b>ERG</b>	Eastern Research Group
<b>ESN</b>	Environmental Services Network
<b>ESOD</b>	erythrocyte Cu, Zn-superoxide dismutase
<b>EWI</b>	Energy Water Initiative
<b>FDA</b>	U.S. Food and Drug Administration
<b>FOIA</b>	Freedom of Information Act
<b>FRS</b>	fluids recovery services
<b>GES</b>	Groundwater & Environmental Services, Inc.
<b>GHGRP</b>	Greenhouse Gas Reporting Program
<b>GNB</b>	Government of New Brunswick
<b>GRAS</b>	generally recognized as safe
<b>GRO</b>	gasoline range organics
<b>GTI</b>	Gas Technology Institute
<b>GWPC</b>	Ground Water Protection Council
<b>HBCD</b>	hexabromocyclododecane
<b>HDPE</b>	high-density polyethylene
<b>HF</b>	hydraulic fracturing
<b>HHBP</b>	Human Health Benchmarks for Pesticides
<b>HISA</b>	Highly Influential Scientific Assessment
<b>HPG</b>	hydroxypropylguar
<b>HTS</b>	high throughput screening
<b>HUC</b>	hydrological unit code
<b>IAEA</b>	International Atomic Energy Agency
<b>IARC</b>	International Agency for Research on Cancer
<b>IHS</b>	Information Handling Services
<b>IOGCC</b>	Interstate Oil and Gas Compact Commission

---

---

<b>IPCC</b>	Intergovernmental Panel on Climate Change
<b>IPCS</b>	International Programme on Chemical Safety
<b>IRIS</b>	Integrated Risk Information System
<b>IUPAC</b>	International Union of Pure and Applied Chemistry
<b>KWO</b>	Kansas Water Office
<b>LDEQ</b>	Louisiana Department of Environmental Quality
<b>LOAEL</b>	lowest observed adverse effect level
<b>MCDA</b>	multicriteria decision analysis
<b>MCL</b>	maximum contaminant level
<b>MCLG</b>	maximum containment level goal
<b>MCOR</b>	Marcellus Center for Outreach and Research
<b>MGD</b>	million gallons per day
<b>MIT</b>	mechanical integrity test
<b>MMCF</b>	million cubic feet
<b>MRL</b>	minimum risk level
<b>MSC</b>	Marcellus shale coalition
<b>MTBE</b>	methyl tert-butyl ether
<b>MVR</b>	mechanical vapor recompression
<b>NAS</b>	National Academy of Sciences
<b>NDDMR</b>	North Dakota Department of Mineral Resources
<b>NDDOH</b>	North Dakota Department of Health
<b>NDMA</b>	N-nitrosodimethylamine
<b>NDPES</b>	National Pollution Discharge Elimination System
<b>NDSWC</b>	North Dakota State Water Commission
<b>NETL</b>	National Energy Technology Laboratory
<b>NGO</b>	non-governmental organization
<b>NIH</b>	National Institutes of Health
<b>NM OCD</b>	New Mexico Oil Conservation Division
<b>NM OSE</b>	New Mexico Office of the State Engineer
<b>NOAEL</b>	no observed adverse effect level
<b>NORM</b>	naturally occurring radioactive material
<b>NPC</b>	National Petroleum Council
<b>NPDES</b>	National Pollution Discharge Elimination System
<b>NPDWR</b>	National Primary Drinking Water Regulations
<b>NRC</b>	National Resource Council
<b>NTP</b>	U.S. National Toxicology Program
<b>NYSDEC</b>	New York State Department of Environmental Conservation
<b>O&amp;G</b>	oil and gas
<b>ODNR</b>	Ohio Department of Natural Resources
<b>DMRM</b>	Division of Mineral Resources Management
<b>OECD</b>	The Organisation for Economic Co-operation and Development

---

---

<b>OEPA</b>	Ohio Environmental Protection Agency
<b>OMB</b>	Office of Management and Budget
<b>ORB</b>	Ohio River Basin
<b>ORD</b>	Office of Research and Development
<b>OSF</b>	oral slope factor
<b>OSHA</b>	Occupational Safety & Health Administration
<b>OSWER</b>	Office of Solid Water and Emergency Response
<b>OWRB</b>	Oklahoma Water Resources Board
<b>PA DCNR</b>	Pennsylvania Department of Conservation and Natural Resources
<b>PA DEP</b>	Pennsylvania Department of Environmental Protection
<b>PAH</b>	polycyclic aromatic hydrocarbon
<b>PCB</b>	polychlorinated biphenyl
<b>PFBC</b>	Pennsylvania Fish and Boat Commission
<b>PDL</b>	positive determination letter
<b>PMF</b>	Positive Matrix Factorization
<b>PMN</b>	pre-manufacturing notices
<b>POD</b>	point-of-departure
<b>POTW</b>	publicly owned treatment work
<b>PPRTV</b>	provisional peer-reviewed toxicity value
<b>PVC</b>	polyvinyl chloride
<b>PWS</b>	public water system
<b>PWSA</b>	Pittsburgh Water and Sewer Authority
<b>QA</b>	quality assurance
<b>QAPP</b>	quality assurance project plan
<b>QC</b>	quality control
<b>QSAR</b>	Quantitative Structure Activity Relationship
<b>RAHC</b>	reasonably anticipated to be a human carcinogen
<b>RBC</b>	red blood cells
<b>RfD</b>	reference dose
<b>RfV</b>	reference value
<b>RO</b>	reverse osmosis
<b>SAB</b>	Science Advisory Board
<b>SAIC</b>	Science Applications International Corporation
<b>SAR</b>	sodium adsorption ratio
<b>SCN</b>	thiocyanates
<b>SDWA</b>	Safe Drinking Water Act
<b>SDWIS</b>	Safe Drinking Water Information System
<b>SEECO</b>	Southern Electrical Equipment Company
<b>SGEIS</b>	supplemented generic environmental impact statement
<b>SHS MSC</b>	statewide health standards for medium-specific concentrations
<b>SMCL</b>	secondary maximum contaminant level
<b>SPE</b>	Society of Petroleum Engineers

---

---

<b>SRB</b>	Susquehanna River basin
<b>SRBC</b>	Susquehanna River Basin Commission
<b>STO</b>	Statoil
<b>STRONGER</b>	State review of oil and natural gas environmental regulations
<b>SVOC</b>	semi-volatile organic compounds
<b>SWE</b>	Southwestern Energy
<b>TARM</b>	TerrAqua Resource Management
<b>TBA</b>	tert-butyl alcohol
<b>TDI</b>	tolerable daily intake
<b>TDS</b>	total dissolved solids
<b>TENORM</b>	technologically enhanced naturally occurring radioactive material
<b>THM</b>	trihalomethane
<b>TIPRO</b>	Texas Independent Producers and Royalty Owners Association
<b>TMDL</b>	total maximum daily load
<b>TOC</b>	total organic carbon
<b>TOPKAT</b>	Toxicity Prediction by Komputer Assisted Technology
<b>TPH</b>	total petroleum hydrocarbons
<b>TPHWG</b>	Total Petroleum Hydrocarbon Criteria Working Group
<b>TSS</b>	total suspended solids
<b>TTC</b>	Threshold of Toxicological Concern
<b>TTHM</b>	total trihalomethane
<b>TWDB</b>	Texas Water Development Board
<b>TXRRC</b>	Texas Railroad Commission
<b>UCRB</b>	Upper Colorado River basin
<b>UIC</b>	underground injection control
<b>UOG</b>	unconventional oil and gas
<b>USGAO</b>	U.S. Government Accountability Office
<b>USGS</b>	U.S. Geological Survey
<b>UWS</b>	Universal Well Services
<b>VES</b>	viscoelastic surfactant
<b>VOC</b>	volatile organic compounds
<b>WAWSA</b>	Western Area Water Supply Authority
<b>WFR</b>	Well File Review
<b>WHO</b>	World Health Organization
<b>WOE</b>	weight of evidence
<b>WRF</b>	Water Research Foundation
<b>WVDEP</b>	West Virginia Department of Environmental Protection
<b>WWTP</b>	wastewater treatment plant
<b>WYOGCC</b>	Wyoming Oil and Gas Conservation Commission

---

## Preface

Hydraulic fracturing is a technique used to increase oil and gas production from underground oil- or gas-bearing rock formations. Since the mid-2000s, the combination of hydraulic fracturing and directional drilling has become widespread, raising concerns about the potential impacts of hydraulic fracturing on drinking water resources. This concern is the focus of this report.

In 2010, the U.S. Environmental Protection Agency (EPA) initiated a study of the potential impacts of hydraulic fracturing activities on drinking water resources. The EPA defined the scope of its study to focus on the acquisition, use, disposal, and reuse of water used for hydraulic fracturing—what we call the hydraulic fracturing water cycle. This was done in recognition that concerns raised about potential impacts were not limited to the relatively short-term act of fracturing rock, but can include impacts related to other activities associated with hydraulic fracturing.

The EPA's study included the development of multiple research projects using the following research approaches: the analysis of existing data, scenario and modeling evaluations, laboratory studies, toxicological assessments, and five case studies. Throughout the study, the EPA engaged with stakeholders, including industry, the states, tribal nations, academia, and others, for input on the scope, approach, and initial results. To date, the study has resulted in the publication of multiple peer-reviewed scientific products, including 13 EPA technical reports and 14 journal articles.

This report represents the capstone product of the EPA's hydraulic fracturing drinking water study. It captures the state-of-the-science concerning drinking water impacts from activities in the hydraulic fracturing activities water cycle and integrates the results of the EPA's study of the subject with approximately 1,200 other publications and sources of information. The goals of this report were to assess the potential for activities in the hydraulic fracturing water cycle to impact the quality or quantity of drinking water resources and to identify factors that affect the frequency or severity of those impacts.

This report is a science document and does not present or evaluate policy options or make policy recommendations. A draft of this report was reviewed by the EPA's independent Science Advisory Board (SAB). Reflecting the complexity of the subject, the expert ad hoc panel formed by the SAB was the largest ever convened for the review of a scientific product. Combined with over 100,000 comments submitted by members of the public, SAB comments helped the EPA to refine, clarify, and better support the final conclusions presented in this report.

The release of this final assessment report marks the completion of the EPA's hydraulic fracturing drinking water study. The study has already prompted increased dialogue among industry, the states, tribal nations, the public, and others concerning how drinking water resources can be better protected in areas where hydraulic fracturing is occurring or being considered. However, there are data gaps and uncertainties limiting our understanding of the impacts of hydraulic fracturing activities on drinking water resources. As additional data become available, and with continued dialogue among stakeholders, our understanding of the potential impacts of hydraulic fracturing on drinking water resources will improve.



---

## **Authors, Contributors, and Reviewers**

### **Authors of the Final Assessment (EPA 600-R-16-236Fa and EPA 600-R-16-236Fb)**

Susan Burden, USEPA-Office of Research and Development, Washington, DC  
Megan M. Fleming, USEPA-Office of Research and Development, Washington, DC  
Jeffrey Frithsen, USEPA-Office of Research and Development, Washington, DC  
Linda Hills, The Cadmus Group, Inc., Helena, MT  
Kenneth Klewicki, The Cadmus Group, Inc., Arlington, VA  
Christopher D. Knightes, USEPA-Office of Research and Development, Athens, GA  
Sandie Koenig, The Cadmus Group, Inc., Helena, MT  
Jonathan Koplos, The Cadmus Group, Inc., Waltham, MA  
Stephen D. LeDuc, USEPA-Office of Research and Development, Washington, DC  
Caroline E. Ridley, USEPA-Office of Research and Development, Washington, DC  
Shari Ring, The Cadmus Group, Inc., Arlington, VA  
Sarah Solomon, Student Services Contractor, USEPA-Office of Research and Development, Washington, DC  
John Stanek, USEPA-Office of Research and Development, Research Triangle Park, NC  
Mary Ellen Tuccillo, The Cadmus Group, Inc., Waltham, MA  
Jim Weaver, USEPA-Office of Research and Development, Ada, OK  
Anna Weber, The Cadmus Group, Inc., Arlington, VA  
Nathan Wiser, USEPA-Office of Research and Development, Denver, CO  
Erin Yost, USEPA-Office of Research and Development, Research Triangle Park, NC

### **Authors of the June 2015 External Review Draft (EPA-600-R-15-047a)**

William Bates, USEPA-Office of Water, Washington, DC  
Glen Boyd, The Cadmus Group, Inc., Seattle, WA  
Jeanne Briskin, USEPA-Office of Research and Development, Washington, DC  
Lyle Burgoon, USEPA-Office of Research and Development, Research Triangle Park, NC; currently with  
US-ACOE, Research Triangle Park, NC  
Susan Burden, USEPA-Office of Research and Development, Washington, DC  
Christopher M. Clark, USEPA-Office of Research and Development, Washington, DC  
Maryam Cluff, Student Services Contractor, USEPA-Office of Research and Development, Washington, DC  
Rebecca Daiss, USEPA-Office of Research and Development, Washington, DC  
Jill Dean, USEPA-Office of Water, Washington, DC  
Inci Demirkanli, The Cadmus Group, Inc., Arlington, VA  
Megan M. Fleming, USEPA-Office of Research and Development, Washington, DC  
Jeffrey Frithsen, USEPA-Office of Research and Development, Washington, DC  
Linda Hills, The Cadmus Group, Inc., Helena, MT  
Kenneth Klewicki, The Cadmus Group, Inc., Arlington, VA  
Christopher D. Knightes, USEPA-Office of Research and Development, Athens, GA  
Sandie Koenig, The Cadmus Group, Inc., Helena, MT  
Jonathan Koplos, The Cadmus Group, Inc., Waltham, MA  
Stephen D. LeDuc, USEPA-Office of Research and Development, Washington, DC

---

Claudia Meza-Cuadra, Student Services Contractor, USEPA-Office of Research and Development, Washington, DC  
Brent Ranalli, The Cadmus Group, Inc., Waltham, MA  
Caroline E. Ridley, USEPA-Office of Research and Development, Washington, DC  
Shari Ring, The Cadmus Group, Inc., Arlington, VA  
Alison Singer, Student Services Contractor, USEPA-Office of Research and Development, Washington, DC  
John Stanek, USEPA-Office of Research and Development, Research Triangle Park, NC  
M. Jason Todd, USEPA-Office of Research and Development, Washington, DC  
Mary Ellen Tuccillo, The Cadmus Group, Inc., Waltham, MA  
Jim Weaver, USEPA-Office of Research and Development, Ada, OK  
Anna Weber, The Cadmus Group, Inc., Arlington, VA  
Larke Williams, USEPA-Office of Research and Development, Washington, DC; currently with the US State Department, Washington, DC  
Liabeth Yohannes, Student Services Contractor, USEPA-Office of Research and Development, Washington, DC  
Erin Yost, USEPA-Office of Research and Development, Research Triangle Park, NC

### **Contributors**

Maryam Akhavan, The Cadmus Group, Inc., Arlington, VA  
Natalie Auer, The Cadmus Group, Inc., Arlington, VA  
Kevin Blackwood, Student Services Contractor, USEPA-Office of Research and Development, Ada, OK  
Alison Cullity, The Cadmus Group, Rollinsford, NH  
Rob Dewoskin, USEPA-Office of Research and Development, Research Triangle Park, NC  
Krissy Downing, The Cadmus Group, Inc., Seattle, WA  
Christopher Impellitteri, USEPA-Office of Research and Development, Cincinnati, OH  
Will Jobs, The Cadmus Group, Inc., Waltham, MA  
Richard Judson, USEPA-Office of Research and Development, Research Triangle Park, NC  
Erina Keefe, The Cadmus Group, Waltham, MA  
Ava Lazor, The Cadmus Group, Inc., Arlington, VA  
Matt Landis, USEPA-Office of Research and Development, Research Triangle Park, NC  
Ralph Ludwig, USEPA-Office of Research and Development, Ada, OK  
John Martin, The Cadmus Group, Inc., Waltham, MA  
Ashley McElmury, Student Services Contractor, USEPA-Office of Research and Development, Ada, OK  
Gary Norris, USEPA-Office of Research and Development, Research Triangle Park, NC  
Kay Pinley, Senior Environmental Employment Program, USEPA-Office of Research and Development, Ada, OK  
Jesse Pritts, USEPA-Office of Water, Washington, DC  
Ann Richard, USEPA-Office of Research and Development, Research Triangle Park, NC  
Ana Rosner, The Cadmus Group, Inc., Waltham, MA  
Susan Sharkey, USEPA-Office of Research and Development, Washington, DC  
Jessica Wilhelm, Student Services Contractor, USEPA-Office of Research and Development, Ada, OK  
Holly Wooten, The Cadmus Group, Inc., Arlington, VA  
Jie Xu, Student Services Contractor, USEPA-Office of Research and Development, Ada, OK

---

## **U.S. Environmental Protection Agency Science Advisory Board**

Joseph Arvai, University of Michigan, Ann Arbor, MI  
Kiros T. Berhane, University of Southern California, Los Angeles, CA  
Sylvie M. Brouder, Purdue University, West Lafayette, IN  
Ingrid Burke, University of Wyoming, Laramie, WY  
Thomas Carpenter, Designated Federal Officer, U.S. Environmental Protection Agency, Science Advisory Board, Washington, DC  
Ana V. Diez Roux, Drexel University, Philadelphia, PA  
Michael Dourson, University of Cincinnati, Cincinnati, OH  
Joel J. Ducoste, North Carolina State University, Raleigh, NC  
David A. Dzombak, Carnegie Mellon University, Pittsburgh, PA  
Elaine M. Faustman, University of Washington, Seattle, WA  
Susan P. Felter, Proctor & Gamble, Mason, OH  
R. William Field, University of Iowa, Iowa City, IA  
H. Christopher Frey, North Carolina State University, Raleigh, NC  
Steven Hamburg, Environmental Defense Fund, Boston, MA  
Cynthia M. Harris, Florida A&M University, Tallahassee, FL  
Robert J. Johnston, Clark University, Worcester, MA  
Kimberly L. Jones, Howard University, Washington, DC  
Catherine J. Karr, University of Washington, Seattle, WA  
Madhu Khanna, University of Illinois at Urbana-Champaign, Urbana, IL  
Francine Laden, Brigham and Women's Hospital and Harvard Medical School, Boston, MA  
Lois Lehman-McKeeman, Bristol-Myers Squibb, Princeton, NJ  
Robert E. Mace, Texas Water Development Board, Austin, TX  
Mary Sue Marty, The Dow Chemical Company, Midland, MI  
Denise Mauzerall, Princeton University, Princeton, NJ  
Kristina D. Mena, University of Texas Health Science Center at Houston, El Paso, TX  
Surabi Menon, ClimateWorks Foundation, San Francisco, CA  
James R. Mihelcic, University of South Florida, Tampa, FL  
Keith H. Moo-Young, Washington State University, Tri-Cities, Richland, WA  
Kari Nadeau, Stanford University School of Medicine, Stanford, CA  
James Opaluch, University of Rhode Island, Kingston, RI  
Thomas F. Parkerton, ExxonMobil Biomedical Science, Houston, TX  
Richard L. Poirot, Independent Consultant, Burlington, VT  
Kenneth M. Portier, American Cancer Society, Atlanta, GA  
Kenneth Ramos, University of Arizona, Tucson, AZ  
David B. Richardson, University of North Carolina, Chapel Hill, NC  
Tara L. Sabo-Attwood, University of Florida, Gainesville, FL  
William Schlesinger, Cry Institute of Ecosystem Studies, Millbrook, NY  
Gina Solomon, California Environmental Protection Agency, Sacramento, CA  
Daniel O. Stram, University of Southern California, Los Angeles, CA  
Peter S. Thorne (Chair), University of Iowa, Iowa City, IA

---

Jay Turner, Washington University, St. Louis, MO  
Edwin van Wijngaarden, University of Rochester, Rochester, NY  
Jeanne M. VanBriesen, Carnegie Mellon University, Pittsburgh, PA  
John Vena, Medical University of South Carolina, Charleston, SC  
Elke Weber, Columbia Business School, New York, NY  
Charles Werth, University of Texas at Austin, Austin, TX  
Peter J. Wilcoxon, Syracuse University, Syracuse, NY  
Robyn S. Wilson, The Ohio State University, Columbus, OH

**U.S. Environmental Protection Agency Science Advisory Board Hydraulic Fracturing  
Research Advisory Panel**

Stephen W. Almond, Fritz Industries, Inc., Houston, TX  
E. Scott Bair, The Ohio State University, Columbus, OH  
Peter Bloomfield, North Carolina State University, Raleigh, NC  
Steven R. Bohlen, State of California Department of Conservation, Sacramento, CA  
Elizabeth W. Boyer, Pennsylvania State University, University Park, PA  
Susan L. Brantley, Pennsylvania State University, University Park, PA  
James V. Bruckner, University of Georgia, Athens, GA  
Thomas L. Davis, Colorado School of Mines, Golden, CO  
Joseph J. DeGeorge, Merck Research Laboratories, Lansdale, PA  
Joel Ducoste, North Carolina State University, Raleigh, NC  
Shari Dunn-Norman, Missouri University of Science and Technology, Rolla, MO  
David A. Dzombak (Chair), Carnegie Mellon University, Pittsburgh, PA  
Katherine Bennett Ensor, Rice University, Houston, TX  
Elaine M. Faustman, University of Washington, Seattle, WA  
John V. Fontana, Vista GeoScience LLC, Golden, CO  
Daniel J. Goode, U.S. Geological Survey, Exton, PA  
Edward Hanlon, Designated Federal Officer, U.S. Environmental Protection Agency, Science Advisory  
Board Staff, Washington, DC  
Bruce D. Honeyman, Colorado School of Mines, Golden, CO  
Walter R. Hufford, Talisman Energy USA Inc. – REPSOL, Warrendale, PA  
Richard F. Jack, Thermo Fisher Scientific Inc., San Jose, CA  
Dawn S. Kaback, Amec Foster Wheeler, Denver, CO  
Abby A. Li, Exponent Inc., San Francisco, CA  
Dean N. Malouta, White Mountain Energy Consulting, LLC, Houston, TX  
Cass T. Miller, University of North Carolina, Chapel Hill, NC  
Laura J. Pyrak-Nolte, Purdue University, West Lafayette, IN  
Stephen Randtke, University of Kansas, Lawrence, KS  
Joseph N. Ryan, University of Colorado-Boulder, Boulder, CO  
James E. Saiers, Yale University, New Haven, CT  
Azra N. Tutuncu, Colorado School of Mines, Golden, CO  
Paul K. Westerhoff, Arizona State University, Tempe, AZ  
Thomas M. Young, University of California-Davis, Davis, CA

---

## **U.S. Environmental Protection Agency Internal Technical Reviewers**

Lisa Biddle, Office of Water, Washington, DC  
Britta Bierwagen, Office of Research and Development, Washington, DC  
Frank Brock, Region 2, New York, NY  
Thomas Burke, Office of Research and Development, Washington, DC  
Kyle Carey, Office of Water, Washington, DC  
Mark Corrales, Office of Policy, Washington, DC  
Brian D'Amico, Office of Water, Washington, DC  
Kathleen Deener, Office of Research and Development, Washington, DC  
Tim Elkins, Region 5, Chicago, IL  
Malcolm Field, Office of Research and Development, Washington, DC  
Erin Floto, Region 2, New York, NY  
Robert Ford, Office of Research and Development, Cincinnati, OH  
Greg Fritz, Office of Chemical Safety and Pollution Prevention, Washington, DC  
Andrew Gillespie, Office of Research and Development, Research Triangle Park, NC  
Janet Goodwin, Office of Water, Washington, DC  
Bradley Grams, Region 5, Chicago, IL  
Holly Green, Office of Water, Washington, DC  
Richard Hall, Region 4, Atlanta, GA  
Mary Hanley, Administrator's Office, Washington, DC  
Mohamed Hantush, Office of Research and Development, Cincinnati, OH  
Jana Harvill, Region 6, Dallas, TX  
Fred Hauchman, Office of Science Policy, Washington, DC  
Kurt Hildebrandt, Region 7, Lenexa, KS  
Charles Hillenbrand, Region 2, New York, NY  
Mark W. Howard, Office of Solid Waste and Emergency Response, Washington, DC  
Junqi Huang, Office of Research and Development, Ada, OK  
Stephen Jann, Region 5, Chicago, IL  
Thomas Johnson, Office of Research and Development, Washington, DC  
Jeff Jollie, Office of Water, Washington, DC  
Robert Kavlock, Office of Research and Development, Washington, DC  
James Kenney, Office of Enforcement and Compliance Assurance, Washington, DC  
Kristin Keteles, Region 8, Denver, CO  
Bruce Kobelski, Office of Water, Washington, DC  
Stephen Kraemer, Office of Research and Development, Athens, GA  
Paul Lewis, Office of Chemical Safety and Pollution Prevention, Washington, DC  
Chris Lister, Region 6, Dallas, TX  
Barbara Martinez, ORISE Fellow to USEPA-Office of Research and Development, Washington, DC  
Mike Mattheisen, Office of Chemical Safety and Pollution Prevention, Washington, DC  
Damon McElroy, Region 6, Dallas, TX  
Karen Milam, Office of Water, Washington, DC  
Keara Moore, Office of Water, Washington, DC

---

Nathan Mottl, Office of Chemical Safety and Pollution Prevention, Washington, DC  
Greg Oberley, Region 8, Denver, CO  
Mike Overbay, Region 6, Dallas, TX  
Pooja Parikh, Office of General Council, Washington, DC  
Dale Perry, Administrator's Office, Washington, DC  
Tricia Pfeiffer, Region 8, Denver, CO  
Steve Platt, Region 3, Philadelphia, PA  
Dave Rectenwald, Region 3, Philadelphia, PA  
Meredith Russell, Office of Water, Washington, DC  
Daniel Ryan, Region 3, Philadelphia, PA  
Greg Schweer, Office of Chemical Safety and Pollution Prevention, Washington, DC  
Brian Smith, Region 4, Atlanta, GA  
Kelly Smith, Office of Research and Development, Cincinnati, OH  
Steve Souders, Office of Solid Waste and Emergency Response, Washington, DC  
Kate Sullivan, Office of Research and Development, Athens, GA  
Kevin Teichman, Office of Research and Development, Washington, DC  
Chuck Tinsley, Region 8, Denver, CO  
Scott Wilson, Office of Water, Washington, DC  
Jose Zambrana, Office of Research and Development, Washington, DC

---

## Acknowledgements

The development of this assessment involved individuals from across the Agency, many of which have been listed as authors, contributors or reviewers, or acknowledged below. We want to specifically highlight and acknowledge Jeanne Briskin for her role with making the EPA's Hydraulic Fracturing Drinking Water Study a success. Jeanne was responsible for the development of the 2011 Study Plan and for coordinating the implementation of the projects outlined in that Study Plan. Jeanne also played a large role with reaching out to stakeholders for input that informed the development of the reports and publications resulting from Study Plan projects, and the development of this assessment. We also want to acknowledge Fred Hauchman for providing senior leadership during the development of the Hydraulic Fracturing Drinking Water Study.

Other individuals who have made this assessment report possible and have not been previously mentioned include: Jessica Agatstein, Adam Banasiak, Tom Beneke, Amy Bergdale, Ann Calamai, Amy Clark, Brian Devir, Dayna Gibbons, Chris Grulke, Seth Haines, H. Jason Harmon, Cheryl Itkin, Maureen Johnson, Randy Lamdin, Audrey Levine, Jordan Macknick, Kelsey Maloney, Lisa Matthews, Angela McFadden, Connie Meacham, Marc Morandi, Jean-Philippe Nicot, Jennifer Orme-Zavaleta, Nancy Parrotta, Robert Puls, Bridget R. Scanlon, Ayn Schmit, Cynthia Sonich-Mullen, Vicki Soto, Inthirany Thillainadarajah, Vincent Tidwell, Martha Walters, and Steve Watkins.

Contract support was provided by The Cadmus Group, Inc. under contracts EP-C-08-015 and EP-C-15-022 and by Neptune & Co., Inc. under contract EP-C-13-022. Authors and contributors included student service contractors to USEPA: Kevin Blackwood (Contract EP-13-C-000133); Maryam Cluff (Contract EP-13-H-000438); Ashley McElmury (Contract EP-12-C-000025); Claudia Meza-Cuadra (Contract EP-13-H-000054); Alison Singer (Contract EP-13-H-000474); Sarah Solomon (Contract EP-D-15-003); Jessica Wilhelm (Contract EP-D-15-003); Jie Xu (Contract EP-13-C-00120); Liabeth Yohannes (Contract EP-14-H-000455). Kay Pinley was supported under the Senior Environmental Employment Program under agreement CQ-835363 with NCCBA.

---

This page is intentionally left blank.



---

# **Executive Summary**

This page is intentionally left blank.

## Executive Summary

People rely on clean and plentiful water resources to meet their basic needs, including drinking, bathing, and cooking. In the early 2000s, members of the public began to raise concerns about potential impacts on their drinking water from hydraulic fracturing at nearby oil and gas production wells. In response to these concerns, Congress urged the U.S. Environmental Protection Agency (EPA) to study the relationship between hydraulic fracturing for oil and gas and drinking water in the United States.

The goals of the study were to assess the potential for activities in the hydraulic fracturing water cycle to impact the quality or quantity of drinking water resources and to identify factors that affect the frequency or severity of those impacts. To achieve these goals, the EPA conducted independent research, engaged stakeholders through technical workshops and roundtables, and reviewed approximately 1,200 cited sources of data and information. The data and information gathered through these efforts served as the basis for this report, which represents the culmination of the EPA's study of the potential impacts of hydraulic fracturing for oil and gas on drinking water resources.

The hydraulic fracturing water cycle describes the use of water in hydraulic fracturing, from water withdrawals to make hydraulic fracturing fluids, through the mixing and injection of hydraulic fracturing fluids in oil and gas production wells, to the collection and disposal or reuse of produced water. These activities can impact drinking water resources under some circumstances. Impacts can range in frequency and severity, depending on the combination of hydraulic fracturing water cycle activities and local- or regional-scale factors. The following combinations of activities and factors are more likely than others to result in more frequent or more severe impacts:

- Water withdrawals for hydraulic fracturing in times or areas of low water availability, particularly in areas with limited or declining groundwater resources;
- Spills during the management of hydraulic fracturing fluids and chemicals or produced water that result in large volumes or high concentrations of chemicals reaching groundwater resources;
- Injection of hydraulic fracturing fluids into wells with inadequate mechanical integrity, allowing gases or liquids to move to groundwater resources;
- Injection of hydraulic fracturing fluids directly into groundwater resources;
- Discharge of inadequately treated hydraulic fracturing wastewater to surface water resources; and
- Disposal or storage of hydraulic fracturing wastewater in unlined pits, resulting in contamination of groundwater resources.

The above conclusions are based on cases of identified impacts and other data, information, and analyses presented in this report. Cases of impacts were identified for all stages of the hydraulic fracturing water cycle. Identified impacts generally occurred near hydraulically fractured oil and

gas production wells and ranged in severity, from temporary changes in water quality to contamination that made private drinking water wells unusable.

The available data and information allowed us to qualitatively describe factors that affect the frequency or severity of impacts at the local level. However, significant data gaps and uncertainties in the available data prevented us from calculating or estimating the national frequency of impacts on drinking water resources from activities in the hydraulic fracturing water cycle. The data gaps and uncertainties described in this report also precluded a full characterization of the severity of impacts.

The scientific information in this report can help inform decisions by federal, state, tribal, and local officials; industry; and communities. In the short-term, attention could be focused on the combinations of activities and factors outlined above. In the longer-term, attention could be focused on reducing the data gaps and uncertainties identified in this report. Through these efforts, current and future drinking water resources can be better protected in areas where hydraulic fracturing is occurring or being considered.

## **Drinking Water Resources in the United States**

In this report, drinking water resources are defined as any water that now serves, or in the future could serve, as a source of drinking water for public or private use. This includes both surface water resources and groundwater resources (Text Box ES-1). In 2010, approximately 58% of the total volume of water withdrawn for public and non-public water supplies came from surface water resources and approximately 42% came from groundwater resources ([Maupin et al., 2014](#)).<sup>1</sup> Most people (86% of the population) in the United States relied on public water supplies for their drinking water in 2010, and approximately 14% of the population obtained drinking water from non-public water supplies. Non-public water supplies are often private water wells that supply drinking water to a residence.

Future access to high-quality drinking water in the United States will likely be affected by changes in climate and water use. Since 2000, about 30% of the total area of the contiguous United States has experienced moderate drought conditions and about 20% has experienced severe drought conditions. Declines in surface water resources have led to increased withdrawals and net depletions of groundwater in some areas. As a result, non-fresh water resources (e.g., wastewater from sewage treatment plants, brackish groundwater and surface water, and seawater) are increasingly treated and used to meet drinking water demand.

Natural processes and human activities can affect the quality and quantity of current and future drinking water resources. This report focuses on the potential for activities in the hydraulic fracturing water cycle to impact drinking water resources; other processes or activities are not discussed.

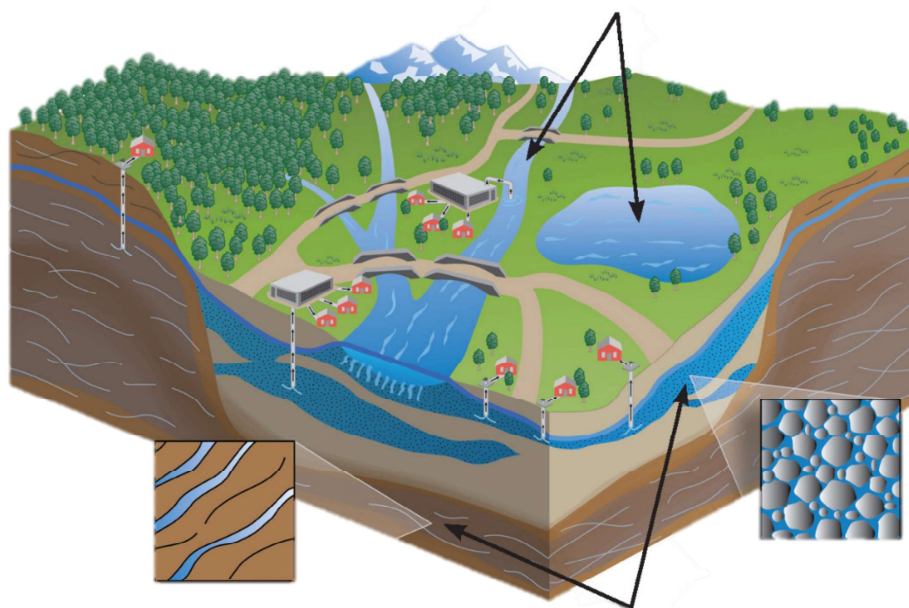
---

<sup>1</sup> Public water systems provide water for human consumption from surface or groundwater through pipes or other infrastructure to at least 15 service connections or serve an average of at least 25 people for at least 60 days a year. Non-public water systems have fewer than 15 service connections and serve fewer than 25 individuals.

### Text Box ES-1. Drinking Water Resources.

In this report, drinking water resources are considered to be any water that now serves, or in the future could serve, as a source of drinking water for public or private use. This includes both surface water bodies and underground rock formations that contain water.

**Surface water resources** include water bodies located on the surface of the Earth. Rivers, springs, lakes, and reservoirs are examples of surface water resources. Water quality and quantity are often considered when determining whether a surface water resource could be used as a drinking water resource.

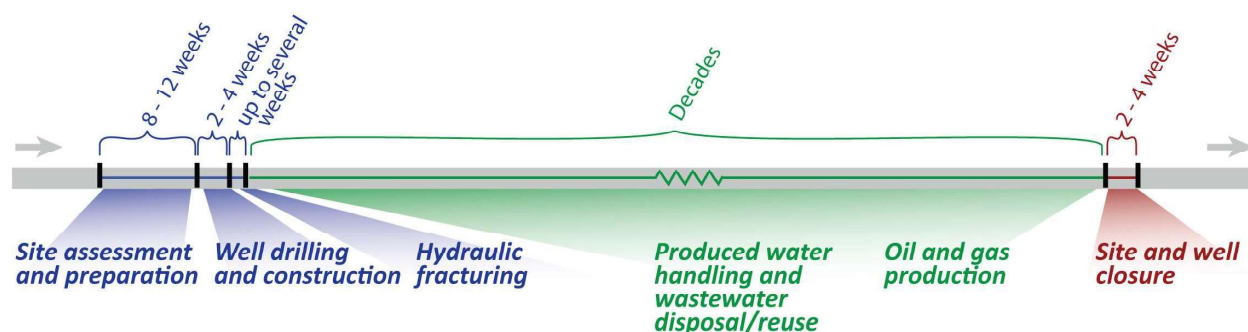


**Groundwater resources** are underground rock formations that contain water. Groundwater resources are found at different depths nearly everywhere in the United States. Resource depth, water quality, and water yield are often considered when determining whether a groundwater resource could be used as a drinking water resource.

## Hydraulic Fracturing for Oil and Gas in the United States

Hydraulic fracturing is frequently used to enhance oil and gas production from underground rock formations and is one of many activities that occur during the life of an oil and gas production well (Figure ES-1). During hydraulic fracturing, hydraulic fracturing fluid is injected down an oil or gas production well and into the targeted rock formation under pressures great enough to fracture the oil- and gas-bearing rock.<sup>1</sup> The hydraulic fracturing fluid usually carries proppant (typically sand) into the newly-created fractures to keep the fractures “propped” open. After hydraulic fracturing, oil, gas, and other fluids flow through the fractures and up the production well to the surface, where they are collected and managed.

<sup>1</sup> The targeted rock formation (sometimes called the “target zone” or “production zone”) is the portion of a subsurface rock formation that contains the oil or gas to be extracted.



**Figure ES-1. General timeline and summary of activities at a hydraulically fractured oil or gas production well.**

Hydraulically fractured oil and gas production wells have significantly contributed to the surge in domestic oil and gas production, accounting for slightly more than 50% of oil production and nearly 70% of gas production in 2015 ([EIA, 2016c, d](#)). The surge occurred when hydraulic fracturing was combined with directional drilling technologies around 2000. Directional drilling allows oil and gas production wells to be drilled horizontally or directionally along the targeted rock formation, exposing more of the oil- or gas-bearing rock formation to the production well. When combined with directional drilling technologies, hydraulic fracturing expanded oil and gas production to oil- and gas-bearing rock formations previously considered uneconomical. Although hydraulic fracturing is commonly associated with oil and gas production from deep, horizontal wells drilled into shale (e.g., the Marcellus Shale in Pennsylvania or the Bakken Shale in North Dakota), it has been used in a variety of oil and gas production wells (Text Box ES-2) and other types of oil- or gas-bearing rock (e.g., sandstone, carbonate, and coal).

Approximately 1 million wells have been hydraulically fractured since the technique was first developed in the late 1940s ([Gallegos and Varela, 2015](#); [IOGCC, 2002](#)). Roughly one third of those wells were hydraulically fractured between 2000 and approximately 2014. Wells hydraulically fractured between 2000 and 2013 were located in pockets of activity across the United States (Figure ES-2). Based on several different data compilations, we estimate that 25,000 to 30,000 new wells were drilled and hydraulically fractured in the United States each year between 2011 and 2014, in addition to existing wells that were hydraulically fractured to increase production.<sup>1</sup> Following the decline in oil and gas prices, the number of new wells drilled and hydraulically fractured appears to have decreased, with about 20,000 new wells drilled and hydraulically fractured in 2015.

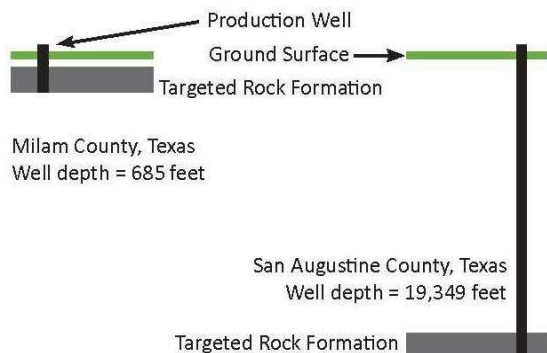
<sup>1</sup> See Table 3-1 in Chapter 3.

## Text Box ES-2. Hydraulically Fractured Oil and Gas Production Wells.

Hydraulically fractured oil and gas production wells come in different shapes and sizes. They can have different depths, orientations, and construction characteristics. They can include new wells (i.e., wells that are hydraulically fractured soon after construction) and old wells (i.e., wells that are hydraulically fractured after producing oil and gas for some time).

### Well Depth

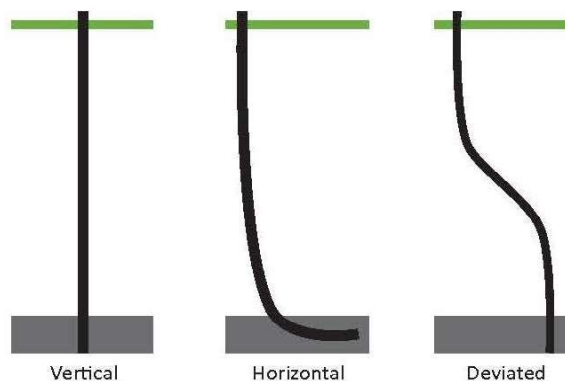
Wells can be relatively shallow or relatively deep, depending on the depth of the targeted rock formation.



Well depths and locations from *FracFocus.org*.

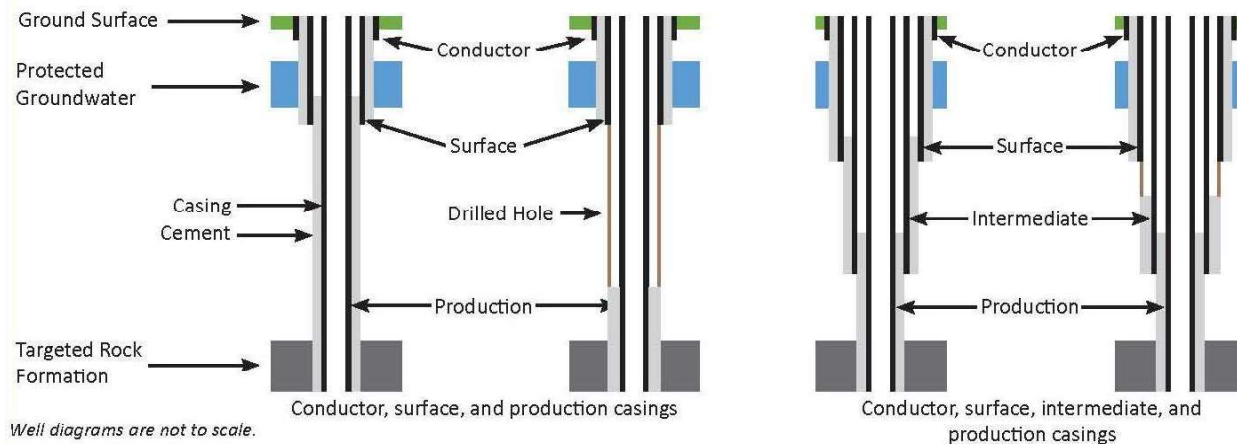
### Well Orientation

Wells can be vertical, horizontal, or deviated.



### Well Construction Characteristics

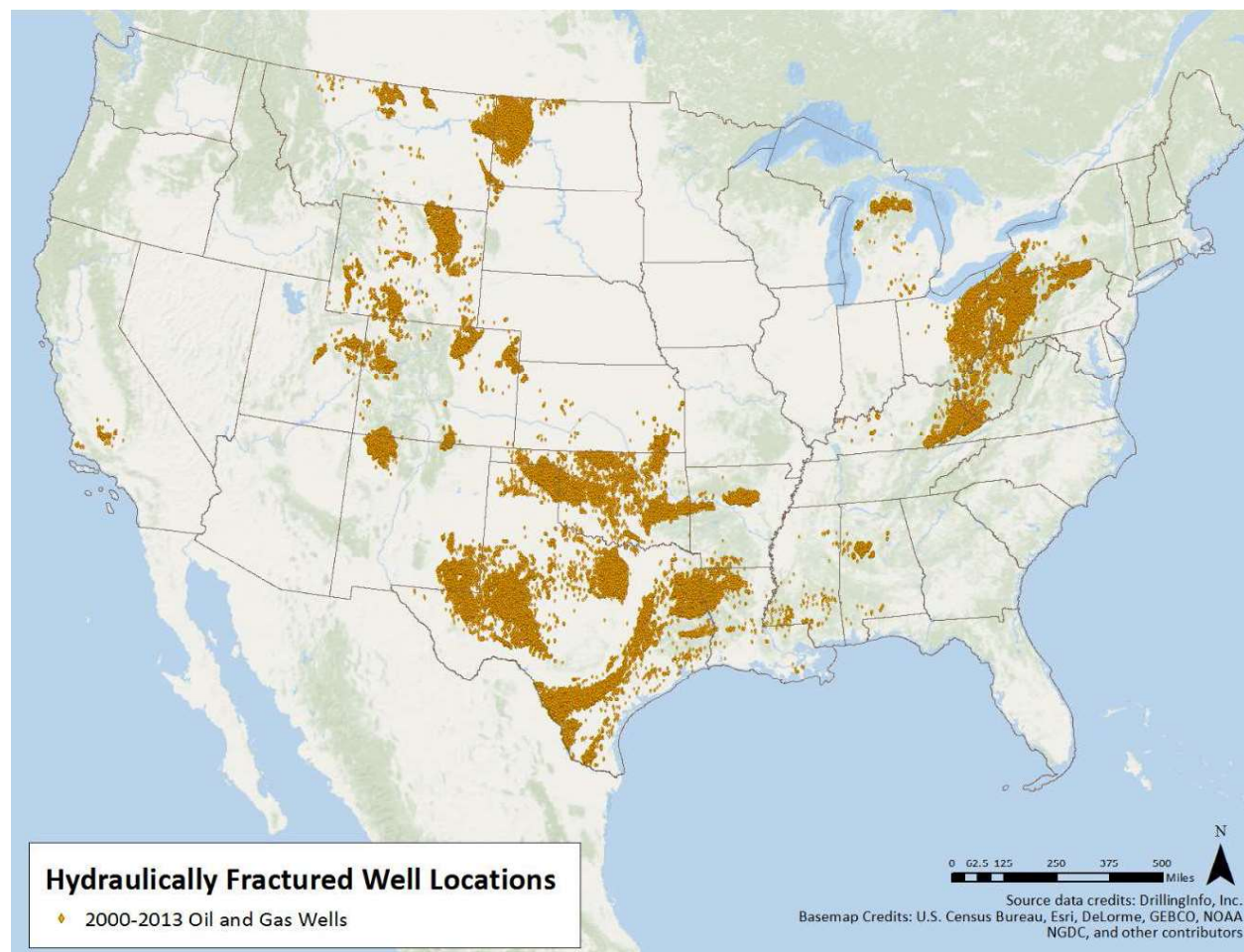
Wells are typically constructed using multiple layers of casing and cement. The subsurface environment, state and federal regulations, and industry experience and practices influence the number and placement of casing and cement.



### Oil and Gas Production Well Dictionary

Casing	Steel pipe that extends from the ground surface to the bottom of the drilled hole
Cement	A slurry that hardens around the outside of the casing; cement fills the space between casings or between a casing and the drilled hole and provides support for the casing
Conductor casing	Casing that prevents the in-fill of dirt and rock in the uppermost few feet of drilled hole
Intermediate casing	Casing that seals off intermediate rock formations that may have different pressures than deeper or shallower rock formations
Production casing	Casing that transports fluids up and down the well
Surface casing	Casing that seals off groundwater resources that are identified as drinking water or useable
Targeted rock formation	The part of a rock formation that contains the oil and/or gas to be extracted





**Figure ES-2. Locations of approximately 275,000 wells that were drilled and likely hydraulically fractured between 2000 and 2013.**

Data from [DrillingInfo \(2014a\)](#).

Hydraulically fractured oil and gas production wells can be located near or within sources of drinking water. Between 2000 and 2013, approximately 3,900 public water systems were estimated to have had at least one hydraulically fractured well within 1 mile of their water source; these public water systems served more than 8.6 million people year-round in 2013. An additional 3.6 million people were estimated to have obtained drinking water from non-public water supplies in counties with at least one hydraulically fractured well.<sup>1</sup> Underground, hydraulic fracturing can occur in close vertical proximity to drinking water resources. In some parts of the United States (e.g., the Powder River Basin in Montana and Wyoming), there is no vertical distance between the top of the hydraulically fractured oil- or gas-bearing rock formation and the bottom of treatable water, as determined by data from state oil and gas agencies and state geological survey data.<sup>2</sup> In other parts of the country (e.g., the Eagle Ford Shale in Texas), there can be thousands of feet of

<sup>1</sup> This estimate only includes counties in which 30% or more of the population (i.e., two or more times the national average) relied on non-public water supplies in 2010. See Section 2.5 in Chapter 2.

<sup>2</sup> In these cases, water that is naturally found in the oil- and gas-bearing rock formation meets the definition of drinking water in some parts of the basin. See Section 6.3.2 in Chapter 6.



rock that separate treatable water from the hydraulically fractured oil- or gas-bearing rock formation. When hydraulically fractured oil and gas production wells are located near or within drinking water resources, there is a greater potential for activities in the hydraulic fracturing water cycle to impact those resources.

## Approach: The Hydraulic Fracturing Water Cycle

The EPA studied the relationship between hydraulic fracturing for oil and gas and drinking water resources using the hydraulic fracturing water cycle (Figure ES-3). The hydraulic fracturing water cycle has five stages; each stage is defined by an activity involving water that supports hydraulic fracturing. The stages and activities of the hydraulic fracturing water cycle include:

- **Water Acquisition:** the withdrawal of groundwater or surface water to make hydraulic fracturing fluids;
- **Chemical Mixing:** the mixing of a base fluid (typically water), proppant, and additives at the well site to create hydraulic fracturing fluids;<sup>1</sup>
- **Well Injection:** the injection and movement of hydraulic fracturing fluids through the oil and gas production well and in the targeted rock formation;
- **Produced Water Handling:** the on-site collection and handling of water that returns to the surface after hydraulic fracturing and the transportation of that water for disposal or reuse;<sup>2</sup> and
- **Wastewater Disposal and Reuse:** the disposal and reuse of hydraulic fracturing wastewater.<sup>3</sup>

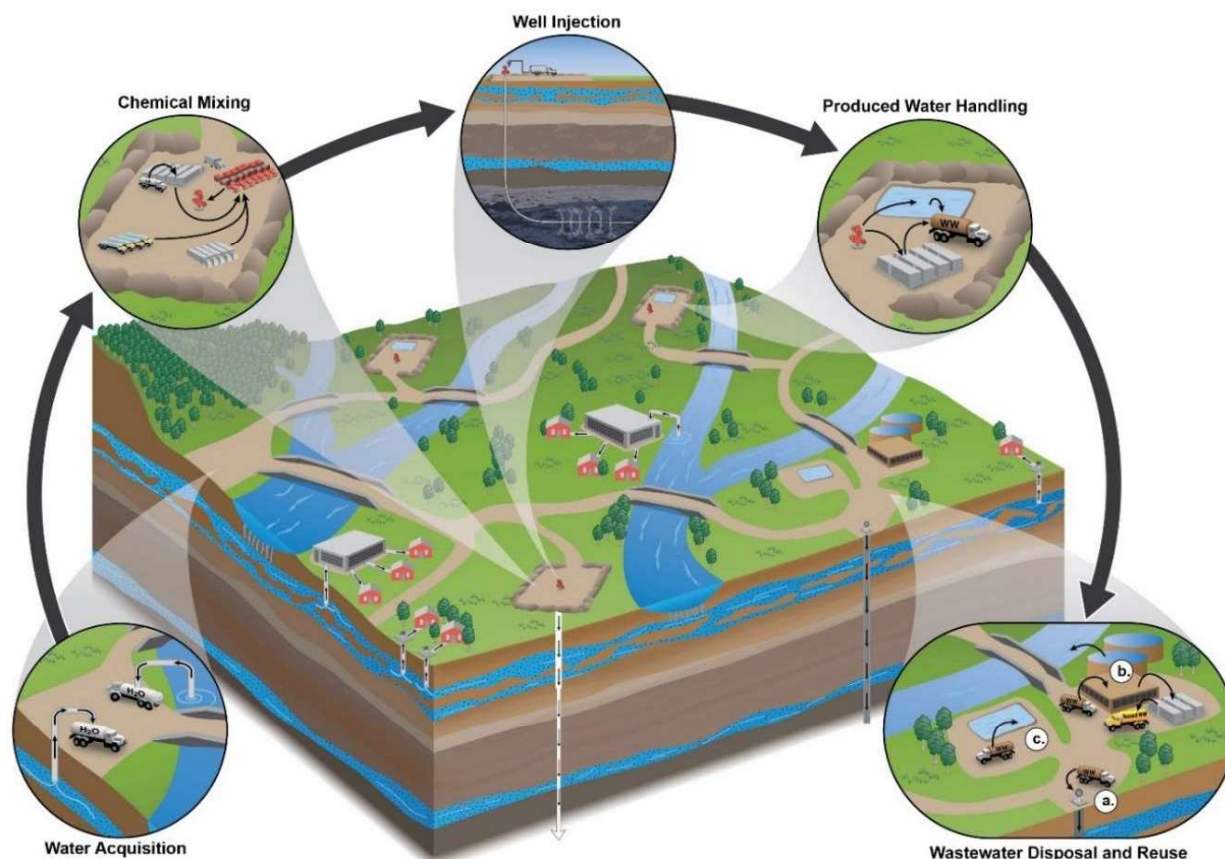
Potential impacts on drinking water resources from the above activities are considered in this report. We do not address other concerns that have been raised by stakeholders about hydraulic fracturing (e.g., potential air quality impacts or induced seismicity) or other oil and gas exploration and production activities (e.g., environmental impacts from site selection and development), as these were not included in the scope of the study. Additionally, this report is not a human health risk assessment; it does not identify populations exposed to hydraulic fracturing-related chemicals, and it does not estimate the extent of exposure or estimate the incidence of human health impacts.

---

<sup>1</sup> A base fluid is the fluid into which proppants and additives are mixed to make a hydraulic fracturing fluid; water is an example of a base fluid. Additives are chemicals or mixtures of chemicals that are added to the base fluid to change its properties.

<sup>2</sup> "Produced water" is defined in this report as water that flows from and through oil and gas wells to the surface as a by-product of oil and gas production.

<sup>3</sup> "Hydraulic fracturing wastewater" is defined in this report as produced water from hydraulically fractured oil and gas wells that is being managed using practices that include, but are not limited to, injection in Class II wells, reuse in other hydraulic fracturing operations, and various aboveground disposal practices. The term "wastewater" is being used as a general description of certain waters and is not intended to constitute a term of art for legal or regulatory purposes. Class II wells are used to inject wastewater associated with oil and gas production underground and are regulated under the Underground Injection Control Program of the Safe Drinking Water Act.



**Figure ES-3. The five stages of the hydraulic fracturing water cycle.**

The stages (shown in the insets) identify activities involving water that support hydraulic fracturing for oil and gas. Activities may take place in the same watershed or different watersheds and close to or far from drinking water resources. Thin arrows in the insets depict the movement of water and chemicals. Specific activities in the “Wastewater Disposal and Reuse” inset include (a) disposal of wastewater through underground injection, (b) wastewater treatment followed by reuse in other hydraulic fracturing operations or discharge to surface waters, and (c) disposal through evaporation or percolation pits.

Each stage of the hydraulic fracturing water cycle was assessed to identify (1) the potential for impacts on drinking water resources and (2) factors that affect the frequency or severity of impacts. Specific definitions used in this report are provided below:

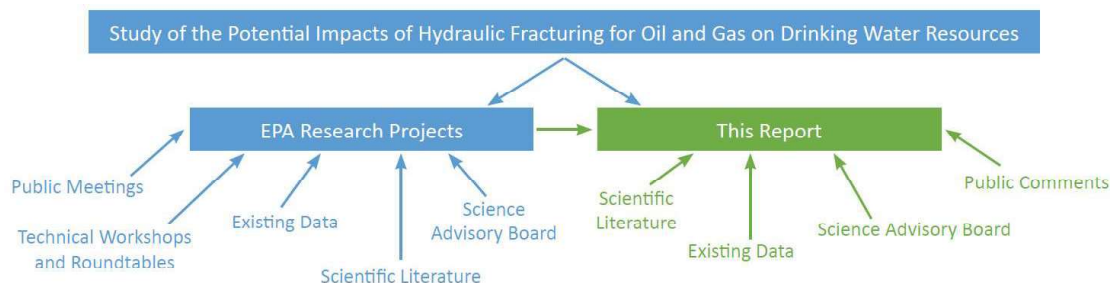
- An **impact** is any change in the quality or quantity of drinking water resources, regardless of severity, that results from an activity in the hydraulic fracturing water cycle.
- A **factor** is a feature of hydraulic fracturing operations or an environmental condition that affects the frequency or severity of impacts.
- **Frequency** is the number of impacts per a given unit (e.g., geographic area, unit of time, number of hydraulically fractured wells, or number of water bodies).
- **Severity** is the magnitude of change in the quality or quantity of a drinking water resource as measured by a given metric (e.g., duration, spatial extent, or contaminant concentration).

Factors affecting the frequency or severity of impacts were identified because they describe conditions under which impacts are more or less likely to occur and because they could inform the development of future strategies and actions to prevent or reduce impacts. Although no attempt was made to identify or evaluate best practices, ways to reduce the frequency or severity of impacts from activities in the hydraulic fracturing water cycle are described in this report when they were reported in the scientific literature. Laws, regulations, and policies also exist to protect drinking water resources, but a comprehensive summary and broad evaluation of current or proposed regulations and policies was beyond the scope of this report.

Relevant scientific literature and data were evaluated for each stage of the hydraulic fracturing water cycle. Literature included articles published in science and engineering journals, federal and state government reports, non-governmental organization reports, and industry publications. Data sources included federal- and state-collected data sets, databases maintained by federal and state government agencies, other publicly available data, and industry data provided to the EPA.<sup>1</sup> The relevant literature and data complement research conducted by the EPA under its *Plan to Study the Potential Impacts of Hydraulic Fracturing on Drinking Water Resources* (Text Box ES-3).

### **Text Box ES-3. The EPA's Study of the Potential Impacts of Hydraulic Fracturing for Oil and Gas on Drinking Water Resources.**

The EPA's study is the first national study of the potential impacts of hydraulic fracturing for oil and gas on drinking water resources. It included independent research projects conducted by EPA scientists and contractors and a state-of-the-science assessment of available data and information on the relationship between hydraulic fracturing and drinking water resources (i.e., this report).



Throughout the study, the EPA consulted with the Agency's independent Science Advisory Board (SAB) on the scope of the study and the progress made on the research projects. The SAB also conducted a peer review of both the *Plan to Study the Potential Impacts of Hydraulic Fracturing on Drinking Water Resources* (U.S. EPA, 2011d; referred to as the Study Plan in this report) and a draft of this report.

Stakeholder engagement also played an important role in the development and implementation of the study. While developing the scope of the study, the EPA held public meetings to get input from stakeholders on the study scope and design. While conducting the study, the EPA requested information from the public and engaged with technical, subject-matter experts on topics relevant to the study in a series of technical workshops and roundtables. For more information on the EPA's study, including the role of the SAB and stakeholders, visit [www.epa.gov/hfstudy](http://www.epa.gov/hfstudy).

<sup>1</sup> Industry data was provided to the EPA in response to two separate information requests to oil and gas service companies and oil and gas production well operators. Some of these data were claimed as confidential business information under the Toxic Substances Control Act and were treated as such in this report.

A draft of this report underwent peer review by the EPA's Science Advisory Board (SAB). The SAB is an independent federal advisory committee that often conducts peer reviews of high-profile scientific matters relevant to the EPA. Members of the SAB and ad hoc panels formed under the auspices of the SAB are nominated by the public and selected based on factors such as technical expertise, knowledge, experience, and absence of any real or perceived conflicts of interest. Peer review comments provided by the SAB and public comments submitted to the SAB during their peer review, including comments on major conclusions and technical content, were carefully considered in the development of this final document.

A summary of the activities in the hydraulic fracturing water cycle and their potential to impact drinking water resources is provided below, including what is known about human health hazards associated with chemicals identified across all stages of the hydraulic fracturing water cycle. Additional details are available in the full report.

## Water Acquisition

**Activity:** The withdrawal of groundwater or surface water to make hydraulic fracturing fluids.

**Relationship to Drinking Water Resources:** Groundwater and surface water resources that provide water for hydraulic fracturing fluids can also provide drinking water for public or non-public water supplies.

Water is the major component of nearly all hydraulic fracturing fluids, typically making up 90–97% of the total fluid volume injected into a well. The median volume of water used, per well, for hydraulic fracturing was approximately 1.5 million gallons (5.7 million liters) between January 2011 and February 2013, as reported in FracFocus 1.0 (Text Box ES-4). There was wide variation in the water volumes reported per well, with 10<sup>th</sup> and 90<sup>th</sup> percentiles of 74,000 gallons (280,000 liters) and 6 million gallons (23 million liters) per well, respectively. There was also variation in water use per well within and among states (Table ES-1). This variation likely results from several factors, including the type of well, the fracture design, and the type of hydraulic fracturing fluid used. An analysis of hydraulic fracturing fluid data from [Gallegos et al. \(2015\)](#) indicates that water volumes used per well have increased over time as more horizontal wells have been drilled.

Water used for hydraulic fracturing is typically fresh water taken from available groundwater and/or surface water resources located near hydraulically fractured oil and gas production wells. Water sources can vary across the United States, depending on regional or local water availability; laws, regulations, and policies; and water management practices. Hydraulic fracturing operations in the humid eastern United States generally rely on surface water resources, whereas operations in the arid and semi-arid western United States generally rely on groundwater or surface water. Geographic differences in water use for hydraulic fracturing are illustrated in Figure ES-4, which shows that most of the water used for hydraulic fracturing in the Marcellus Shale region of the Susquehanna River Basin came from surface water resources between approximately 2008 and 2013. In comparison, less than half of the water used for hydraulic fracturing in the Barnett Shale region of Texas came from surface water resources between approximately 2011 and 2013.

**Text Box ES-4. FracFocus Chemical Disclosure Registry.**

The FracFocus Chemical Disclosure Registry is a publicly-accessible website ([www.fracfocus.org](http://www.fracfocus.org)) managed by the Ground Water Protection Council (GWPC) and the Interstate Oil and Gas Compact Commission (IOGCC). Oil and gas production well operators can disclose information at this website about water and chemicals used in hydraulic fracturing fluids at individual wells. In many states where oil and gas production occurs, well operators are required to disclose to FracFocus well-specific information on water and chemical use during hydraulic fracturing.

The GWPC and the IOGCC provided the EPA with over 39,000 PDF disclosures submitted by well operators to FracFocus (version 1.0) before March 1, 2013. Data in the disclosures were extracted and compiled in a project database, which was used to conduct analyses on water and chemical use for hydraulic fracturing. Analyses were conducted on over 38,000 unique disclosures for wells located in 20 states that were hydraulically fractured between January 1, 2011, and February 28, 2013.

Despite the challenge of adapting a dataset originally created for local use and single-PDF viewing to answer broader questions, the project database created by the EPA provided substantial insight into water and chemical use for hydraulic fracturing. The project database represents the data reported to FracFocus 1.0 rather than all hydraulic fracturing that occurred in the United States during the study time period. The project database is an incomplete picture of all hydraulic fracturing due to voluntary reporting in some states for certain time periods (in the absence of state reporting requirements), the omission of information on confidential chemicals from disclosures, and invalid or erroneous information in the original disclosures or created during the development of the database. The development of FracFocus 2.0, which became the exclusive reporting mechanism in June 2013, was intended to increase the quality, completeness, and consistency of the data submitted by providing dropdown menus, warning and error messages during submission, and automatic formatting of certain fields. The GWPC has announced additional changes and upgrades for FracFocus 3.0 to enhance data searchability, increase system security, provide greater data accuracy, and further increase data transparency.

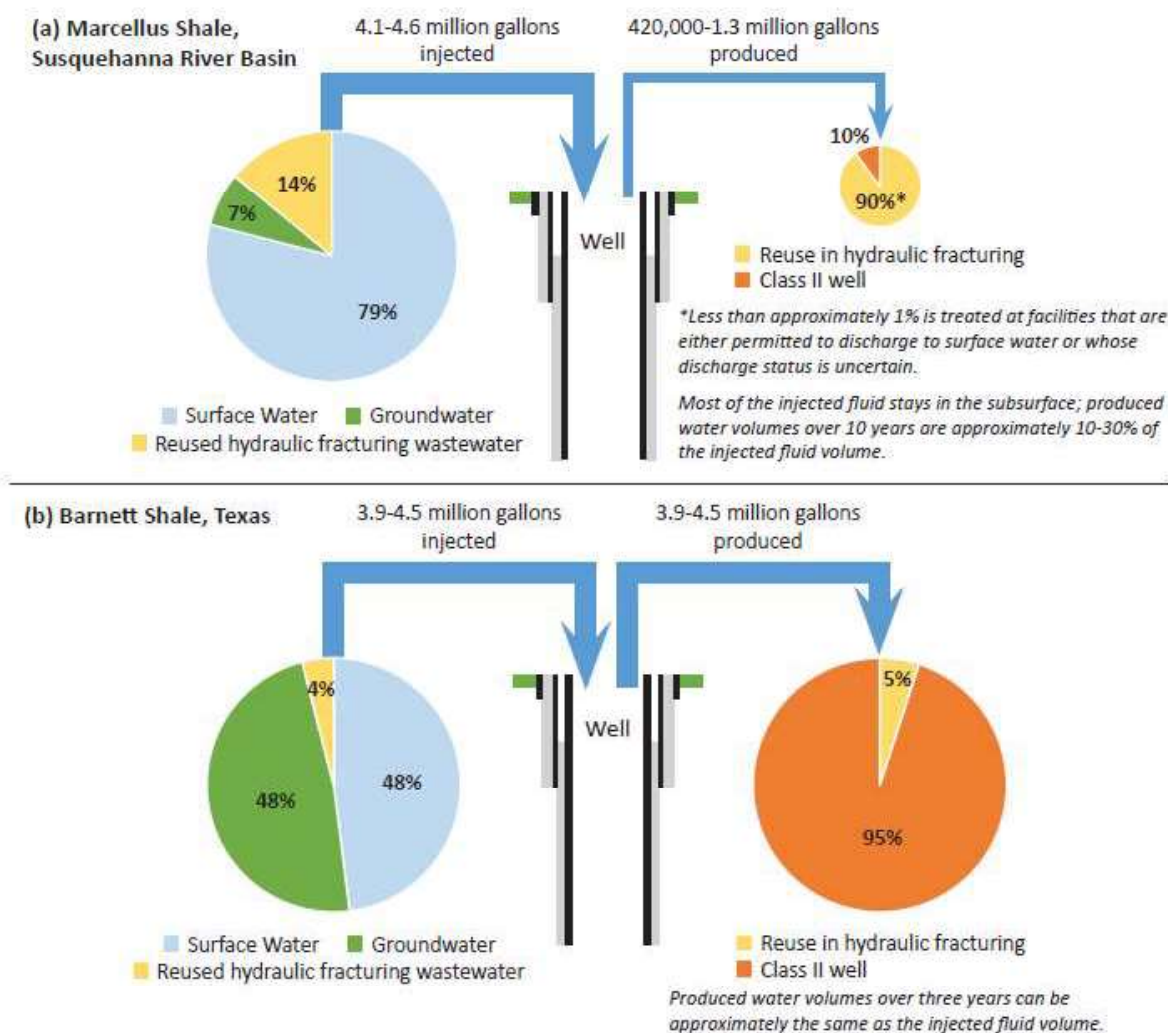
**Table ES-1. Water use per hydraulically fractured well between January 2011 and February 2013.**

Medians and percentiles were calculated from data submitted to FracFocus 1.0 (Appendix B).

State	Number of FracFocus 1.0 disclosures	Median volume per well (gallons)	10 <sup>th</sup> percentile (gallons)	90 <sup>th</sup> percentile (gallons)
Arkansas	1,423	5,259,965	3,234,963	7,121,249
California	711	76,818	21,462	285,306
Colorado	4,898	463,462	147,353	3,092,024
Kansas	121	1,453,788	10,836	2,227,926
Louisiana	966	5,077,863	1,812,099	7,945,630
Montana	207	1,455,757	367,326	2,997,552
New Mexico	1,145	175,241	35,638	1,871,666
North Dakota	2,109	2,022,380	969,380	3,313,482
Ohio	146	3,887,499	2,885,568	5,571,027
Oklahoma	1,783	2,591,778	1,260,906	7,402,230
Pennsylvania	2,445	4,184,936	2,313,649	6,615,981
Texas	16,882	1,420,613	58,709	6,115,195
Utah	1,406	302,075	76,286	769,360
West Virginia	273	5,012,238	3,170,210	7,297,080
Wyoming	1,405	322,793	5,727	1,837,602



Hydraulic fracturing wastewater and other lower-quality water can also be used in hydraulic fracturing fluids to offset the need for fresh water, although the proportion of injected fluid that is reused hydraulic fracturing wastewater varies by location (Figure ES-4).<sup>1</sup> Overall, the proportion of



**Figure ES-4. Water budgets illustrative of hydraulic fracturing water management practices in the Marcellus Shale in the Susquehanna River Basin between approximately 2008 and 2013 and the Barnett Shale in Texas between approximately 2011 and 2013.**

Class II wells are used to inject wastewater associated with oil and gas production underground and are regulated under the Underground Injection Control Program of the Safe Drinking Water Act. Data sources are described in Figure 10-1 in Chapter 10.

<sup>1</sup> Reused hydraulic fracturing wastewater as a percentage of injected fluid differs from the percentage of produced water that is managed through reuse in other hydraulic fracturing operations. For example, in the Marcellus Shale region of the Susquehanna River Basin, approximately 14% of injected fluid was reused hydraulic fracturing wastewater, while approximately 90% of produced water was managed through reuse in other hydraulic fracturing operations (Figure ES-4a).

water used in hydraulic fracturing that comes from reused hydraulic fracturing wastewater appears to be low. In a survey of literature values from 10 states, basins, or plays, the median percentage of the injected fluid volume that came from reused hydraulic fracturing wastewater was 5% between approximately 2008 and 2014.<sup>1</sup> There was an increase in the reuse of hydraulic fracturing wastewater as a percentage of the injected hydraulic fracturing fluid in both Pennsylvania and West Virginia between approximately 2008 and 2014. This increase is likely due to the limited availability of Class II wells, which are commonly used to dispose of oil and gas wastewater, and the costs of trucking wastewater to Ohio, where Class II wells are more prevalent.<sup>2</sup> Class II wells are also prevalent in Texas, and the reuse of wastewater in hydraulic fracturing fluids in the Barnett Shale appears to be lower than in the Marcellus Shale (Figure ES-4).

Because the same water resource can be used to support hydraulic fracturing and to provide drinking water, withdrawals for hydraulic fracturing can directly impact drinking water resources by changing the quantity or quality of the remaining water. Although every water withdrawal affects water quantity, we focused on water withdrawals that have the potential to significantly impact drinking water resources by limiting the availability of drinking water or altering its quality. Water withdrawals for a single hydraulically fractured oil and gas production well are not expected to significantly impact drinking water resources, because the volume of water needed to hydraulically fracture a single well is unlikely to limit the availability of drinking water or alter its quality. If, however, multiple oil and gas production wells are located within an area, the total volume of water needed to hydraulically fracture all of the wells has the potential to be a significant portion of the water available and impacts on drinking water resources can occur.

To assess whether hydraulic fracturing operations are a relatively large or small user of water, we compared water use for hydraulic fracturing to total water use at the county level (Text Box ES-5). In most counties studied, the average annual water volumes reported in FracFocus 1.0 were generally less than 1% of total water use. This suggests that hydraulic fracturing operations represented a relatively small user of water in most counties. There were exceptions, however. Average annual water volumes reported in FracFocus 1.0 were 10% or more of total water use in 26 of the 401 counties studied, 30% or more in nine counties, and 50% or more in four counties.<sup>3</sup> In these counties, hydraulic fracturing operations represented a relatively large user of water.

The above results suggest that hydraulic fracturing operations can significantly increase the volume of water withdrawn in particular areas. Increased water withdrawals can result in significant impacts on drinking water resources if there is insufficient water available in the area to accommodate all users. To assess the potential for these impacts, we compared hydraulic fracturing water use to estimates of water availability at the county level.<sup>4</sup> In most counties studied, average

---

<sup>1</sup> See Section 4.2 in Chapter 4.

<sup>2</sup> See Chapter 8 for additional information on Class II wells.

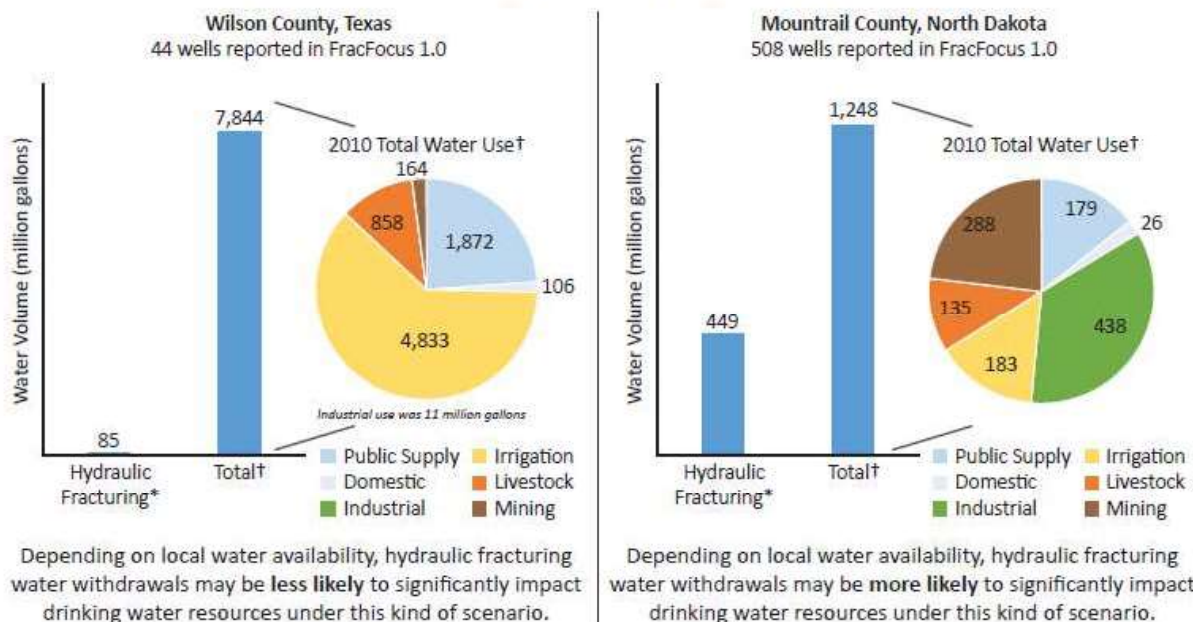
<sup>3</sup> Hydraulic fracturing water consumption estimates followed the same general pattern as the water use estimates presented here, but with slightly larger percentages in each category (Section 4.4 in Chapter 4).

<sup>4</sup> County-level water availability estimates were derived from the [Tidwell et al. \(2013\)](#) estimates of water availability for siting new thermoelectric power plants (see Text Box 4-2 in Chapter 4 for details). The county-level water availability estimates used in this report represent the portion of water available to new users within a county.

### Text Box ES-5. County-Level Water Use for Hydraulic Fracturing.

To assess whether hydraulic fracturing operations are a relatively large or small user of water, the average annual water use for hydraulic fracturing in 2011 and 2012 was compared, at the county-level, to total water use in 2010. For most counties studied, average annual water volumes reported for individual counties in FracFocus 1.0 were less than 1% of total water use in those counties. But in some counties, hydraulic fracturing operations reported in FracFocus 1.0 represented a relatively large user of water.

#### Examples of Water Use in Two Counties: Wilson County, Texas, and Mountrail County, North Dakota



\*Hydraulic fracturing water use is a function of the water use per well and the total number of wells hydraulically fractured within a county. Average annual water use for hydraulic fracturing was calculated at the county-level using data reported in FracFocus 1.0 in 2011 and 2012 (Appendix B).

†The U.S. Geological Survey compiles national water use estimates every five years in the National Water Census. Total water use at the county-level was obtained from the most recent census, which was conducted in 2010 (Maupin et al., 2014).

#### 2010 Total Water Use Categories

Public supply	Water withdrawn by public and private water suppliers that provide water to at least 25 people or have a minimum of 15 connections
Domestic	Self-supplied water withdrawals for indoor household purposes such as drinking, food preparation, bathing, washing clothes and dishes, flushing toilets, and outdoor purposes such as watering lawns and gardens
Industrial	Water used for fabrication, processing, washing, and cooling
Irrigation	Water that is applied by an irrigation system to assist crop and pasture growth or to maintain vegetation on recreational lands (e.g., parks and golf courses)
Livestock	Water used for livestock watering, feedlots, dairy operations, and other on-farm needs
Mining	Water used for the extraction of naturally-occurring minerals, including solids (e.g., coal, sand, gravel, and other ores), liquids (e.g., crude petroleum), and gases (e.g., natural gas)

annual water volumes reported for hydraulic fracturing were less than 1% of the estimated annual volume of readily-available fresh water. However, average annual water volumes reported for hydraulic fracturing were greater than the estimated annual volume of readily-available fresh water in 17 counties in Texas. This analysis suggests that there was enough water available annually to support the level of hydraulic fracturing reported to FracFocus 1.0 in most, but not all,



areas of the country. This observation does not preclude the possibility of local impacts in other areas of the country, nor does it indicate that local impacts have occurred or will occur in the 17 counties in Texas. To better understand whether local impacts have occurred, and the factors that affect those impacts, local-level studies, such as the ones described below, are needed.

Local impacts on drinking water quantity have occurred in areas with increased hydraulic fracturing activity. In 2011, for example, drinking water wells in an area overlying the Haynesville Shale ran out of water due to higher than normal groundwater withdrawals and drought ([LA Ground Water Resources Commission, 2012](#)). Water withdrawals for hydraulic fracturing contributed to these conditions, along with other water users and the lack of precipitation. Groundwater impacts have also been reported in Texas. In a detailed case study, [Scanlon et al. \(2014b\)](#) estimated that groundwater levels in approximately 6% of the area studied dropped by 100 feet (31 meters) to 200 feet (61 meters) or more after hydraulic fracturing activity increased in 2009.

In contrast, studies in the Upper Colorado and Susquehanna River basins found minimal impacts on drinking water resources from hydraulic fracturing. In the Upper Colorado River Basin, the EPA found that high-quality water produced from oil and gas wells in the Piceance tight sands provided nearly all of the water for hydraulic fracturing in the study area ([U.S. EPA, 2015e](#)). Due to this high reuse rate, the EPA did not identify any locations in the study area where hydraulic fracturing contributed to locally high water use. In the Susquehanna River Basin, multiple studies and state reports have identified the potential for hydraulic fracturing water withdrawals in the Marcellus Shale to impact surface water resources. Evidence suggests, however, that current water management strategies, including passby flows and reuse of hydraulic fracturing wastewater, help protect streams from depletion by hydraulic fracturing water withdrawals. A passby flow is a prescribed, low-streamflow threshold below which water withdrawals are not allowed.

The above examples highlight factors that can affect the frequency or severity of impacts on drinking water resources from hydraulic fracturing water withdrawals. In particular, areas of the United States that rely on declining groundwater resources are vulnerable to more frequent and more severe impacts from all water withdrawals, including withdrawals for hydraulic fracturing. Extensive groundwater withdrawals can limit the availability of belowground drinking water resources and can also change the quality of the water remaining in the resource. Because groundwater recharge rates can be low, impacts can last for many years. Seasonal or long-term drought can also make impacts more frequent and more severe for groundwater and surface water resources. Hot, dry weather reduces or prevents groundwater recharge and depletes surface water bodies, while water demand often increases simultaneously (e.g., for irrigation). This combination of factors—high hydraulic fracturing water use and relatively low water availability due to declining groundwater resources and/or frequent drought—was found to be present in southern and western Texas.

Water management strategies can also affect the frequency and severity of impacts on drinking water resources from hydraulic fracturing water withdrawals. These strategies include using hydraulic fracturing wastewater or brackish groundwater for hydraulic fracturing, transitioning from limited groundwater resources to more abundant surface water resources, and using passby

flows to control water withdrawals from surface water resources. Examples of these water management strategies can be found throughout the United States. In western and southern Texas, for example, the use of brackish water is currently reducing impacts on fresh water sources, and could, if increased, reduce future impacts. Louisiana and North Dakota have encouraged well operators to withdraw water from surface water resources instead of high-quality groundwater resources. And, as described above, the Susquehanna River Basin Commission limits surface water withdrawals during periods of low stream flow.

## **Water Acquisition Conclusions**

With notable exceptions, hydraulic fracturing uses a relatively small percentage of water when compared to total water use and availability at large geographic scales. Despite this, hydraulic fracturing water withdrawals can affect the quantity and quality of drinking water resources by changing the balance between the demand on local water resources and the availability of those resources. Changes that have the potential to limit the availability of drinking water or alter its quality are more likely to occur in areas with relatively high hydraulic fracturing water withdrawals and low water availability, particularly due to limited or declining groundwater resources. Water management strategies (e.g., encouragement of alternative water sources or water withdrawal restrictions) can reduce the frequency or severity of impacts on drinking water resources from hydraulic fracturing water withdrawals.

## **Chemical Mixing**

**Activity:** The mixing of a base fluid, proppant, and additives at the well site to create hydraulic fracturing fluids.

**Relationship to Drinking Water Resources:** Spills of additives and hydraulic fracturing fluids can reach groundwater and surface water resources.

Hydraulic fracturing fluids are engineered to create and grow fractures in the targeted rock formation and to carry proppant through the oil and gas production well into the newly-created fractures. Hydraulic fracturing fluids are typically made up of base fluids, proppant, and additives. Base fluids make up the largest proportion of hydraulic fracturing fluids by volume. As illustrated in Text Box ES-6, base fluids can be a single substance (e.g., water in the slickwater example) or can be a mixture of substances (e.g., water and nitrogen in the energized fluid example). The EPA's analysis of hydraulic fracturing fluid data reported to FracFocus 1.0 suggests that water was the most commonly used base fluid between January 2011 and February 2013 ([U.S. EPA, 2015a](#)). Non-water substances, such as gases and hydrocarbon liquids, were reported to be used alone or blended with water to form a base fluid in fewer than 3% of wells in FracFocus 1.0.

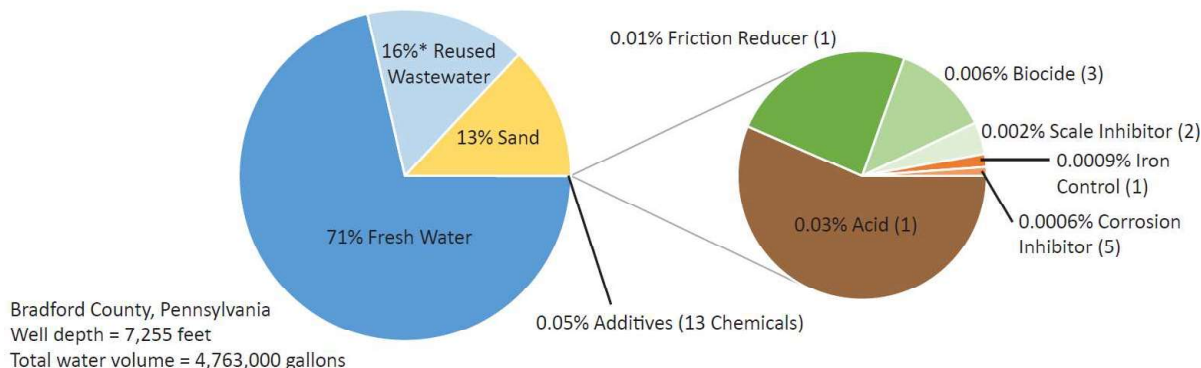
Proppant makes up the second largest proportion of hydraulic fracturing fluids (Text Box ES-6). Sand (i.e., quartz) was the most commonly reported proppant between January 2011 and February 2013, with 98% of wells in FracFocus 1.0 reporting sand as the proppant ([U.S. EPA, 2015a](#)). Other

### Text Box ES-6. Examples of Hydraulic Fracturing Fluids.

Hydraulic fracturing fluids are engineered to create and extend fractures in the targeted rock formation and to carry proppant through the production well into the newly-created fractures. While there is no universal hydraulic fracturing fluid, there are general types of hydraulic fracturing fluids. Two types of hydraulic fracturing fluids are described below.

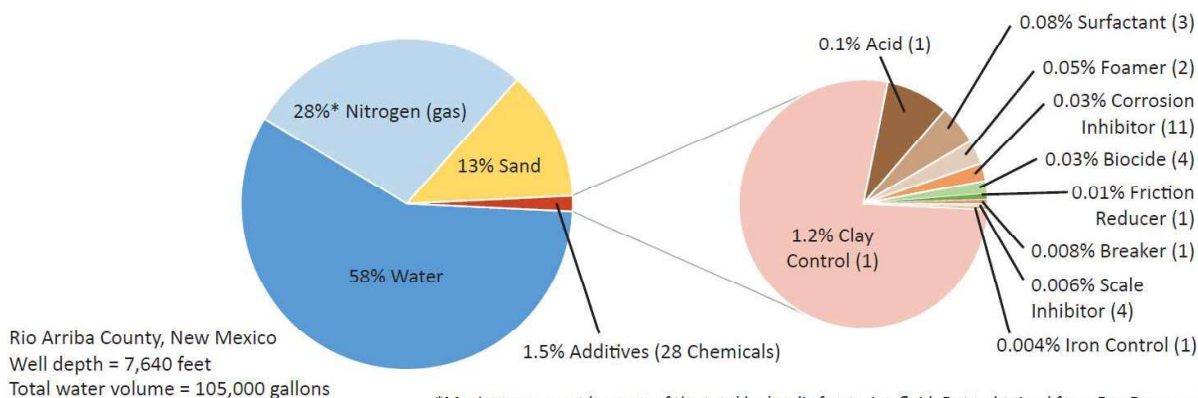
#### Slickwater

Slickwater hydraulic fracturing fluids are water-based fluids that generally contain a friction reducer. The friction reducer makes it easier for the fluid to be pumped down the oil and gas production well at high rates. Slickwater is commonly used to hydraulically fracture shale formations.



#### Energized Fluid

Energized fluids are mixtures of liquids and gases. They can be used for hydraulic fracturing in under-pressured gas formations.



\*Maximum percent by mass of the total hydraulic fracturing fluid. Data obtained from [FracFocus.org](http://FracFocus.org)

#### Additive Dictionary

Acid	Dissolves minerals and creates pre-fractures in the rock
Biocide	Controls or eliminates bacteria in the hydraulic fracturing fluid
Breaker	Reduces the thickness of the hydraulic fracturing fluid
Clay control	Prevents swelling and migration of formation clays
Corrosion inhibitor	Protects iron and steel equipment from rusting
Foamer	Creates a foam hydraulic fracturing fluid
Friction reducer	Reduces friction between the hydraulic fracturing fluid and pipes during pumping
Iron control	Prevents the precipitation of iron-containing chemicals
Scale inhibitor	Prevents the formation of scale buildup within the well
Surfactant	Reduces the surface tension of the hydraulic fracturing fluid

proppants can include man-made or specially engineered particles, such as high-strength ceramic materials or sintered bauxite.<sup>1</sup>

Additives generally make up the smallest proportion of the overall composition of hydraulic fracturing fluids (Text Box ES-6), yet have the greatest potential to impact the quality of drinking water resources compared to proppant and base fluids. Additives, which can be a single chemical or a mixture of chemicals, are added to the base fluid to change its properties (e.g., adjust pH, increase fluid thickness, or limit bacterial growth). The choice of which additives to use depends on the characteristics of the targeted rock formation (e.g., rock type, temperature, and pressure), the economics and availability of desired additives, and well operator or service company preferences and experience.

The variability of additives, both in their purpose and chemical composition, suggests that a large number of different chemicals may be used in hydraulic fracturing fluids across the United States. The EPA identified 1,084 chemicals that were reported to have been used in hydraulic fracturing fluids between 2005 and 2013.<sup>2,3</sup> The EPA's analysis of FracFocus 1.0 data indicates that between 4 and 28 chemicals were used per well between January 2011 and February 2013 and that no single chemical was used in all wells ([U.S. EPA, 2015a](#)). Three chemicals—methanol, hydrotreated light petroleum distillates, and hydrochloric acid—were reported in 65% or more of the wells in FracFocus 1.0; 35 chemicals were reported in at least 10% of the wells (Table ES-2).

**Table ES-2. Chemicals reported in 10% or more of disclosures in FracFocus 1.0.**

Disclosures provided information on chemicals used at individual well sites between January 1, 2011, and February 28, 2013.

Chemical Name (CASRN) <sup>a</sup>	Percent of FracFocus 1.0 disclosures <sup>b</sup>
Methanol (67-56-1)	72
Hydrotreated light petroleum distillates (64742-47-8)	65
Hydrochloric acid (7647-01-0)	65
Water (7732-18-5) <sup>c</sup>	48
Isopropanol (67-63-0)	47
Ethylene glycol (107-21-1)	46
Peroxydisulfuric acid, diammonium salt (7727-54-0)	44
Sodium hydroxide (1310-73-2)	39
Guar gum (9000-30-0)	37

---

<sup>1</sup> Sintered bauxite is crushed and powdered bauxite that is fused into spherical beads at high temperatures.

<sup>2</sup> This list includes 1,084 unique Chemical Abstracts Service Registration Numbers (CASRN)s, which can be assigned to a single chemical (e.g., hydrochloric acid) or a mixture of chemicals (e.g., hydrotreated light petroleum distillates). Throughout this report, we refer to the substances identified by unique CASRN)s as “chemicals.”

<sup>3</sup> [Dayalu and Konschnik \(2016\)](#) identified 995 unique CASRN)s from data submitted to FracFocus between March 9, 2011, and April 13, 2015. Two hundred sixty-three of these CASRN)s are not on the list of unique CASRN)s identified by the EPA (Appendix H). Only one of the 263 chemicals was reported at greater than 1% of wells, which suggests that these chemicals were used at only a few sites.

Chemical Name (CASRN) <sup>a</sup>	Percent of FracFocus 1.0 disclosures <sup>b</sup>
Quartz (14808-60-7) <sup>c</sup>	36
Glutaraldehyde (111-30-8)	34
Propargyl alcohol (107-19-7)	33
Potassium hydroxide (1310-58-3)	29
Ethanol (64-17-5)	29
Acetic acid (64-19-7)	24
Citric acid (77-92-9)	24
2-Butoxyethanol (111-76-2)	21
Sodium chloride (7647-14-5)	21
Solvent naphtha, petroleum, heavy aromatic (64742-94-5)	21
Naphthalene (91-20-3)	19
2,2-Dibromo-3-nitrilopropionamide (10222-01-2)	16
Phenolic resin (9003-35-4)	14
Choline chloride (67-48-1)	14
Methenamine (100-97-0)	14
Carbonic acid, dipotassium salt (584-08-7)	13
1,2,4-Trimethylbenzene (95-63-6)	13
Quaternary ammonium compounds, benzyl-C12-16-alkyldimethyl, chlorides (68424-85-1)	12
Poly(oxy-1,2-ethanediyl)-nonylphenyl- hydroxy (mixture) (127087-87-0)	12
Formic acid (64-18-6)	12
Sodium chlorite (7758-19-2)	11
Nonyl phenol ethoxylate (9016-45-9)	11
Tetrakis(hydroxymethyl)phosphonium sulfate (55566-30-8)	11
Polyethylene glycol (25322-68-3)	11
Ammonium chloride (12125-02-9)	10
Sodium persulfate (7775-27-1)	10

<sup>a</sup> “Chemical” refers to chemical substances with a single CASRN; these may be pure chemicals (e.g., methanol) or chemical mixtures (e.g., hydrotreated light petroleum distillates).

<sup>b</sup> Analysis considered 34,675 disclosures that met selected quality assurance criteria. See Table 5-2 in Chapter 5.

<sup>c</sup> Quartz and water were reported as ingredients in additives, in addition to proppants and base fluids.

Concentrated additives are delivered to the well site and stored until they are mixed with the base fluid and proppant and pumped down the oil and gas production well (Text Box ES-7). While the overall concentration of additives in hydraulic fracturing fluids is generally small (typically 2% or less of the total volume of the injected fluid), the total volume of additives delivered to the well site can be large. Because over 1 million gallons (3.8 million liters) of hydraulic fracturing fluid are generally injected per well, thousands of gallons of additives can be stored on site and used during hydraulic fracturing.

As illustrated in Text Box ES-7, additives are often stored in multiple, closed containers [typically 200 gallons (760 liters) to 375 gallons (1,420 liters) per container] and moved around the site in hoses and tubing. This equipment is designed to contain additives and blended hydraulic fracturing fluid, but spills can occur. Changes in drinking water quality can occur if spilled fluids reach groundwater or surface water resources.

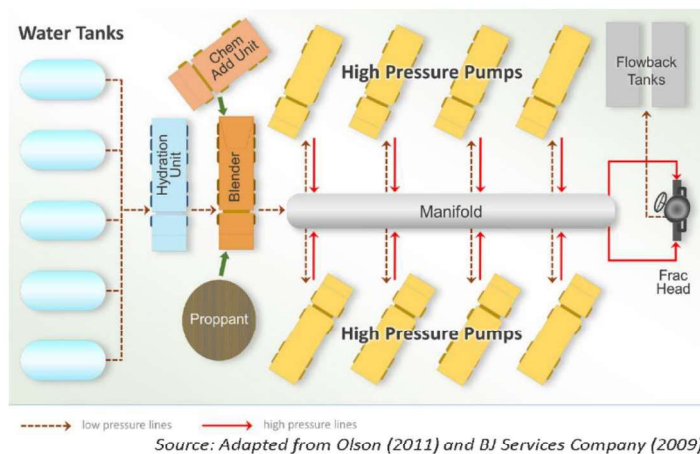
Several studies have documented spills of hydraulic fracturing fluids or additives. Nearly all of these studies identified spills from state-managed spill databases. Data gathered for these studies suggest that spills of hydraulic fracturing fluids or additives were primarily caused by equipment failure or human error. For example, an EPA analysis of spill reports from nine state agencies, nine oil and gas well operators, and nine hydraulic fracturing service companies characterized 151 spills of hydraulic fracturing fluids or additives on or near well sites in 11 states between January 2006 and April 2012 ([U.S. EPA, 2015m](#)). These spills were primarily caused by equipment failure (34% of the spills) or human error (25%), and more than 30% of the spills were from fluid storage units (e.g., tanks, totes, and trailers). Similarly, a study of spills reported to the Colorado Oil and Gas Conservation Commission identified 125 spills during well stimulation (i.e., a part of the life of an oil and gas well that often, but not always, includes hydraulic fracturing) between January 2010 and August 2013 ([COGCC, 2014](#)). Of these spills, 51% were caused by human error and 46% were due to equipment failure.

Studies of spills of hydraulic fracturing fluids or additives provide insights on spill volumes, but little information on chemical-specific spill composition. Among the 151 spills characterized by the EPA, the median volume of fluid spilled was 420 gallons (1,600 liters), although the volumes spilled ranged from 5 gallons (19 liters) to 19,320 gallons (73,130 liters). Spilled fluids were often described as acids, biocides, friction reducers, crosslinkers, gels, and blended hydraulic fracturing fluid, but few specific chemicals were mentioned.<sup>1</sup> [Considine et al. \(2012\)](#) identified spills related to oil and gas development in the Marcellus Shale that occurred between January 2008 and August 2011 from Notices of Violations issued by the Pennsylvania Department of Environmental Protection. The authors identified spills greater than 400 gallons (1,500 liters) and spills less than 400 gallons (1,500 liters).

---

<sup>1</sup> A crosslinker is an additive that increases the thickness of gelled fluids by connecting polymer molecules in the gelled fluid.



**Text Box ES-7. Chemical Mixing Equipment.****Typical Layout of Chemical Mixing Equipment**

This illustration shows how the different pieces of equipment fit together to contain, mix, and inject hydraulic fracturing fluid into a production well.

Water, proppant, and additives are blended together and pumped to the manifold, where high pressure pumps transfer the fluid to the frac head.

Additives and proppant can be blended with water at different times and in different amounts during hydraulic fracturing. Thus, the composition of hydraulic fracturing fluids can vary during the hydraulic fracturing job.

**Well Pad During Hydraulic Fracturing**

Equipment set up for hydraulic fracturing.



Source: Schlumberger

**Chemical Mixing Equipment Dictionary**

Blender	Blends water, proppant, and additives
Chemical additive unit	Transports additives to the site and stores additives onsite
Flowback tanks	Stores liquid that returns to the surface after hydraulic fracturing
Frac head	Connects hydraulic fracturing equipment to the production well
High pressure pumps	Pressurize mixed fluids before injection into the production well
Hydration unit	Creates and stores gels used in some hydraulic fracturing fluids
Manifold	Transfers fluids from the blender to the frac head
Proppant	Stores proppant (often sand)
Water tanks	Stores water

Spills of hydraulic fracturing fluids or additives have reached, and therefore impacted, surface water resources. Thirteen of the 151 spills characterized by the EPA were reported to have reached a surface water body (often creeks or streams). Among the 13 spills, reported spill volumes ranged from 28 gallons (105 liters) to 7,350 gallons (27,800 liters). Additionally, [Brantley et al. \(2014\)](#) and [Considine et al. \(2012\)](#) identified fewer than 10 total instances of spills of additives and/or hydraulic fracturing fluids greater than 400 gallons (1,500 liters) that reached surface waters in

Pennsylvania between January 2008 and June 2013. Reported spill volumes for these spills ranged from 3,400 gallons (13,000 liters) to 227,000 gallons (859,000 liters).

Although impacts on surface water resources have been documented, site-specific studies that could be used to describe factors that affect the frequency or severity of impacts were not available. In the absence of such studies, we relied on fundamental scientific principles to identify factors that affect how hydraulic fracturing fluids and chemicals can move through the environment to drinking water resources. Because these factors influence whether spilled fluids reach groundwater and surface water resources, they affect the frequency and severity of impacts on drinking water resources from spills during the chemical mixing stage of the hydraulic fracturing water cycle.

The potential for spilled fluids to impact groundwater or surface water resources depends on the characteristics of the spill, the environmental fate and transport of the spilled fluid, and spill response activities (Figure ES-5). Site-specific characteristics affect how spilled liquids move through soil into the subsurface or over the land surface. Generally, highly permeable soils or fractured rock can allow spilled liquids to move quickly into and through the subsurface, limiting the opportunity for spilled liquids to move over land to surface water resources. In low permeability soils, spilled liquids are less able to move into the subsurface and are more likely to move over the land surface. In either case, the volume spilled and the distance between the location of the spill and nearby water resources affects whether spilled liquids reach drinking water resources. Large-volume spills are generally more likely to reach drinking water resources because they are more likely to be able to travel the distance between the location of the spill and nearby water resources.

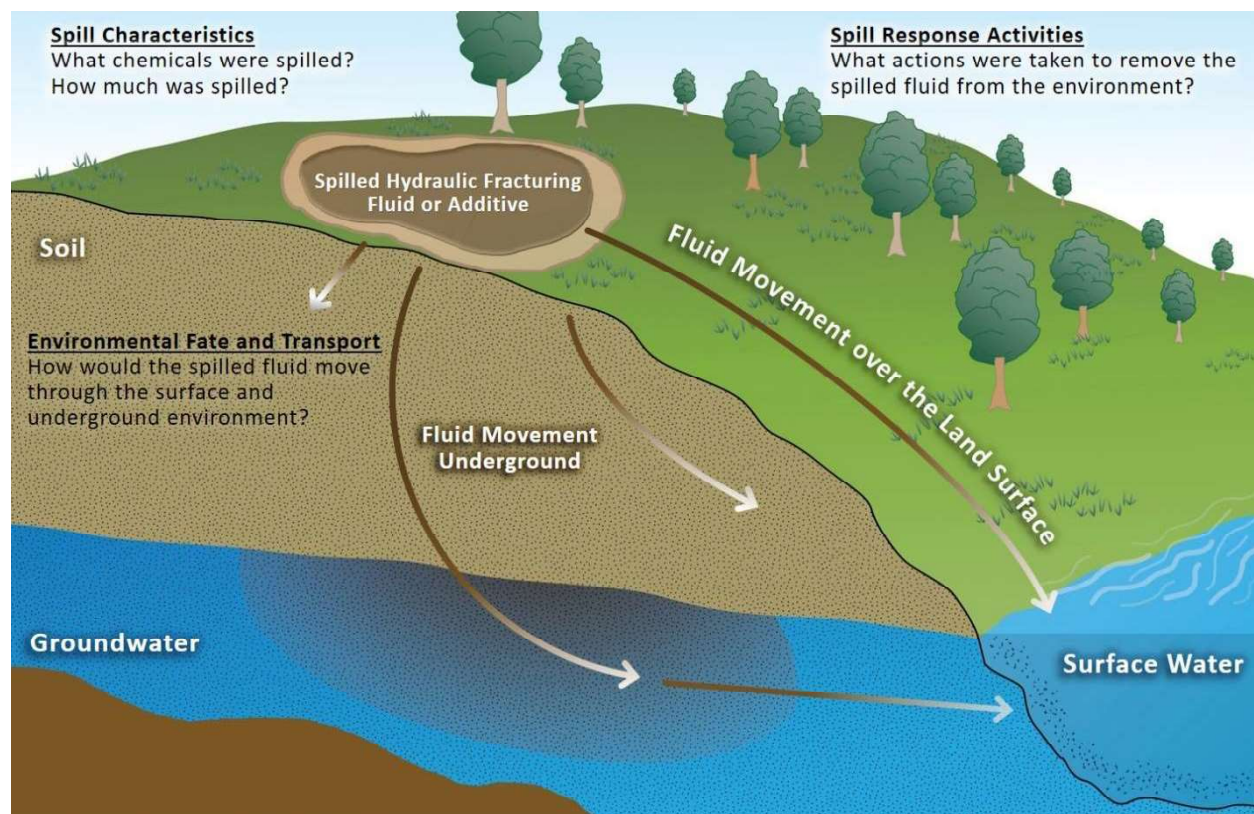
In general, chemical and physical properties, which depend on the identity and structure of a chemical, control whether spilled chemicals evaporate, stick to soil particles, or move with water. The EPA identified measured or estimated chemical and physical properties for 455 of the 1,084 chemicals used in hydraulic fracturing fluids between 2005 and 2013.<sup>1</sup> The properties of these chemicals varied widely, from chemicals that are more likely to move quickly through the environment with a spilled liquid to chemicals that are more likely to move slowly through the environment because they stick to soil particles.<sup>2</sup> Chemicals that move slowly through the environment may act as longer-term sources of contamination if spilled.

---

<sup>1</sup> Chemical and physical properties were identified using EPI Suite™. EPI Suite™ is a collection of chemical and physical property and environmental fate estimation programs developed by the EPA and Syracuse Research Corporation. It can be used to estimate chemical and physical properties of individual organic compounds. Of the 1,084 hydraulic fracturing fluid chemicals identified by the EPA, 629 were not individual organic compounds, and thus EPI Suite™ could not be used to estimate their chemical and physical properties.

<sup>2</sup> These results describe how some hydraulic fracturing chemicals behave in infinitely dilute aqueous solutions, which is a simplified approximation of the real-world mixtures found in hydraulic fracturing fluids. The presence of other chemicals in a mixture can affect the fate and transport of a chemical.





**Figure ES-5. Generalized depiction of factors that influence whether spilled hydraulic fracturing fluids or additives reach drinking water resources, including spill characteristics, environmental fate and transport, and spill response activities.**

Spill prevention practices and spill response activities are designed to prevent spilled fluids from reaching groundwater or surface water resources and minimize impacts from spilled fluids. Spill prevention and response activities are influenced by federal, state, and local regulations and company practices. Spill prevention practices include secondary containment systems (e.g., liners and berms), which are designed to contain spilled fluids and prevent them from reaching soil, groundwater, or surface water. Spill response activities include activities taken to stop the spill, contain spilled fluids (e.g., the deployment of emergency containment systems), and clean up spilled fluids (e.g., removal of contaminated soil). It was beyond the scope of this report to evaluate the implementation and efficacy of spill prevention practices and spill response activities.

The severity of impacts on water quality from spills of hydraulic fracturing fluids or additives depends on the identity and amount of chemicals that reach groundwater or surface water resources, the toxicity of the chemicals, and the characteristics of the receiving water resource.<sup>1</sup> Characteristics of the receiving groundwater or surface water resource (e.g., water resource size and flow rate) can affect the magnitude and duration of impacts by reducing the concentration of spilled chemicals in a drinking water resource. Impacts on groundwater resources have the

<sup>1</sup> Human health hazards associated with hydraulic fracturing fluid chemicals are discussed in Chapter 9 and summarized in the “Chemicals in the Hydraulic Fracturing Water Cycle” section below.

potential to be more severe than impacts on surface water resources because it takes longer to naturally reduce the concentration of chemicals in groundwater and because it is generally difficult to remove chemicals from groundwater resources. Due to a lack of data, particularly in terms of groundwater monitoring after spill events, little is publicly known about the severity of drinking water impacts from spills of hydraulic fracturing fluids or additives.

### **Chemical Mixing Conclusions**

Spills of hydraulic fracturing fluids and additives during the chemical mixing stage of the hydraulic fracturing water cycle have reached surface water resources in some cases and have the potential to reach groundwater resources. Although the available data indicate that spills of various volumes can reach surface water resources, large volume spills are more likely to travel longer distances to nearby groundwater or surface water resources. Consequently, large volume spills likely increase the frequency of impacts on drinking water resources. Large volume spills, particularly of concentrated additives, are also likely to result in more severe impacts on drinking water resources than small volume spills because they can deliver a large quantity of potentially hazardous chemicals to groundwater or surface water resources. Impacts on groundwater resources are likely to be more severe than impacts on surface water resources because of the inherent characteristics of groundwater. Spill prevention and response activities are designed to prevent spilled fluids from reaching groundwater or surface water resources and minimize impacts from spilled fluids.

### **Well Injection**

**Activity:** The injection and movement of hydraulic fracturing fluids through the oil and gas production well and in the targeted rock formation.

**Relationship to Drinking Water Resources:** Belowground pathways, including the production well itself and newly-created fractures, can allow hydraulic fracturing fluids or other fluids to reach underground drinking water resources.

Hydraulic fracturing fluids primarily move along two pathways during the well injection stage: the oil and gas production well and the newly-created fracture network. Oil and gas production wells are designed and constructed to move fluids to and from the targeted rock formation without leaking and to prevent fluid movement along the outside of the well. This is generally accomplished by installing multiple layers of casing and cement within the drilled hole (Text Box ES-2), particularly where the well intersects oil-, gas-, and/or water-bearing rock formations. Casing and cement, in addition to other well components (e.g., packers), can control hydraulic fracturing fluid movement by creating a preferred flow pathway (i.e., inside the casing) and preventing unintentional fluid movement (e.g., from the inside of the casing to the surrounding environment or vertically along the well from the targeted rock formation to shallower formations).<sup>1</sup> An EPA survey of oil and gas production wells hydraulically fractured between approximately September 2009 and September 2010 suggests that hydraulically fractured wells are often, but not always, constructed

---

<sup>1</sup> Packers are mechanical devices installed with casing. Once the casing is set in the drilled hole, packers swell to fill the space between the outside of the casing and the surrounding rock or casing.

with multiple casings that have varying amounts of cement surrounding each casing ([U.S. EPA, 2015n](#)). Among the wells surveyed, the most common number of casings per well was two: surface casing and production casing (Text Box ES-2). The presence of multiple cemented casings that extend from the ground surface to below the designated drinking water resource is one of the primary well construction features that protects underground drinking water resources.

During hydraulic fracturing, a well is subjected to greater pressure and temperature changes than during any other activity in the life of the well. As hydraulic fracturing fluid is injected into the well, the pressure applied to the well increases until the targeted rock formation fractures; then pressure decreases. Maximum pressures applied to wells during hydraulic fracturing have been reported to range from less than 2,000 pounds per square inch (psi) [14 megapascals (MPa)] to approximately 12,000 psi (83 MPa).<sup>1</sup> A well can also experience temperature changes as cooler hydraulic fracturing fluid enters the warmer well. In some cases, casing temperatures have been observed to drop from 212°F (100°C) to 64°F (18°C). A well can experience multiple pressure and temperature cycles if hydraulic fracturing is done in multiple stages or if a well is re-fractured.<sup>2</sup> Casing, cement, and other well components need to be able to withstand these changes in pressure and temperature, so that hydraulic fracturing fluids can flow to the targeted rock formation without leaking.

The fracture network created during hydraulic fracturing is the other primary pathway along which hydraulic fracturing fluids move. Fracture growth during hydraulic fracturing is complex and depends on the characteristics of the targeted rock formation and the characteristics of the hydraulic fracturing operation. In general, rock characteristics, particularly the natural stresses placed on the targeted rock formation due to the weight of the rock above, affect how the rock fractures, including whether newly-created fractures grow vertically (i.e., perpendicular to the ground surface) or horizontally (i.e., parallel to the ground surface) (Text Box ES-8). Because hydraulic fracturing fluids are used to create and grow fractures, fracture growth during hydraulic fracturing can be controlled by limiting the rate and volume of hydraulic fracturing fluid injected into the well.

Publicly available data on fracture growth are currently limited to microseismic and tiltmeter data collected during hydraulic fracturing operations in five shale plays in the United States. Analyses of these data by [Fisher and Warpinski \(2012\)](#) and [Davies et al. \(2012\)](#) indicate that the direction of fracture growth generally varied with depth and that upward vertical fracture growth was often on the order of tens to hundreds of feet in the shale formations studied (Text Box ES-8). One percent of the fractures had a fracture height greater than 1,148 feet (350 meters), and the maximum fracture height among all of the data reported was 1,929 feet (588 meters). These reported fracture heights suggest that some fractures can grow out of the targeted rock formation and into an overlying formation. It is unknown whether these observations apply to other hydraulically fractured rock formations because similar data from hydraulic fracturing operations in other rock formations are not currently available to the public.

---

<sup>1</sup> For comparison, average atmospheric pressure is approximately 15 psi.

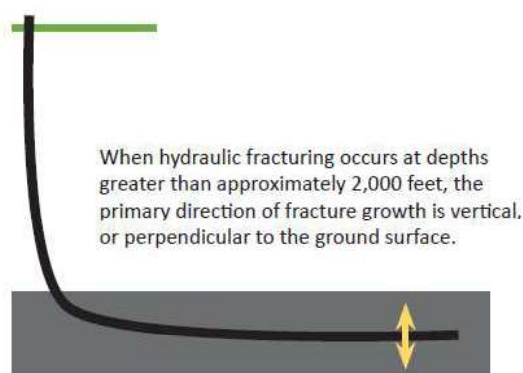
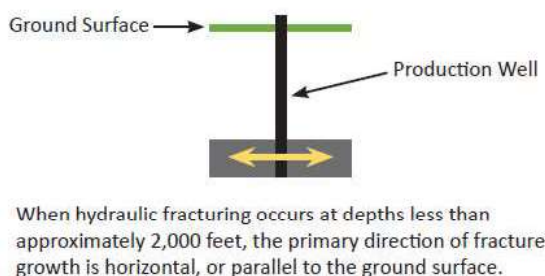
<sup>2</sup> In a multi-stage hydraulic fracturing operation, specific parts of the well are isolated and hydraulically fractured until the total desired length of the well has been hydraulically fractured.

### Text Box ES-8. Fracture Growth.

Fracture growth during hydraulic fracturing is complex and depends on the characteristics of the targeted rock formation and the characteristics of the hydraulic fracturing operation.

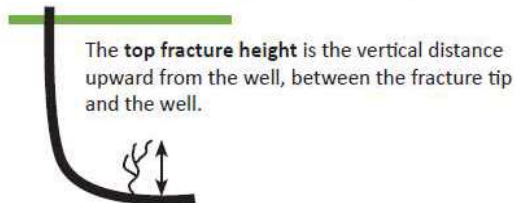
#### Primary Direction of Fracture Growth

In general, the weight of the rock above the point of hydraulic fracturing affects the primary direction of fracture growth. Therefore, the depth at which hydraulic fracturing occurs affects whether fractures grow vertically or horizontally.

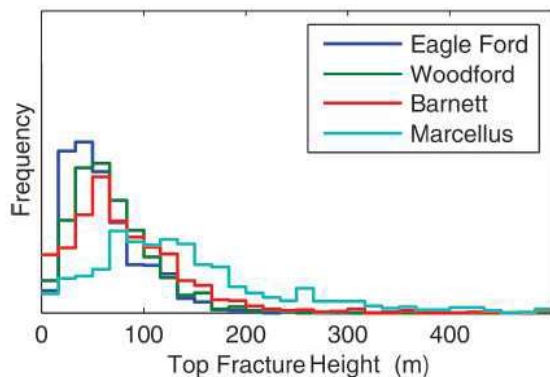


#### Fracture Height

Fisher and Warpinski (2012) and Davies et al. (2012) analyzed microseismic and tiltmeter data collected during thousands of hydraulic fracturing operations in the Barnett, Eagle Ford, Marcellus, Niobrara, and Woodford shale plays. Their data provide information on fracture heights in shale. Top fracture heights varied between shale plays and within individual shale plays.



SHALE PLAY	APPROXIMATE MEDIAN TOP FRACTURE HEIGHT [FEET (METERS)]
Eagle Ford	130 (40)
Woodford	160 (50)
Barnett	200 (60)
Marcellus	400 (120)
Niobrara	160 (50)

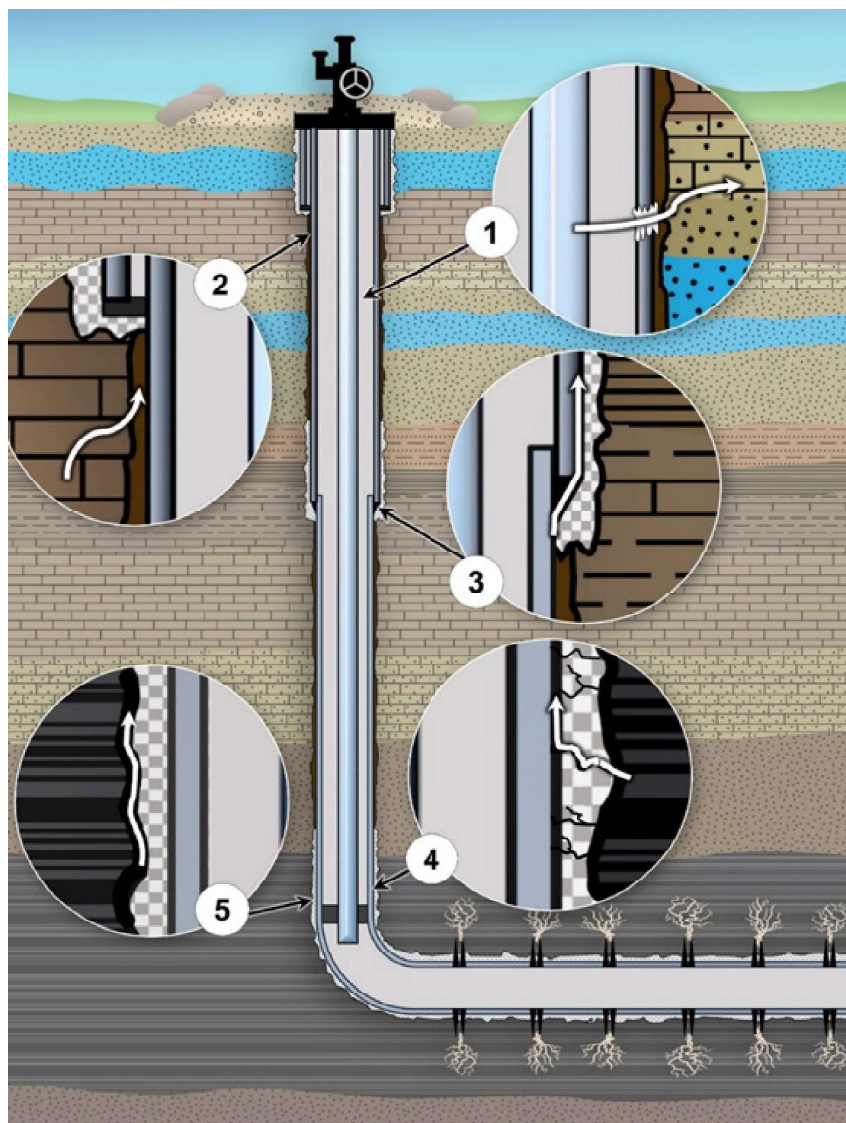


Source: Davies et. (2012)

The potential for hydraulic fracturing fluids to reach, and therefore impact, underground drinking water resources is related to the pathways along which hydraulic fracturing fluids primarily move during hydraulic fracturing: the oil and gas production well itself and the fracture network created during hydraulic fracturing. Because the well can be a pathway for fluid movement, the mechanical integrity of the well is an important factor that affects the frequency and severity of impacts from



the well injection stage of the hydraulic fracturing water cycle.<sup>1</sup> A well with insufficient mechanical integrity can allow unintended fluid movement, either from the inside to the outside of the well (pathway 1 in Figure ES-6) or vertically along the outside of the well (pathways 2-5). The existence of one or more of these pathways can result in impacts on drinking water resources if hydraulic fracturing fluids reach groundwater resources. Impacts on drinking water resources can also occur if gases or liquids released from the targeted rock formation or other formations during hydraulic fracturing travel along these pathways to groundwater resources.



**Figure ES-6. Potential pathways for fluid movement in a cemented well.**

These pathways (represented by the white arrows) include: (1) a casing and tubing leak into the surrounding rock, (2) an uncemented annulus (i.e., the space behind the casing), (3) microannuli between the casing and cement, (4) gaps in cement due to poor cement quality, and (5) microannuli between the cement and the surrounding rock. This figure is intended to provide a conceptual illustration of pathways that can be present in a well and is not to scale.

<sup>1</sup> Mechanical integrity is the absence of significant leakage within or outside of the well components.

The pathways shown in Figure ES-6 can exist because of inadequate well design or construction (e.g., incomplete cement around the casing where the well intersects with water-, oil-, or gas-bearing formations) or can develop over the well's lifetime, including during hydraulic fracturing. In particular, casing and cement can degrade over the life of the well because of exposure to corrosive chemicals, formation stresses, and operational stresses (e.g., pressure and temperature changes during hydraulic fracturing). As a result, some hydraulically fractured oil and gas production wells may develop one or more of the pathways shown in Figure ES-6. Changes in mechanical integrity over time have implications for older wells that are hydraulically fractured because these wells may not be able to withstand the stresses applied during hydraulic fracturing. Older wells may also be hydraulically fractured at shallower depths, where cement around the casing may be inadequate or missing.

Examples of mechanical integrity problems have been documented in hydraulically fractured oil and gas production wells. In one case, hydraulic fracturing of an inadequately cemented gas well in Bainbridge Township, Ohio, contributed to the movement of methane into local drinking water resources.<sup>1</sup> In another case, an inner string of casing burst during hydraulic fracturing of an oil well near Killdeer, North Dakota, resulting in a release of hydraulic fracturing fluids and formation fluids that impacted a groundwater resource.

The potential for hydraulic fracturing fluids or other fluids to reach underground drinking water resources is also related to the fracture network created during hydraulic fracturing. Because fluids travel through the newly-created fractures, the location of these fractures relative to underground drinking water resources is an important factor affecting the frequency and severity of potential impacts on drinking water resources. Data on the relative location of induced fractures to underground drinking water resources are generally not available, because fracture networks are infrequently mapped and because there can be uncertainty in the depth of the bottom of the underground drinking water resource at a specific location.

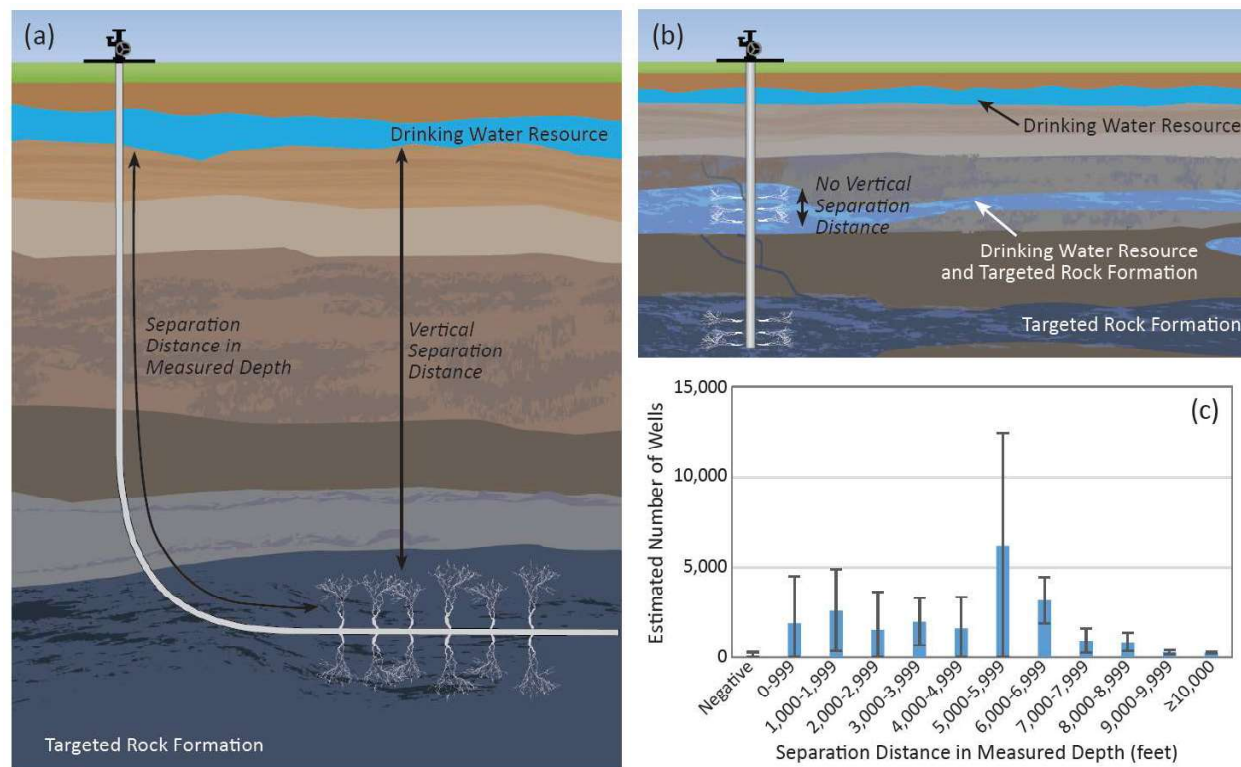
Without these data, we were often unable to determine with certainty whether fractures created during hydraulic fracturing have reached underground drinking water resources. Instead, we considered the vertical separation distance between hydraulically fractured rock formations and the bottom of underground drinking water resources. Based on computer modeling studies, [Birdsell et al. \(2015a\)](#) concluded that it is less likely that hydraulic fracturing fluids would reach an overlying drinking water resource if (1) the vertical separation distance between the targeted rock formation and the drinking water resource is large and (2) there are no open pathways (e.g., natural faults or fractures, or leaky wells). As the vertical separation distance between the targeted rock formation and the underground drinking water resource decreases, the likelihood of upward migration of hydraulic fracturing fluids to the drinking water resource increases ([Birdsell et al. 2015a](#)).

Figure ES-7 illustrates how the vertical separation distance between the targeted rock formation and underground drinking water resources can vary across the United States. The two example

---

<sup>1</sup> Although ingestion of methane is not considered to be toxic, methane can pose a physical hazard. Methane can accumulate to explosive levels when allowed to exsolve (degas) from groundwater in closed environments.

environments depicted in panels a and b represent the range of separation distances shown in panel c. In Figure ES-7a, there are thousands of feet between the bottom of the underground drinking water resource and the hydraulically fractured rock formation. These conditions are generally reflective of deep shale formations (e.g., Haynesville Shale), where oil and gas production wells are first drilled vertically and then horizontally along the targeted rock formation. Microseismic data and modeling studies suggest that, under these conditions, fractures created during hydraulic fracturing are unlikely to grow through thousands of feet of rock into underground drinking water resources.



**Figure ES-7. Examples of different subsurface environments in which hydraulic fracturing takes place.**

In panel a, there are thousands of feet between the base of the underground drinking water resource and the part of the well that is hydraulically fractured. Panel b illustrates the co-location of groundwater and oil and gas resources. In these types of situations, there is no separation between the shallowest point of hydraulic fracturing within the well and the bottom of the underground drinking water resource. Panel c shows the estimated distribution of separation distances for approximately 23,000 oil and gas production wells hydraulically fractured by nine service companies between 2009 and 2019 ([U.S. EPA, 2015n](#)). The separation distance is the distance along the well between the point of shallowest hydraulic fracturing in the well and the base of the protected groundwater resource (illustrated in panel a). The error bars in panel c display 95% confidence intervals.

When drinking water resources are co-located with oil and gas resources and there is no vertical separation between the hydraulically fractured rock formation and the bottom of the underground drinking water resource (Figure ES-7b), the injection of hydraulic fracturing fluids impacts the quality of the drinking water resource. According to the information examined in this report, the overall occurrence of hydraulic fracturing within a drinking water resource appears to be low, with

the activity generally concentrated in some areas in the western United States (e.g., the Wind River Basin near Pavillion, Wyoming, and the Powder River Basin of Montana and Wyoming).<sup>1</sup> Hydraulic fracturing within drinking water resources introduces hydraulic fracturing fluid into formations that may currently serve, or in the future could serve, as a drinking water source for public or private use. This is of concern in the short-term if people are currently using these formations as a drinking water supply. It is also of concern in the long-term, because drought or other conditions may necessitate the future use of these formations for drinking water.

Regardless of the vertical separation between the targeted rock formation and the underground drinking water resource, the presence of other wells near hydraulic fracturing operations can increase the potential for hydraulic fracturing fluids or other subsurface fluids to move to drinking water resources. There have been cases in which hydraulic fracturing at one well has affected a nearby oil and gas well or its fracture network, resulting in unexpected pressure increases at the nearby well, damage to the nearby well, or spills at the surface of the nearby well. These well communication events, or “frac hits,” have been reported in New Mexico, Oklahoma, and other locations. Based on the available information, frac hits most commonly occur when multiple wells are drilled from the same surface location and when wells are spaced less than 1,100 feet (335 meters) apart. Frac hits have also been observed at wells up to 8,422 feet (2,567 meters) away from a well undergoing hydraulic fracturing.

Abandoned wells near a well undergoing hydraulic fracturing can provide a pathway for vertical fluid movement to drinking water resources if those wells were not properly plugged or if the plugs and cement have degraded over time. For example, an abandoned well in Pennsylvania produced a 30-foot (9-meter) geyser of brine and gas for more than a week after hydraulic fracturing of a nearby gas well. The potential for fluid movement along abandoned wells may be a significant issue in areas with historic oil and gas exploration and production. Various studies estimate the number of abandoned wells in the United States to be significant. For instance, the Interstate Oil and Gas Compact Commission estimates that over 1 million wells were drilled in the United States prior to the enactment of state oil and gas regulations ([IOGCC, 2008](#)). The location and condition of many of these wells are unknown, and some states have programs to find and plug abandoned wells.

## Well Injection Conclusions

Impacts on drinking water resources associated with the well injection stage of the hydraulic fracturing water cycle have occurred in some instances. In particular, mechanical integrity failures have allowed gases or liquids to move to underground drinking water resources. Additionally, hydraulic fracturing has occurred within underground drinking water resources in parts of the United States. This practice introduces hydraulic fracturing fluids into underground drinking water resources. Consequently, the mechanical integrity of the well and the vertical separation distance between the targeted rock formation and underground drinking water resources are important factors that affect the frequency and severity of impacts on drinking water resources. The presence of multiple layers of cemented casing and thousands of feet of rock between hydraulically fractured

---

<sup>1</sup> Section 6.3.2 in Chapter 6.



rock formations and underground drinking water resources can reduce the frequency of impacts on drinking water resources during the well injection stage of the hydraulic fracturing water cycle.

## Produced Water Handling

**Activity:** The on-site collection and handling of water that returns to the surface after hydraulic fracturing and the transportation of that water for disposal or reuse.

**Relationship to Drinking Water Resources:** Spills of produced water can reach groundwater and surface water resources.

After hydraulic fracturing, the injection pressure applied to the oil or gas production well is released, and the direction of fluid flow reverses, causing fluid to flow out of the well. The fluid that initially returns to the surface after hydraulic fracturing is mostly hydraulic fracturing fluid and is sometimes called “flowback” (Text Box ES-9). As time goes on, the fluid that returns to the surface contains water and economic quantities of oil and/or gas that are separated and collected. Water that returns to the surface during oil and gas production is similar in composition to the fluid naturally found in the targeted rock formation and is typically called “produced water.” The term “produced water” is also used to refer to any water, including flowback, that returns to the surface through the production well as a by-product of oil and gas production. This latter definition of “produced water” is used in this report.

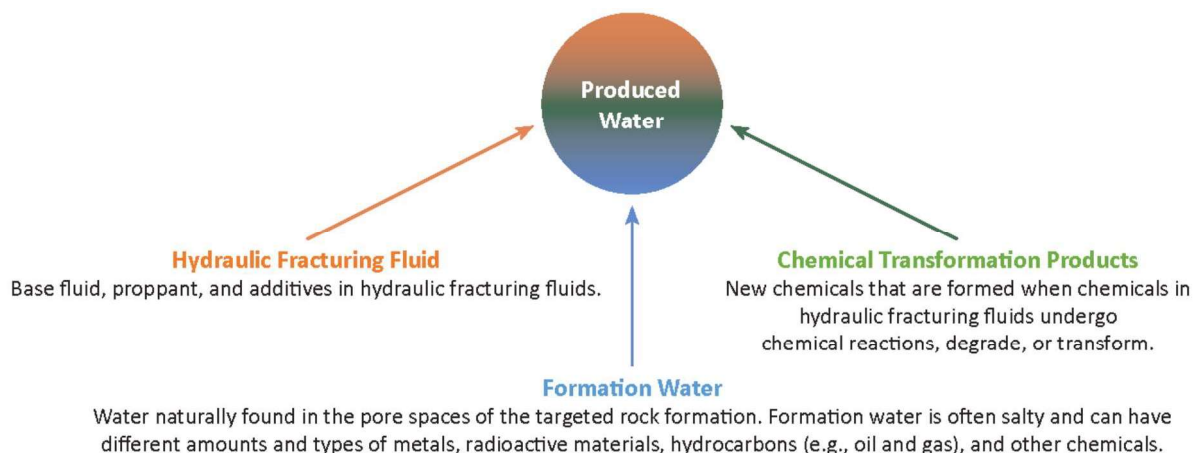
Produced water can contain many constituents, depending on the composition of the injected hydraulic fracturing fluid and the type of rock hydraulically fractured. Knowledge of the chemical composition of produced water comes from the collection and analysis of produced water samples, which often requires advanced laboratory equipment and techniques that can detect and quantify chemicals in produced water. In general, produced water has been found to contain:

- Salts, including those composed from chloride, bromide, sulfate, sodium, magnesium, and calcium;
- Metals, including barium, manganese, iron, and strontium;
- Naturally-occurring organic compounds, including benzene, toluene, ethylbenzene, xylenes (BTEX), and oil and grease;
- Radioactive materials, including radium; and
- Hydraulic fracturing chemicals and their chemical transformation products.

The amount of these constituents in produced water varies across the United States, both within and among different rock formations. Produced water from shale and tight gas formations is typically very salty compared to produced water from coalbed methane formations. For example, the salinity of produced water from the Marcellus Shale has been reported to range from less than 1,500 milligrams per liter (mg/L) of total dissolved solids to over 300,000 mg/L, while produced water from coalbed methane formations has been reported to range from 170 mg/L of total

**Text Box ES-9. Produced Water from Hydraulically Fractured Oil and Gas Production Wells.**

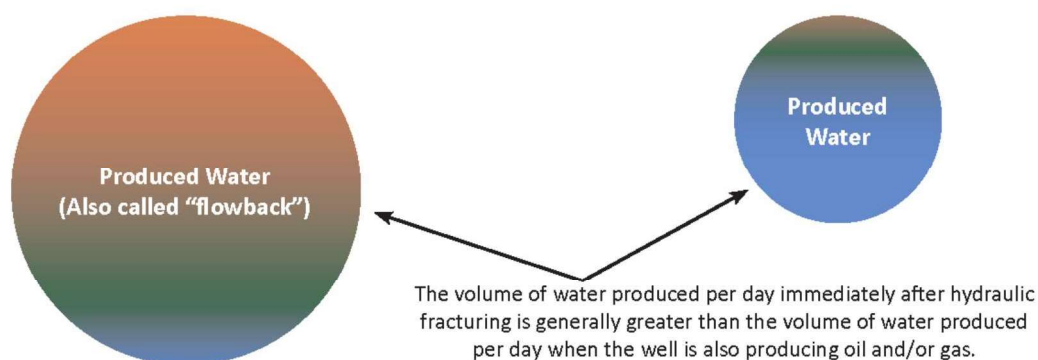
Water of varying quality is a byproduct of oil and gas production. The composition and volume of produced water varies by well, rock formation, and time after hydraulic fracturing. Produced water can contain hydraulic fracturing fluid, formation water, and chemical transformation products.

**Water Produced Immediately After Hydraulic Fracturing**

Generally, the fluid that initially returns to the surface is mostly a mixture of the injected hydraulic fracturing fluid and its reaction and degradation products.

**Water Produced During Oil or Gas Production**

The fluid that returns to the surface when oil and/or gas is produced generally resembles the formation water.



dissolved solids to nearly 43,000 mg/L.<sup>1</sup> Shale and sandstone formations also commonly contain radioactive materials, including uranium, thorium, and radium. As a result, radioactive materials have been detected in produced water from these formations.

Produced water volumes can vary by well, rock formation, and time after hydraulic fracturing. Volumes are often described in terms of the volume of hydraulic fracturing fluid used to fracture the well. For example, Figure ES-4 shows that wells in the Marcellus Shale typically produce 10-30% of the volume injected in the first 10 years after hydraulic fracturing. In comparison, some wells in the Barnett Shale have produced 100% of the volume injected in the first three years.

<sup>1</sup> For comparison, the average salinity of seawater is approximately 35,000 mg/L of total dissolved solids.

Because of the large volumes used for hydraulic fracturing [about 4 million gallons (15 million liters) per well in the Marcellus Shale and the Barnett Shale], hundreds of thousands to millions of gallons of produced water need to be collected and handled at the well site. The volume of water produced per day generally decreases with time, so the volumes handled on site immediately after hydraulic fracturing can be much larger than the volumes handled when the well is producing oil and/or gas (Text Box ES-9).

Produced water flows from the well to on-site tanks or pits through a series of pipes or flowlines (Text Box ES-10) before being transported offsite via trucks or pipelines for disposal or reuse. While produced water collection, storage, and transportation systems are designed to contain produced water, spills can occur. Changes in drinking water quality can occur if produced water spills reach groundwater or surface water resources.

Produced water spills have been reported across the United States. Median spill volumes among the datasets reviewed for this report ranged from approximately 340 gallons (1,300 liters) to 1,000 gallons (3,800 liters) per spill.<sup>1</sup> There were, however, a small number of large volume spills. In North Dakota, for example, there were 12 spills greater than 21,000 gallons (79,500 liters), five spills greater than 42,000 gallons (160,000 liters), and one spill of 2.9 million gallons (11 million liters) in 2015. Common causes of produced water spills included human error and equipment leaks or failures. Common sources of produced water spills included hoses or lines and storage equipment.

Spills of produced water have reached groundwater and surface water resources. In [U.S. EPA \(2015m\)](#), 30 of the 225 (13%) produced water spills characterized were reported to have reached surface water (e.g., creeks, ponds, or wetlands), and one was reported to have reached groundwater. Of the spills that were reported to have reached surface water, reported spill volumes ranged from less than 170 gallons (640 liters) to almost 74,000 gallons (280,000 liters). A separate assessment of produced water spills reported to the California Office of Emergency Services between January 2009 and December 2014 reported that 18% of the spills impacted waterways ([CCST, 2015a](#)).

Documented cases of water resource impacts from produced water spills provide insights into the types of impacts that can occur. In most of the cases reviewed for this report, documented impacts included elevated levels of salinity in groundwater and/or surface water resources.<sup>2</sup> For example, the largest produced water spill reported in this report occurred in North Dakota in 2015, when approximately 2.9 million gallons (11 million liters) of produced water spilled from a broken pipeline. The spilled fluid flowed into Blacktail Creek and increased the concentration of chloride and the electrical conductivity of the creek; these observations are consistent with an increase in water salinity. Elevated levels of electrical conductivity and chloride were also found downstream in the Little Muddy River and the Missouri River. In another example, pits holding flowback fluids overflowed in Kentucky in 2007. The spilled fluid reached the Acorn Fork Creek, decreasing the pH of the creek and increasing the electrical conductivity.

---

<sup>1</sup> See Section 7.4 in Chapter 7.

<sup>2</sup> Groundwater impacts from produced water management practices are described in Chapter 8 and summarized in the “Wastewater Disposal and Reuse” section below.

### Text Box ES-10. On-Site Storage of Produced Water.

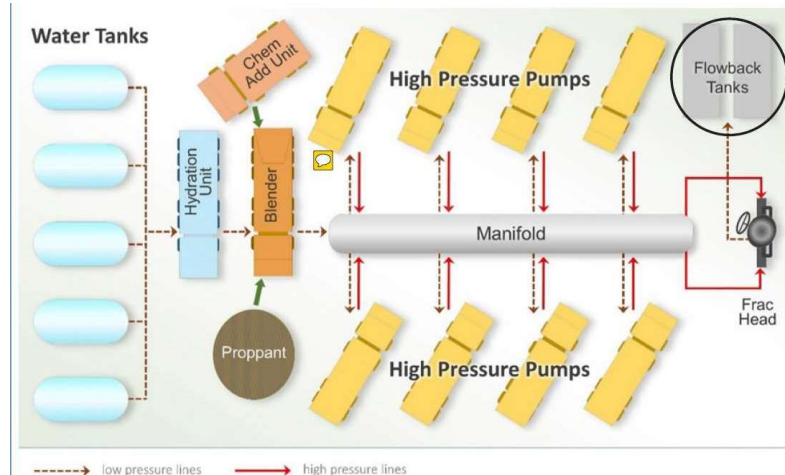
Water that returns to the surface after hydraulic fracturing is collected and stored on site in pits or tanks.



Above: Flowback pit. (Source: US DOE/NETL)



Right: Flowback tanks. (Source: US EPA)



#### Produced Water Storage Immediately after Hydraulic Fracturing

After hydraulic fracturing, water is returned to the surface. Water initially produced from the well after hydraulic fracturing is sometimes called “flowback.” This water can be stored onsite in tanks or pits before being taken offsite for injection in Class II wells, reuse in other hydraulic fracturing operations, or aboveground disposal.

Source: Adapted from Olson (2011) and BJ Services Company (2009)

#### Produced Water Storage During Oil or Gas Production

Water is generally produced throughout the life of an oil and gas production well. During oil and gas production, the equipment on the well pad often includes the wellhead and storage tanks or pits for gas, oil, and produced water.



Above: Produced water storage pit. (Source: US EPA)

Left: Produced water storage tanks. (Source: US EPA)



Site-specific studies of historical produced water releases highlight the role of local geology in the movement of produced water through the environment. [Whittemore \(2007\)](#) described a site in Kansas where low permeability soils and rock caused produced water to primarily flow over the land surface to nearby surface water resources, reducing the amount of produced water that infiltrated soil. In contrast, [Otton et al. \(2007\)](#) explored the release of produced water and oil from two pits in Oklahoma. In this case, produced water from the pits flowed through thin soil and into the underlying, permeable rock. Produced water was also identified in deeper, less permeable rock. The authors suggest that produced water moved into the deeper, less permeable rock through natural fractures. Together, these studies highlight the role of preferential flow paths (i.e., paths of least resistance) in the movement of produced water through the environment.

Spill response activities likely reduce the severity of impacts on groundwater and surface water resources from produced water spills. For example, in the North Dakota example noted above, absorbent booms were placed in the affected creek and contaminated soil and oil-coated ice were removed from the site. In another example, a pipeline leak in Pennsylvania spilled approximately 11,000 gallons (42,000 liters) of produced water, which flowed into a nearby stream. In response, the pipeline was shut off, a dam was constructed to contain the spilled produced water, water was removed from the stream, and the stream was flushed with fresh water. In both examples, it was not possible to quantify how spill response activities reduced the severity of impacts on groundwater or surface water resources. However, actions taken after the spills were designed to stop produced water from entering the environment (e.g., shutting off a pipeline), remove produced water from the environment (e.g., using absorbent booms), and reduce the concentration of produced water constituents introduced into water resources (e.g., flushing a stream with fresh water).

The severity of impacts on water quality from spills of produced water depends on the identity and amount of produced water constituents that reach groundwater or surface water resources, the toxicity of those constituents, and the characteristics of the receiving water resource.<sup>1</sup> In particular, spills of produced water can have high levels of total dissolved solids, which affects how the spilled fluid moves through the environment. When a spilled fluid has greater levels of total dissolved solids than groundwater, the higher-density fluid can move downward through groundwater resources. Depending on the flow rate and other properties of the groundwater resource, impacts from produced water spills can last for years.

### **Produced Water Handling Conclusions**

Spills of produced water during the produced water handling stage of the hydraulic fracturing water cycle have reached groundwater and surface water resources in some cases. Several cases of water resource impacts from produced water spills suggest that impacts are characterized by increases in the salinity of the affected groundwater or surface water resource. In the absence of direct pathways to groundwater resources (e.g., fractured rock), large volume spills are more likely to travel further from the site of the spill, potentially to groundwater or surface water resources.

---

<sup>1</sup> Human health hazards associated with chemicals detected in produced water are discussed in Chapter 9 and summarized in the “Chemicals in the Hydraulic Fracturing Water Cycle” section below.

Additionally, saline produced water can migrate downward through soil and into groundwater resources, leading to longer-term groundwater contamination. Spill prevention and response activities can prevent spilled fluids from reaching groundwater or surface water resources and minimize impacts from spilled fluids.

## **Wastewater Disposal and Reuse**

**Activity:** The disposal and reuse of hydraulic fracturing wastewater.

**Relationship to Drinking Water Resources:** Disposal practices can release inadequately treated or untreated hydraulic fracturing wastewater to groundwater and surface water resources.

In general, produced water from hydraulically fractured oil and gas production wells is managed through injection in Class II wells, reuse in other hydraulic fracturing operations, or various aboveground disposal practices (Text Box ES-11). In this report, produced water from hydraulically fractured oil and gas wells that is being managed through one of the above management strategies is referred to as “hydraulic fracturing wastewater.” Wastewater management choices are affected by cost and other factors, including: the local availability of disposal methods; the quality of produced water; the volume, duration, and flow rate of produced water; federal, state, and local regulations; and well operator preferences.

Available information suggests that hydraulic fracturing wastewater is mostly managed through injection in Class II wells. [Veil \(2015\)](#) estimated that 93% of produced water from the oil and gas industry was injected in Class II wells in 2012. Although this estimate included produced water from oil and gas wells in general, it is likely indicative of nationwide management practices for hydraulic fracturing wastewater. Disposal of hydraulic fracturing wastewater in Class II wells is often cost-effective, especially when a Class II disposal well is located within a reasonable distance from a hydraulically fractured oil or gas production well. In particular, large numbers of active Class II disposal wells are found in Texas (7,876), Kansas (5,516), Oklahoma (3,837), Louisiana (2,448), and Illinois (1,054) ([U.S. EPA, 2016d](#)). Disposal of hydraulic fracturing wastewater in Class II wells has been associated with earthquakes in several states, which may reduce the availability of injection in Class II wells as a wastewater disposal option in these states.

Nationwide, aboveground disposal and reuse of hydraulic fracturing wastewater are currently practiced to a much lesser extent compared to injection in Class II wells, and these management strategies appear to be concentrated in certain parts of the United States. For example, approximately 90% of hydraulic fracturing wastewater from Marcellus Shale gas wells in Pennsylvania was reused in other hydraulic fracturing operations in 2013 (Figure ES-4a). Reuse in hydraulic fracturing operations is practiced in some other areas of the United States as well, but at lower rates (approximately 5-20%). Evaporation ponds and percolation pits have historically been used in the western United States to manage produced water from the oil and gas industry and have likely been used to manage hydraulic fracturing wastewater. Percolation pits, in particular, were commonly reported to have been used to manage produced water from stimulated wells in Kern