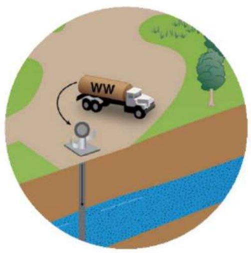
Text Box ES-11. Hydraulic Fracturing Wastewater Management.

Produced water from hydraulically fractured oil and gas production wells is often, but not always, considered a waste product to be managed. Hydraulic fracturing wastewater (i.e., produced water from hydraulically fractured wells) is generally managed through injection in Class II wells, reuse in other hydraulic fracturing operations, and various aboveground disposal practices.

Injection in Class II Wells

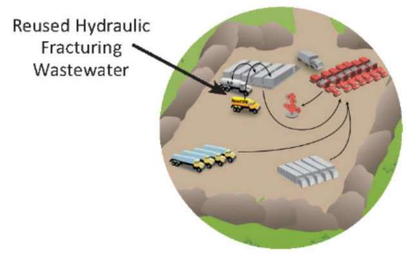
Most oil and gas wastewater—including hydraulic fracturing wastewater—is injected in Class II wells, which are regulated under the Underground Injection Control Program of the Safe Drinking Water Act.



Class II wells are used to inject wastewater associated with oil and gas production underground. Fluids can be injected for disposal or to enhance oil or gas production from nearby oil and gas production wells.

Reuse in Other Hydraulic Fracturing Operations

Hydraulic fracturing wastewater can be used, in combination with fresh water, to make up hydraulic fracturing fluids at nearby hydraulic fracturing operations.

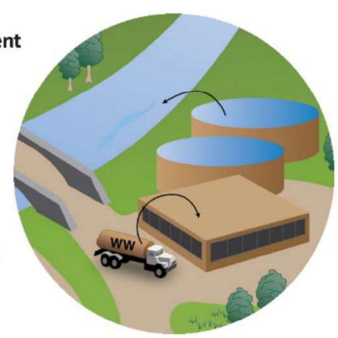


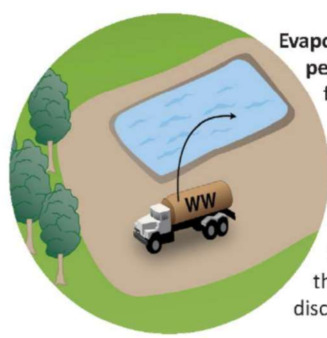
Reuse in other hydraulic fracturing operations depends on the quality and quantity of the available wastewater, the cost associated with treatment and transportation of the wastewater, and local water demand for hydraulic fracturing.

Aboveground Disposal Practices

Aboveground disposal of treated and untreated hydraulic fracturing wastewater can take many forms, including release to surface water resources and land application.

Some **wastewater treatment facilities** treat hydraulic fracturing wastewater and release the treated wastewater to surface water. Solid or liquid by-products of the treatment process can be sent to landfills or injected underground.





Evaporation ponds and **percolation pits** can be used for hydraulic fracturing wastewater disposal. Evaporation ponds allow liquid waste to naturally evaporate. Percolation pits allow wastewater to move into the ground, although this practice has been discontinued in most states.

Federal and state regulations affect aboveground disposal management options. For example, existing federal regulations generally prevent the direct release of wastewater pollutants to waters of the United States from onshore oil and gas extraction facilities east of the 98th meridian. However, in the arid western portion of the continental United States (west of the 98th meridian), direct discharges of wastewater from onshore oil and gas extraction facilities to waters of the United States may be permitted if the produced water has a use in agriculture or wildlife propagation and meets established water quality criteria when discharged.

County, California, between 2011 and 2014.[1] Beneficial uses (e.g., livestock watering and irrigation) are also practiced in the western United States if the water quality is considered acceptable, although available data on the use of these practices are incomplete.

Aboveground disposal practices generally release treated or, under certain conditions, untreated wastewater directly to surface water or the land surface (e.g., wastewater treatment facilities, evaporation pits, or irrigation). If released to the land surface, treated or untreated wastewater can move through soil to groundwater resources. Because the ultimate fate of the wastewater can be groundwater or surface water resources, the aboveground disposal of hydraulic fracturing wastewater, in particular, can impact drinking water resources.

Impacts on drinking water resources from the aboveground disposal of hydraulic fracturing wastewater have been documented. For example, early wastewater management practices in the Marcellus Shale region in Pennsylvania included the use of wastewater treatment facilities that released (i.e., discharged) treated wastewater to surface waters (Figure ES-8). The wastewater treatment facilities were unable to adequately remove the high levels of total dissolved solids found in produced water from Marcellus Shale gas wells, and the discharges contributed to elevated levels of total dissolved solids (particularly bromide) in the Monongahela River Basin. In the Allegheny River Basin, elevated bromide levels were linked to increases in the concentration of hazardous disinfection byproducts in at least one downstream drinking water facility and a shift to more toxic brominated disinfection byproducts.[2] In response, the Pennsylvania Department of Environmental Protection revised existing regulations to prevent these discharges and also requested that oil and gas operators voluntarily stop bringing certain kinds of hydraulic fracturing wastewater to facilities that discharge inadequately treated wastewater to surface waters.[3]

The scientific literature and recent data from the Pennsylvania Department of Environmental Protection suggest that other produced water constituents (e.g., barium, strontium, and radium) may have been introduced to surface waters through the release of inadequately treated hydraulic fracturing wastewater. In particular, radium has been detected in stream sediments at or near wastewater treatment facilities that discharged inadequately treated hydraulic fracturing wastewater. Such sediments can migrate if they are disturbed during dredging or flood events. Additionally, residuals from the treatment of hydraulic fracturing wastewater (i.e., the solids or liquids that remain after treatment) are concentrated in the constituents removed during treatment, and these residuals can impact groundwater or surface water resources if they are not managed properly.

[1] Hydraulic fracturing was the predominant stimulation practice. Other stimulation practices included acid fracturing and matrix acidizing. California updated its regulations in 2015 to prohibit the use of percolation pits for the disposal of fluids produced from stimulated wells.

[2] Disinfection byproducts form through chemical reactions between organic material and disinfectants, which are used in drinking water treatment. Human health hazards associated with disinfection byproducts are described in Section 9.5.6 in Chapter 9.

[3] See Text Box 8-1 in Chapter 8.

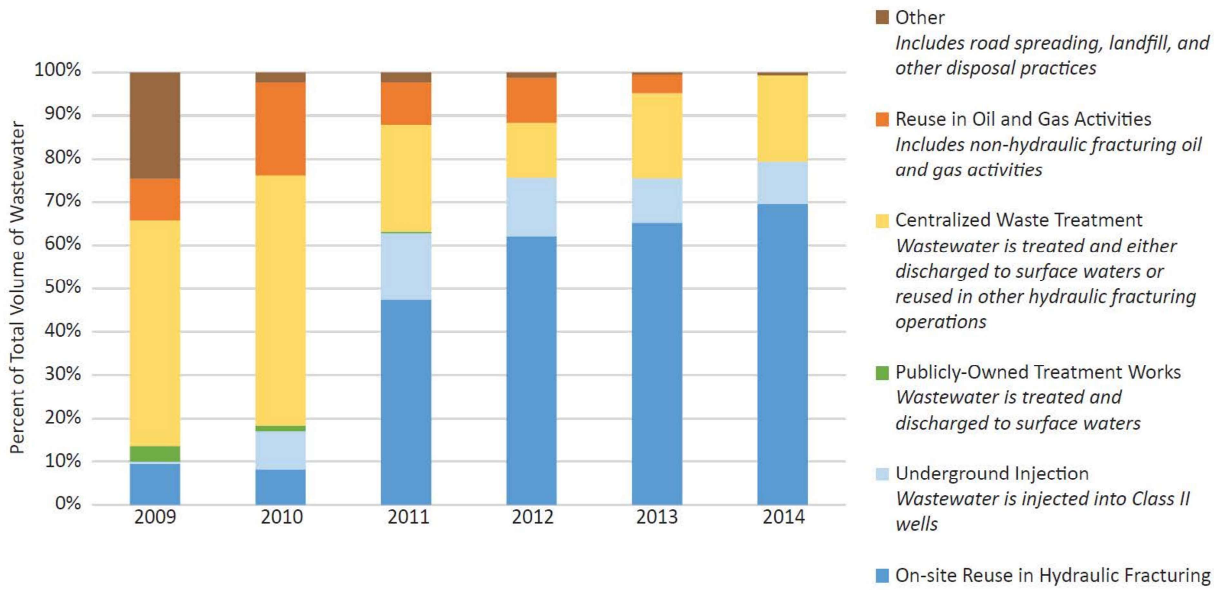


Figure ES-8. Changes in wastewater management practices over time in the Marcellus Shale area of Pennsylvania.
Data from PA DEP (2015a).

Impacts on groundwater and surface water resources from current and historic uses of lined and unlined pits, including percolation pits, in the oil and gas industry have been documented. For example, Kell (2011) reported 63 incidents of non-public water supply contamination from unlined or inadequately constructed pits in Ohio between 1983 and 2007, and 57 incidents of groundwater contamination from unlined produced water disposal pits in Texas prior to 1984. Other cases of impacts have been identified in several states, including New Mexico, Oklahoma, Pennsylvania, and Wyoming.[1] Impacts among these cases included the detection of volatile organic compounds in groundwater resources, wastewater reaching surface water resources from pit overflows, and wastewater reaching groundwater resources through liner failures. Based on documented impacts on groundwater resources from unlined pits, many states have implemented regulations that prohibit percolation pits or unlined storage pits for either hydraulic fracturing wastewater or oil and gas wastewater in general.

The severity of impacts on drinking water resources from the aboveground disposal of hydraulic fracturing wastewater depends on the volume and quality of the discharged wastewater and the characteristics of the receiving water resource. In general, large surface water resources with high flow rates can reduce the severity of impacts through dilution, although impacts may not be eliminated. In contrast, groundwater is generally slow moving, which can lead to an accumulation of hydraulic fracturing wastewater contaminants in groundwater from continuous or repeated discharges to the land surface; the resulting contamination can be long-lasting. The severity of

[1] See Section 8.4.5 in Chapter 8.

impacts on groundwater resources will also be influenced by soil and sediment properties and other factors that control the movement or degradation of wastewater constituents.

Wastewater Disposal and Reuse Conclusions

The aboveground disposal of hydraulic fracturing wastewater has impacted the quality of groundwater and surface water resources in some instances. In particular, discharges of inadequately treated hydraulic fracturing wastewater to surface water resources have contributed to elevated levels of hazardous disinfection byproducts in at least one downstream drinking water system. Additionally, the use of lined and unlined pits for the storage or disposal of oil and gas wastewater has impacted surface and groundwater resources. Unlined pits, in particular, provide a direct pathway for contaminants to reach groundwater. Wastewater management is dynamic, and recent changes in state regulations and practices have been made to limit impacts on groundwater and surface water resources from the aboveground disposal of hydraulic fracturing wastewater.

Chemicals in the Hydraulic Fracturing Water Cycle

Chemicals are present in the hydraulic fracturing water cycle. During the chemical mixing stage of the hydraulic fracturing water cycle, chemicals are intentionally added to water to alter its properties for hydraulic fracturing (Text Box ES-6). Produced water, which is collected, handled, and managed in the last two stages of the hydraulic fracturing water cycle, contains chemicals added to hydraulic fracturing fluids, naturally occurring chemicals found in hydraulically fractured rock formations, and any chemical transformation products (Text Box ES-9). By evaluating available data sources, we compiled a list of 1,606 chemicals that are associated with the hydraulic fracturing water cycle, including 1,084 chemicals reported to have been used in hydraulic fracturing fluids and 599 chemicals detected in produced water. This list represents a national analysis; an individual well would likely have a fraction of the chemicals on this list and may have other chemicals that were not included on this list.

In many stages of the hydraulic fracturing water cycle, the severity of impacts on drinking water resources depends, in part, on the identity and amount of chemicals that enter the environment. The properties of a chemical influence how it moves and transforms in the environment and how it interacts with the human body. Therefore, some chemicals in the hydraulic fracturing water cycle are of more concern than others because they are more likely to move with water (e.g., spilled hydraulic fracturing fluid) to drinking water resources, persist in the environment (e.g., chemicals that do not degrade), and/or affect human health.

Evaluating potential hazards from chemicals in the hydraulic fracturing water cycle is most useful at local and/or regional scales because chemical use for hydraulic fracturing can vary from well to well and because the characteristics of produced water are influenced by the geochemistry of hydraulically fractured rock formations. Additionally, site-specific characteristics (e.g., the local landscape, and soil and subsurface permeability) can affect whether and how chemicals enter drinking water resources, which influences how long people may be exposed to specific chemicals and at what concentrations. As a first step for informing site-specific risk assessments, the EPA compiled toxicity values for chemicals in the hydraulic fracturing water cycle from federal, state, and international sources that met the EPA's criteria for inclusion in this report.[1,2]

The EPA was able to identify chronic oral toxicity values from the selected data sources for 98 of the 1,084 chemicals that were reported to have been used in hydraulic fracturing fluids between 2005 and 2013. Potential human health hazards associated with chronic oral exposure to these chemicals include cancer, immune system effects, changes in body weight, changes in blood chemistry, cardiotoxicity, neurotoxicity, liver and kidney toxicity, and reproductive and developmental toxicity. Of the chemicals most frequently reported to FracFocus 1.0, nine had toxicity values from the selected data sources (Table ES-3). Critical effects for these chemicals include kidney/renal toxicity, hepatotoxicity, developmental toxicity (extra cervical ribs), reproductive toxicity, and decreased terminal body weight.

Table ES-3. Available chronic oral reference values for hydraulic fracturing chemicals reported in 10% or more of disclosures in FracFocus 1.0.

Chemical name (CASRN)[a]	Chronic oral reference value (mg/kg/day)	Critical effect	Percent of FracFocus 1.0 disclosures[b]
Propargyl alcohol (107-19-7)	0.002[c]	Renal and hepatotoxicity	33
1,2,4-Trimethylbenzene (95-63-6)	0.01[c]	Decreased pain sensitivity	13
Naphthalene (91-20-3)	0.02[c]	Decreased terminal body weight	19
Sodium chlorite (7758-19-2)	0.03[c]	Neuro-developmental effects	11
2-Butoxyethanol (111-76-2)	0.1[c]	Hemosiderin deposition in the liver	23
Quaternary ammonium compounds, benzyl-C12-16-alkyldimethyl, chlorides (68424-85-1)	0.44[d]	Decreased body weight and weight gain	12
Formic acid (64-18-6)	0.9[e]	Reproductive toxicity	11
Ethylene glycol (107-21-1)	2[c]	Kidney toxicity	47
Methanol (67-56-1)	2[c]	Extra cervical ribs	73

[a] "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).

[b] Analysis considered 35,957 disclosures that met selected quality assurance criteria. See Table 9-2 in Chapter 9.

[c] From the EPA Integrated Risk Information System database.

[d] From the EPA Human Health Benchmarks for Pesticides database.

[e] From the EPA Provisional Peer-Reviewed Toxicity Value database.

[1] Specifically, the EPA compiled noncancer oral reference values and cancer oral slope factors (Chapter 9). A reference value describes the dose of a chemical that is likely to be without an appreciable risk of adverse health effects. In the context of this report, the term "reference value" generally refers to reference values for noncancer effects occurring via the oral route of exposure and for chronic durations. An oral slope factor is an upper-bound estimate on the increased cancer risk from a lifetime oral exposure to an agent.

[2] The EPA's criteria for inclusion in this report are described in Section 9.4.1 in Chapter 9. Sources of information that met these criteria are listed in Table 9-1 of Chapter 9.

Chronic oral toxicity values from the selected data sources were identified for 120 of the 599 chemicals detected in produced water. Potential human health hazards associated with chronic oral exposure to these chemicals include liver toxicity, kidney toxicity, neurotoxicity, reproductive and developmental toxicity, and carcinogenesis. Chemical-specific toxicity values are included in Chapter 9.

Chemicals in the Hydraulic Fracturing Water Cycle Conclusions

Some of the chemicals in the hydraulic fracturing water cycle are known to be hazardous to human health. Of the 1,606 chemicals identified by the EPA, 173 had chronic oral toxicity values from federal, state, and international sources that met the EPA's criteria for inclusion in this report. These data alone, however, are insufficient to determine which chemicals have the greatest potential to impact drinking water resources and human health. To understand whether specific chemicals can affect human health through their presence in drinking water, data on chemical concentrations in drinking water would be needed. In the absence of these data, relative hazard potential assessments could be conducted at local and/or regional scales using the multi-criteria decision analysis approach outlined in Chapter 9. This approach combines available chemical occurrence data with selected chemical, physical, and toxicological properties to place the severity of potential impacts (i.e., the toxicity of specific chemicals) into the context of factors that affect the likelihood of impacts (i.e., frequency of use, and chemical and physical properties relevant to environmental fate and transport).

Data Gaps and Uncertainties

The information reviewed for this report included cases of impacts on drinking water resources from activities in the hydraulic fracturing water cycle. Using these cases and other data, information, and analyses, we were able to identify factors that likely result in more frequent or more severe impacts on drinking water resources. However, there were instances in which we were unable to form conclusions about the potential for activities in the hydraulic fracturing water cycle to impact drinking water resources and/or the factors that influence the frequency or severity of impacts. Below, we provide perspective on the data gaps and uncertainties that prevented us from drawing additional conclusions about the potential for impacts on drinking water resources and/or the factors that affect the frequency and severity of impacts.

In general, comprehensive information on the location of activities in the hydraulic fracturing water cycle is lacking, either because it is not collected, not publicly available, or prohibitively difficult to aggregate. This includes information on the:

- Above- and belowground locations of water withdrawals for hydraulic fracturing;
- Surface locations of hydraulically fractured oil and gas production wells, where the chemical mixing, well injection, and produced water handling stages of the hydraulic fracturing water cycle take place;
- Belowground locations of hydraulic fracturing, including data on fracture growth; and
- Locations of hydraulic fracturing wastewater management practices, including the disposal of treatment residuals.

There can also be uncertainty in the location of drinking water resources. In particular, depths of groundwater resources that are, or in the future could be, used for drinking water are not always known. If comprehensive data about the locations of both drinking water resources and activities in the hydraulic fracturing water cycle were available, it would have been possible to more completely identify areas in the United States in which hydraulic fracturing-related activities either directly interact with drinking water resources or have the potential to interact with drinking water resources.

In places where we know activities in the hydraulic fracturing water cycle have occurred or are occurring, data that could be used to characterize the presence, migration, or transformation of hydraulic fracturing-related chemicals in the environment before, during, and after hydraulic fracturing were scarce. Specifically, local water quality data needed to compare pre- and post-hydraulic fracturing conditions are not usually collected or readily available. The limited amount of data collected before, during, and after activities in the hydraulic fracturing water cycle reduces the ability to determine whether these activities affected drinking water resources.

Site-specific cases of alleged impacts on underground drinking water resources during the well injection stage of the hydraulic fracturing water cycle are particularly challenging to understand (e.g., methane migration in Dimock, Pennsylvania; the Raton Basin of Colorado; and Parker County, Texas[1]). This is because the subsurface environment is complex and belowground fluid movement is not directly observable. In cases of alleged impacts, activities in the hydraulic fracturing water cycle may be one of several causes of impacts, including other oil and gas activities, other industries, and natural processes. Thorough scientific investigations are often necessary to narrow down the list of potential causes to a single source at site-specific cases of alleged impacts.

Additionally, information on chemicals in the hydraulic fracturing water cycle (e.g., chemical identity; frequency of use or occurrence; and physical, chemical, and toxicological properties) is not complete. Well operators claimed at least one chemical as confidential at more than 70% of wells reported to FracFocus 1.0 (U.S. EPA, 2015a).[2] The identity and concentration of these chemicals, their transformation products, and chemicals in produced water would be needed to characterize how chemicals associated with hydraulic fracturing activities move through the environment and interact with the human body. Identifying chemicals in the hydraulic fracturing water cycle also informs decisions about which chemicals would be appropriate to test for when establishing pre-hydraulic fracturing baseline conditions and in the event of a suspected drinking water impact.

Of the 1,606 chemicals identified by the EPA in hydraulic fracturing fluid and/or produced water, 173 had toxicity values from sources that met the EPA's criteria for inclusion in this report. Toxicity values from these selected data sources were not available for 1,433 (89%) of the chemicals, although many of these chemicals have toxicity data available from other data sources.[3] Given the

[1] See Text Boxes 6-2 (Dimock, Pennsylvania), 6-3 (Raton Basin), and 6-4 (Parker County, Texas) in Chapter 6.

[2] Chemical withholding rates in FracFocus have increased over time. Konschnik and Dayalu (2016) reported that 92% of wells reported in FracFocus 2.0 between approximately March 2011 and April 2015 used at least one chemical that was claimed as confidential.

[3] Chapter 9 describes the availability of data in other data sources. The quality of these data sources was not evaluated as part of this report.

large number of chemicals identified in the hydraulic fracturing water cycle, this missing information represents a significant data gap that makes it difficult to fully understand the severity of potential impacts on drinking water resources.

Because of the significant data gaps and uncertainties in the available data, it was not possible to fully characterize the severity of impacts, nor was it possible to calculate or estimate the national frequency of impacts on drinking water resources from activities in the hydraulic fracturing water cycle. We were, however, able to estimate impact frequencies in some, limited cases (i.e., spills of hydraulic fracturing fluids or produced water and mechanical integrity failures).[1] The data used to develop these estimates were often limited in geographic scope or otherwise incomplete. Consequently, national estimates of impact frequencies for any stage of the hydraulic fracturing water cycle have a high degree of uncertainty. Our inability to quantitatively determine a national impact frequency or to characterize the severity of impacts, however, did not prevent us from qualitatively describing factors that affect the frequency or severity of impacts at the local level.

Report Conclusions

This report describes how activities in the hydraulic fracturing water cycle can impact—and have impacted—drinking water resources and the factors that influence the frequency and severity of those impacts. It also describes data gaps and uncertainties that limited our ability to draw additional conclusions about impacts on drinking water resources from activities in the hydraulic fracturing water cycle. Both types of information—what we know and what we do not know—provide stakeholders with scientific information to support future efforts.

The uncertainties and data gaps identified throughout this report can be used to identify future efforts to further our understanding of the potential for activities in the hydraulic fracturing water cycle to impact drinking water resources and the factors that affect the frequency and severity of those impacts. Future efforts could include, for example, groundwater and surface water monitoring in areas with hydraulically fractured oil and gas production wells or targeted research programs to better characterize the environmental fate and transport and human health hazards associated with chemicals in the hydraulic fracturing water cycle. Future efforts could identify additional vulnerabilities or other factors that affect the frequency and/or severity of impacts.

In the near term, decision-makers could focus their attention on the combinations of hydraulic fracturing water cycle activities and local- or regional-scale factors that are more likely than others to result in more frequent or more severe impacts. These include:

- 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;

[1] See Chapter 10.

- 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 combinations of activities and factors highlight, in particular, the vulnerability of groundwater resources to activities in the hydraulic fracturing water cycle. By focusing attention on the situations described above, impacts on drinking water resources from activities in the hydraulic fracturing water cycle could be prevented or reduced.

Overall, hydraulic fracturing for oil and gas is a practice that continues to evolve. Evaluating the potential for activities in the hydraulic fracturing water cycle to impact drinking water resources will need to keep pace with emerging technologies and new scientific studies. This report provides a foundation for these efforts, while helping to reduce current vulnerabilities to drinking water resources.

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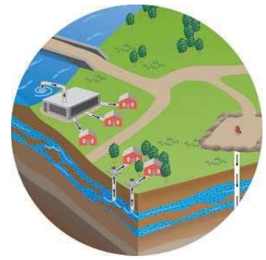
Chapter 1. Introduction



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1. Introduction

1.1 Background

People rely on clean and plentiful water resources to meet their basic needs. In the early 2000s, members of the public began to raise concerns about the use of hydraulic fracturing for oil and gas production and its potential impacts on drinking water resources. Hydraulic fracturing involves the injection of fluids into a well under pressures great enough to fracture oil- and gas-bearing formations. While hydraulic fracturing has been used to enhance oil and gas production from conventional rock formations, the combination of hydraulic fracturing and directional drilling has made it economical to produce oil and gas from previously unused unconventional rock formations.[1] This has led to increases in oil and gas production and expanded activity throughout the United States.

Concerns about the impacts of hydraulic fracturing activities on both the quality and quantity of drinking water resources have been raised by the public. Some residents living close to oil and gas production wells report changes in the quality of groundwater resources used for drinking water and assert that hydraulic fracturing is responsible for these changes. Other concerns include impacts on water availability due to water use in hydraulic fracturing, especially in areas of the country experiencing drought, and impacts on water quality from the disposal of wastewater generated after hydraulic fracturing.

In response to public concerns, the U.S. Congress urged the U.S. Environmental Protection Agency (EPA) to study the relationship between hydraulic fracturing and drinking water (H.R. Rep. 111-316, 2009). In 2011, the EPA published its *Plan to Study the Potential Impacts of Hydraulic Fracturing on Drinking Water Resources* (U.S. EPA, 2011d; hereafter Study Plan), which described the research the Agency would be conducting on activities involving water that support hydraulic fracturing (referred to as the "hydraulic fracturing water cycle"). The research described in the Study Plan began the same year. In 2012, the EPA issued *Study of the Potential Impacts of Hydraulic Fracturing on Drinking Water Resources: Progress Report* (U.S. EPA, 2012h; hereafter Progress Report) to update the public on the status of EPA's research. Since its initiation, the EPA's hydraulic fracturing study has directly resulted in the publication of 27 separate government reports and scientific journal articles. This assessment integrates results from those reports and scientific journal articles with publicly available data and information. It represents the culmination of the EPA's hydraulic fracturing study focused on characterizing the relationship between hydraulic fracturing and drinking water.

[1] Conventional oil- and gas-bearing rock formations are often described as "permeable" and tend to have many large, well-connected pore spaces that allow fluids to move within the rock formation. Unconventional oil- and gas-bearing rock formations do not exhibit these characteristics. See Chapter 3 for more information on uses of the terms conventional and unconventional.

1.2 Goals

The goals of this assessment are 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.

1.3 Scope

The hydraulic fracturing water cycle defines the activities that are within the scope of this assessment. This cycle encompasses activities involving water that support hydraulic fracturing and consists of five stages:

1. **Water Acquisition:** the withdrawal of groundwater or surface water to make hydraulic fracturing fluids;
2. **Chemical Mixing:** the mixing of a base fluid (typically water), proppant, and additives at the well site to create hydraulic fracturing fluids;[1]
3. **Well Injection:** the injection and movement of hydraulic fracturing fluids through the oil and gas production well and in the targeted rock formation;
4. **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; and [2]
5. **Wastewater Disposal and Reuse:** the disposal and reuse of hydraulic fracturing wastewater.[3]

The hydraulic fracturing water cycle, and thus the scope of this assessment, was developed with input from stakeholders (i.e., federal, state, and tribal partners; industry and non-governmental organizations; and the general public) and the EPA's Science Advisory Board (SAB) (U.S. EPA, 2011d). The hydraulic fracturing water cycle and our assessment scope reflect interest from stakeholders in understanding impacts from the act of hydraulic fracturing itself as well as the activities involving water that support it, without examining impacts from oil and gas production development broadly.

[1] 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.

[2] "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.

[3] "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.

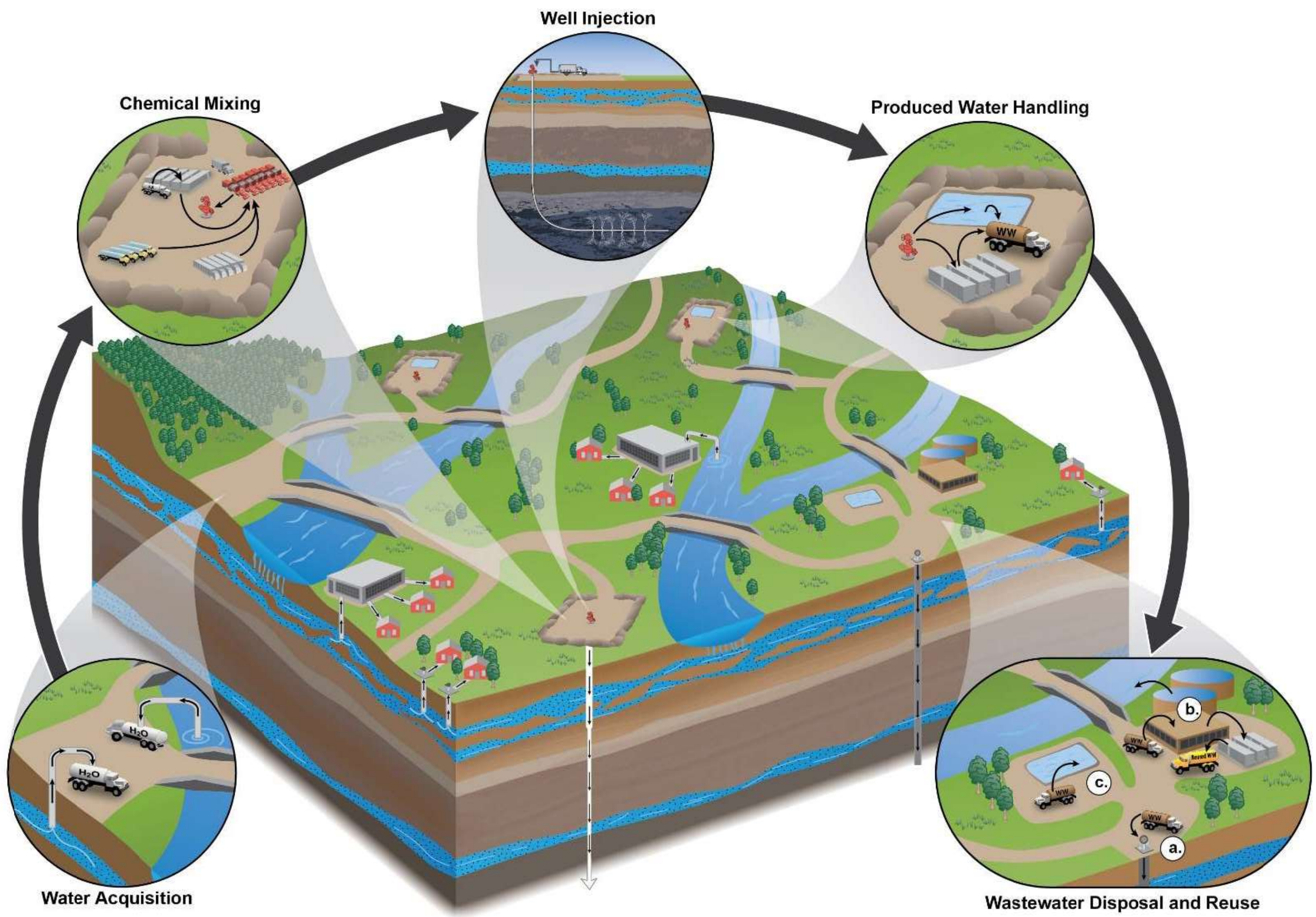

Figure 1-1. Conceptualized view of the stages of the hydraulic fracturing water cycle.

Shown here is a generalized landscape depicting simplified activities of the hydraulic fracturing water cycle, their relationship to each other, and their relationship to drinking water resources. Activities may take place in the same watershed or different watersheds and close to or far from drinking water resources. Drinking water resources are any groundwater or surface water that now serves, or in the future could serve, as a source of drinking water for public or private use. Arrows depict the movement of water and chemicals. Specific activities in the “Wastewater Disposal and Reuse” inset are (a) disposal via injection well, (b) wastewater treatment with reuse or discharge, and (c) evaporation or percolation pit disposal. Note: Figure not to scale.

This assessment focuses on hydraulic fracturing in onshore oil and gas wells in the contiguous United States; limited available information on hydraulic fracturing in Alaska is included. To the extent possible, this assessment addresses hydraulic fracturing in all types of oil- and gas-bearing formations in which it is conducted, including shale, so-called 'tight' formations (e.g., certain sandstones, siltstones, and carbonates), coalbeds, and conventional rock formations. The assessment tends to focus on hydraulic fracturing in shale, reflecting the abundance and availability of literature and data on hydraulic fracturing in this type of rock formation.

In this assessment, we consider how activities in the hydraulic fracturing water cycle interact with drinking water resources. Consistent with the Study Plan (U.S. EPA, 2011d), drinking water resources are defined within this assessment as any groundwater or surface water that now serves, or in the future could serve, as a source of drinking water for public or private use. This definition is broader than most regulatory definitions of "drinking water" to include both fresh and non-fresh bodies of water that are and could be used now or could be used in the future as sources of drinking water (Chapter 2). We note that drinking water resources provide not only water that individuals actually drink but also water used for many additional purposes such as cooking and bathing.

As part of the assessment, we evaluated immediate, near-term, and delayed effects on drinking water resources from normal operations and accidents. For example, we considered how surface spills of hydraulic fracturing fluids may have immediate or near-term impacts on neighboring surface water and shallow groundwater quality (Chapters 5 and 7). We also considered how the potential release of hydraulic fracturing fluids in the subsurface may take years to impact groundwater resources, because liquids and gas often move slowly in the subsurface (Chapter 6). Additionally, impacts may be transient or long-term, often depending on the characteristics of the affected drinking water resource. Finally, impacts may be detected near the hydraulic fracturing water cycle activity or some distance away. For instance, we considered that, depending on the constituents of treated hydraulic fracturing wastewater discharged to a stream and the flow in that stream, drinking water resource quality could be affected a significant distance downstream (Chapter 8).

This assessment focuses predominantly on activities supporting a single well or multiple wells at one site, accompanied by a more limited discussion of cumulative activities and the impacts that could result from having many wells on a landscape. Studies of cumulative effects are generally lacking, but we use the scientific literature to address this topic where possible.[1]

We examine *impacts* of hydraulic fracturing for oil and gas on drinking water resources and address *factors* that affect the *frequency* or *severity* of impacts. Specific definitions used in this assessment 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.

[1] Cumulative effects refer to combined changes in the environment that can take place as a result of multiple activities over time and/or space.

- 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., per geographic area, per unit time, per number of hydraulically fractured wells, per number of water bodies). Reflecting the scientific literature, the most common representation of frequency in this assessment is number of impacts per hydraulically fractured well.
- **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, contaminant concentration).

We identify and discuss factors affecting the frequency or severity of impacts to avoid a simple inventory of all specific situations in which hydraulic fracturing might alter drinking water quality or quantity. This allows knowledge about the conditions under which impacts are likely or unlikely to occur to be applied to new circumstances (e.g., a new area of oil or gas development where hydraulic fracturing is expected to be used) and could inform the development of strategies to prevent impacts. Although no attempt has been made in this assessment to identify or evaluate comprehensive best practices for states, tribes, or the industry, we describe ways to avoid or reduce the frequency or severity of impacts from hydraulic fracturing activities as they have been reported in the scientific literature. Laws, regulations, and policies also exist to protect drinking water resources (Text Box 1-1), but a comprehensive summary and evaluation of current or proposed regulations and policies is beyond the scope of this assessment.

Text Box 1-1. Regulatory Protection for Drinking Water Resources.

The quality and quantity of drinking water resources are protected in the United States by a collection of federal, state, tribal, and local laws, regulations, and polices. They differ with respect to how water resources are defined (Chapter 2) and thus which resources qualify for protection. Some policies protect water resources from oil and gas industry activities as part of a larger set of regulated industries, or from oil and gas industry activities only, or from hydraulic fracturing-related activities, specifically. Multiple federal and state agencies, departments, or divisions are responsible for implementing these laws, regulations, and policies. An exhaustive summary of current and emerging laws, regulations, and policies, those responsible for implementing them, and enforcement or effectiveness is not in the scope of this assessment. The following information is designed to give the reader a general understanding of how the U.S. government and states protect drinking water resources from the potential impacts of activities in the hydraulic fracturing water cycle.

On the federal level, the U.S. government regulates some activities in the hydraulic fracturing water cycle to protect drinking water resources. For example, under the Clean Water Act, the National Pollution Discharge Elimination System (NPDES) program regulates surface discharge of wastewater from the oil and gas sector (in addition to many other industries). Issuance and enforcement of NPDES discharge permits is primarily the responsibility of the states that have received NPDES program authorization from the EPA. In addition, the Safe Drinking Water Act's (SDWA) Underground Injection Control program regulates the underground disposal of hydraulic fracturing wastewater (and wastewater generated in other industries) and, like the NPDES program, allows states to seek program authorization from the EPA. The federal government does not have the authority to regulate hydraulic fracturing as an injection activity under the SDWA except when it

(Text Box 1-1 is continued on the following page.)

Text Box 1-1 (continued). Regulatory Protection for Drinking Water Resources.

(1) involves diesel fuel, a result of legislation passed in 2005, or (2) causes an imminent and substantial endangerment to the health of persons. Additionally, produced water is exempted from regulation as a hazardous waste under the Resource Conservation and Recovery Act Subtitle C. In 2015, the U.S. Department of the Interior published a set of regulations for conducting hydraulic fracturing operations on federal public and tribal lands. It includes requirements to help protect groundwater by updating standards for well mechanical integrity, wastewater disposal, and public disclosure of chemicals. As of late 2016, a federal district court judge has set aside these regulations as outside the scope of the U.S. Department of the Interior's authority, and this decision is being appealed.

States generally have the primary responsibility for protecting drinking water resources from the impacts of hydraulic fracturing activities (Guralnick, 2016; Zirogannis et al., 2016). Some states have put in place broad restrictions or moratoria on hydraulic fracturing activities due in part to concerns about potential risks to drinking water resources. Many other states allow hydraulic fracturing activities, and several sources of information track and/or summarize their laws, regulations, and policies. An online database of statutes and regulations applicable to the oil and gas industry and related to water quality, water quantity, and air quality in 17 states is maintained by LawAtlas (www. lawatlas.org/oilandgas).

State approaches vary widely, from comprehensive laws addressing all aspects of hydraulic fracturing activities to regulations addressing specific activities (Guralnick, 2016). In 2009 and 2014, the Ground Water Protection Council (GWPC) summarized regulations that are designed to protect water resources and applicable to the oil and gas industry in 27 states; they did not investigate compliance (GWPC, 2014, 2009). The summaries revealed that regulations are carried out by either oil and gas agencies, environmental agencies, or both, depending on the state. They also identified general categories of existing regulations that could control impacts on drinking water resources from activities in the hydraulic fracturing water cycle, including permitting, well design and integrity, injection activities, and surface management of fluids. Categories were comprised of regulatory "elements." Certain elements had been adopted across 90% or more of states included in the summaries that allowed hydraulic fracturing as of July 2013: surface casing generally must be set below the deepest protected groundwater zone; protected groundwater depth is determined on a well-specific basis or by rule; and surface casing must be cemented from bottom to top. All other elements were adopted at lower and widely varying rates. For example, as of July 2013, a requirement for water well testing and monitoring adjacent to hydraulic fracturing operations existed in five states. Other states, including California, have added this requirement since then.

State laws, regulations, and policies are continually changing. Changes may be initiated by state legislatures or regulatory agencies (sometimes in response to legal decisions) and generally apply to new wells or future hydraulic fracturing operations and not existing wells or wells that have been hydraulically fractured in the past. Third-party groups, like the State Review of Oil and Natural Gas Environmental Regulations (STRONGER) organization, offer multi-stakeholder reviews of state oil and gas regulatory programs and recommendations to improve those programs according to guidelines developed by their workgroups. Interstate organizations of state agency representatives also have initiatives to develop oil and gas resources while protecting water and other environmental resources, initiatives like the GWPC and Interstate Oil and Gas Compact Commission's States First. In combination with changing policies, new technologies (such as those that make it possible to reuse hydraulic fracturing wastewater in subsequent hydraulic fracturing operations) have the potential to further reduce impacts on drinking water resources.

We identify and evaluate potential human health hazards of hydraulic fracturing-related chemicals (Chapter 9), but this assessment is not a human health risk assessment. It does not identify populations that are exposed to chemicals or other stressors in the environment, estimate the extent of exposure, or estimate the incidence of human health impacts. Relatedly, we did not conduct site-specific predictive modeling to quantitatively estimate contaminant concentrations in drinking water resources, although modeling studies conducted by others are described.

This assessment focuses on the potential for impacts from activities in the hydraulic fracturing water cycle on drinking water resources. It does not address all concerns that have been raised about hydraulic fracturing nor about oil and gas exploration and production more generally. Activities that are not considered in this assessment include acquisition and transport of constituents of hydraulic fracturing fluids besides water (e.g., sand mining and chemical production); site selection and development; other infrastructure development (e.g., roads, pipelines, compressor stations); site reclamation; and well closure. We consider these activities to be outside the scope of the hydraulic fracturing water cycle and, therefore, their impacts are not addressed in this assessment. Disposal of hydraulic fracturing wastewater in underground injection control wells is described and characterized, but consistent with the Study Plan, potential for impacts of this practice on drinking water resources is not included. Additionally, this report does not discuss the potential impacts of hydraulic fracturing on other water uses (e.g., agriculture or industry), other aspects of the environment (e.g., air quality, induced seismicity, or ecosystems), worker health and safety, or communities. Finally, this assessment focuses on the available science and does not review, consider, or recommend policy options.

1.4 Approach

This assessment relies on scientific literature and data that address topics within the scope of the hydraulic fracturing water cycle. Scientific journal articles and peer-reviewed EPA reports containing results from the EPA's hydraulic fracturing study comprise one set of applicable literature. Other literature evaluated includes articles published in science and engineering journals, federal and state government reports, non-governmental organization (NGO) reports, and oil and gas industry publications. Data sources examined include federal- and state-collected data sets, databases curated by federal and state government agencies, other publicly available data and information, and data submitted by industry to the EPA.[1] In total, we cite approximately 1,200 sources of scientific data and information in this assessment.

1.4.1 EPA Hydraulic Fracturing Study Publications

The research topic areas and projects described in the Study Plan were developed with substantial expert and public input and were designed to meet the data and information needs of this assessment. As such, peer-reviewed results of research that the EPA conducted under the Study Plan, published separately as EPA reports or as journal articles, are incorporated and cited

[1] Confidential and non-confidential business information was provided to the EPA by nine hydraulic fracturing service companies in response to a September 2010 information request and by nine oil and gas well operators in response to an August 2011 information request.

frequently throughout this assessment. As is customary in assessments that synthesize a large body of literature and data, the results of EPA research are contextualized and interpreted in combination with the other literature and data described in Section 1.4.2. The journal articles and EPA reports that give complete and detailed project results can be found on the EPA's hydraulic fracturing study website (www.epa.gov/hfstudy). For ease of reference, a description of the individual projects, the type of research activity they represent (i.e., analysis of existing data, scenario evaluation, laboratory study, or case study), and the corresponding citations of published journal articles and EPA reports that are referenced in this assessment can be found in Appendix A.

1.4.2 Literature and Data Search Strategy

We used a broad search strategy to identify approximately 4,100 sources of scientific information applicable to this assessment. This strategy included requesting input from scientists, stakeholders, and the public about relevant data and information, and thorough searches of published information and applicable data.[1]

Over 1,600 articles, reports, data, and other sources of information were obtained through outreach to the public, stakeholders, and scientific experts. The EPA requested material through many venues, as follows. We received recommended literature from the SAB, the EPA's independent federal scientific advisory committee, from its review of the EPA's draft Study Plan; from its consultation on the EPA's Progress Report; during an SAB briefing on new and emerging information related to hydraulic fracturing in fall 2013; and from its peer review of the external review draft of this assessment. Subject matter experts and stakeholders also recommended literature through a series of technical workshops and roundtables organized by the EPA between 2011 and 2013. In addition, the public submitted literature recommendations to the SAB during the SAB review of the draft Study Plan, consultation on the Progress Report, briefing on emerging information, and review of the external review draft of this assessment, as well as in response to a formal request for data and information posted in the *Federal Register* (EPA-HQ-ORD-2010-0674) in November 2012. The submission deadline was extended from April to November 2013 to provide the public with additional opportunity to provide information to the EPA.

Approximately 2,500 additional sources were identified by conducting searches via online scientific databases and federal, state, and stakeholder websites. We searched these databases and websites in particular for (1) materials addressing topics not covered by the documents submitted by experts, stakeholders, and the public as noted above, and (2) newly emerging scientific studies. Multiple targeted and iterative searches on topics determined to be within the scope of the assessment were conducted until June 1, 2016. After that time, we included newer literature as it was recommended to us during our internal technical reviews or as it came to our attention and was determined to be important for filling a gap in information.

[1] This study did not review information contained in state and federal enforcement actions concerning alleged contamination of drinking water resources.

1.4.3 Literature and Data Evaluation Strategy

We evaluated the literature and data identified in the search strategy using the five assessment factors outlined by the EPA Science Policy Council in *A Summary of General Assessment Factors for Evaluating the Quality of Scientific and Technical Information* (U.S. EPA, 2003c). The factors are (1) applicability and utility, (2) evaluation and review, (3) soundness, (4) clarity and completeness, and (5) uncertainty and variability. Table 1-1 lists these factors along with the specific criteria developed for this assessment. We first evaluated all materials for applicability. If we determined that the material was "applicable" under the criteria, the reference was evaluated on the basis of the other four factors.

Our objective was to consider and then cite literature in the assessment that fully conforms to all criteria defining each assessment factor. However, in some cases, literature on a topic did not fully conform to an aspect of the outlined criteria. For instance, the preponderance of literature in some technical areas is published as white papers and reports for which independent peer review is not standard practice or is not well documented. To address these areas in which peer-reviewed literature was limited, we cited literature that may not have been peer-reviewed. These references often provided useful background information or corroborated conclusions in the peer-reviewed literature.

Table 1-1. The five factors and accompanying criteria used to evaluate literature and data cited in this assessment.

Criteria are consistent with those outlined by the EPA's Science Policy Council (U.S. EPA, 2003c). Criteria are incorporated into the Quality Assurance Project Plans for this assessment (U.S. EPA, 2014d, 2013d).

Factor	Criteria
Applicability	Document provides information useful for assessing the potential pathways for hydraulic fracturing activities to change the quality or quantity of drinking water resources, identifies factors that affect the frequency and severity of impacts, or suggests ways that potential impacts may be avoided or reduced.
Review	Document has been peer-reviewed.
Soundness	Document relies on sound scientific theory and approaches, and conclusions are consistent with data presented.
Clarity/completeness	Document provides underlying data, assumptions, procedures, and model parameters, as applicable, as well as information about sponsorship and author affiliations.
Uncertainty/variability	Document identifies uncertainties, variability, sources of error, and/or bias and properly reflects them in any conclusions drawn.

1.4.4 Quality Assurance and Peer Review

The use of quality assurance (QA) and peer review helps ensure that the EPA conducts high-quality science that can be used to inform policymakers, industry, and the public. Quality assurance activities performed by the EPA ensure that the agency's environmental data are of sufficient quantity and quality to support the data's intended use. The EPA prepared a programmatic Quality

Management Plan (U.S. EPA, 2014e) for all of the research conducted under the EPA's Study Plan, including the review and synthesis of the scientific literature in this assessment. The hydraulic fracturing Quality Management Plan describes the QA program's organizational structure; defines and assigns QA and quality control (QC) responsibilities; and describes the processes and procedures used to plan, implement, and assess the effectiveness of the quality system. The broad plan is then supported by more detailed QA Project Plans (QAPPs). The QAPPs developed for this assessment provide the technical approach and associated QA/QC procedures for our data and literature search and evaluation strategies introduced in Section 1.4.2 and 1.4.3 (U.S. EPA, 2014d, 2013d). A QA audit was conducted by the QA Manager during the preparation of this assessment to verify that the appropriate QA procedures, criteria, reviews, and data verification were adequately performed and documented. Identifying uncertainties is another aspect of QA; uncertainty, including data gaps and data limitations, is discussed throughout this assessment.

This report is classified as a Highly Influential Scientific Assessment (HISA), which is defined by the Office of Management and Budget (OMB) as a scientific assessment that (1) could have a potential impact of more than $500 million in any year or (2) is novel, controversial, or precedent-setting or has significant interagency interest (OMB, 2004). The OMB describes specific peer review requirements for HISAs. To meet these requirements, the EPA often engages the SAB as an independent federal advisory committee to conduct peer reviews of high-profile scientific matters relevant to the agency. Members of an ad hoc panel, the same panel that was convened under the auspices of the SAB to provide comment on the Progress Report, also provided comment on an external review draft of this assessment.[1] Panel members were nominated by the public and chosen to create a balanced review panel based on factors such as technical expertise, knowledge, experience, and absence of any real or perceived conflicts of interest. Both peer review comments provided by the SAB panel (SAB, 2016) and public comments submitted to the panel during their deliberations about the external review draft of this assessment were carefully considered in the development of this final document.

1.5 Organization

This assessment begins with an Executive Summary that summarizes our overall content and conclusions. The Executive Summary is written to be accessible to all members of the public.[2]

This introductory chapter establishes the goals, scope, and approach for the rest of the assessment. Following is a characterization of drinking water resources in the contiguous United States (Chapter 2). Next, we present a general description of hydraulic fracturing activities and the role of hydraulic fracturing in the oil and gas industry in the United States (Chapter 3). Chapter 1 is written

[1] Information about this process is available online at http://yosemite.epa.gov/sab/sabproduct.nsf/02ad90b136fc21ef85256eba00436459/b436304ba804e3f885257a5b00521b3b!OpenDocument.

[2] The terminology used in the data and literature cited in this assessment can be very technical in nature and sometimes inconsistent. An attempt has been made throughout this document to provide definitions of technical terms and to use terminology in a consistent way that enhances understanding of the topics presented for the audiences targeted by each part of the assessment.

to be accessible to all members of the public. Chapters 2 and 3 are written to be accessible to an audience with general science knowledge.

Chapters 4 through 8 are organized around the stages of the hydraulic fracturing water cycle (Figure 1-1) and address the potential for activities conducted during those stages to change the quality or quantity of drinking water resources. Each stage is covered by a separate chapter. There is also a chapter devoted to an examination of the properties of the chemicals and constituents in hydraulic fracturing-related fluids (Chapter 9). These chapters are written to be accessible to an audience with a moderate amount of technical training and expertise in the respective topic areas.

The final chapter provides a synthesis of the information in the assessment (Chapter 10). This chapter is written to be accessible to an audience with general science knowledge.

The appendices supply information that support the chapters of the assessment. This includes an appendix with a table of all individual products published under the EPA's hydraulic fracturing study and cited in this assessment, as well as answers to the research questions posed in the Study Plan (Appendix A). These answers were informed by the products of the study and the data and literature reviewed in this assessment.

1.6 Intended Use

This state-of-the-science assessment will contribute to the understanding of the potential impacts of activities in the hydraulic fracturing water cycle on drinking water resources and the factors that influence those impacts. The data and findings can be used by federal, tribal, state, and local officials; industry; and the public to better understand and address vulnerabilities of drinking water resources to hydraulic fracturing activities.

We expect this report will be used to help facilitate and inform dialogue among interested stakeholders, including Congress, other federal agencies, states, tribal governments, the international community, industry, NGOs, academia, and the general public. Additionally, the identification of knowledge gaps will promote greater attention to these areas by researchers.

This report may support future assessment efforts. We anticipate that it could contribute context to site-specific exposure or risk assessments of hydraulic fracturing, to regional public health assessments, or to assessments of cumulative impacts of hydraulic fracturing on drinking water resources over time or over defined geographic areas of interest.

Finally, and most importantly, this assessment presents the science to inform decisions by federal, state, tribal, and local officials; industry; and the public on how best to protect drinking water resources now and in the future.

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Chapter 2. Drinking Water Resources in the United States

Abstract

In this assessment, drinking water resources are defined as any body of groundwater or surface water that now serves, or in the future could serve, as a source of drinking water for public or private use. An estimated 86% of the United States population derives its household drinking water from public water systems (PWSs), which mostly use surface water sources, while nearly all of the remaining 14% of people self-supply their drinking water from groundwater.

Future access to high-quality drinking water in the United States will likely be affected by changes in climate and water use. The existing distribution and abundance of the drinking water resources may not be sufficient in some locations to meet future demand. 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, which often correlates with diminishment of drinking water supplies. As a result, non-fresh water resources, such as wastewater from sewage treatment plants, brackish surface water and groundwater, and seawater are increasingly treated and used to meet the demand for drinking water.

Hydraulically fractured oil and gas production wells can be located near drinking water sources. Between 2000 and 2013, approximately 3,900 PWSs had between one and 144 wells hydraulically fractured within 1 mile of their water source; these PWSs served more than 8.6 million people year-round in 2013. An additional 740,000 people self-supply their drinking water in counties where at least 30% of the population relies on groundwater and where there were at least 400 hydraulically fractured wells. Belowground, hydraulic fracturing can occur in close vertical proximity to drinking water resources. Available data show that depths to hydraulically fractured rock formations containing oil and gas resources can range from less than 1,000 feet (300 meters) to more than 10,000 feet (3,000 meters), while drinking water resources may be found between a few tens of feet to as much as 8,000 feet (2,000 meters) below the surface. The EPA found that, along individual wellbores, where data were available, the distance between these two resources ranged from no separation to more than 10,000 feet (3,000 meters). There is considerable uncertainty in this range of values, however. In many cases, the lack of accessible information about the depth to the base of formations containing groundwater resources in need of current and future protection prevents calculation of a vertical separation distance.

The locations of drinking water resources relative to hydraulically fractured oil and gas production wells influence the potential for activities in the hydraulic fracturing water cycle to impact drinking water resources. With increased proximity, activities in the hydraulic fracturing water cycle have more potential to affect aboveground and belowground drinking water resources.

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2. Drinking Water Resources in the United States

2.1 Introduction

Drinking water resources provide the water humans consume, cook with, bathe in, and need for other purposes. In this assessment, drinking water resources are considered to be any groundwater or surface water that now serves, or in the future could serve, as a source of drinking water for public or private use. [1] This chapter provides information about drinking water resources in the United States, including current sources and indications of future trends for drinking water resources. Assessment of whether and where activities in the hydraulic fracturing water cycle may impact drinking water resources requires consideration, in part, of the locations of water and oil and gas resources and what physically separates them. More information about oil and gas resources and the areas of the United States where hydraulic fracturing occurs is described in Chapter 3, however this chapter focuses on the lateral (horizontal) and vertical distances between hydraulic fracturing operations and drinking water resources.

2.2 Ground and Surface Water Resources

All drinking water derives from the finite amount of water found on or below the earth's surface. Fresh water serves as the source for most drinking water.[2] To get an idea of the fresh water fraction of all water, this section presents an estimate of the earth's water abundance. Shiklomanov (1993) estimates the amounts of all water on earth, and here these amounts are expressed as the percent of the earth's total water volume:

- Oceans account for about 96.5%.
- Saline groundwater, saline lakes, and water in the form of ice or vapor account for 2.7%.
- Fresh groundwater, swamps, lakes, and rivers account for the remaining 0.8%, of which about 99% is groundwater.

Hydrologic Cycle. The process describing the movement of the earth's water through the atmosphere, land, and oceans is referred to as the hydrologic cycle. Text Box 2-1 describes the hydrologic cycle, including the manner in which the finite amount of water on the earth moves through different locations during the stages of the cycle. On land, surface water and groundwater interact, shown in the text box as surface water infiltrating into the ground, and separately as an example of groundwater flowing into the river. Water consumption (for example when used for agriculture, incorporated into a product, or for drinking purposes), temporarily removes water

[1] In this chapter, a "drinking water *source*" means the body of water is now supplying, or is known to be capable of supplying drinking water.

[2] Published estimates of worldwide water supplies, such as by Shiklomanov, do not use a salinity threshold value to define "fresh" or "saline" water. "Fresh" water is characterized in these published estimates as serving as a source for domestic, agricultural, and industrial uses. As described further in Section 2.2.1.1, the term "fresh" in this chapter refers to water having total dissolved solids content up to 3,000 milligrams per liter.

from one local place in the hydrologic cycle, but it may be returned to a different point in the hydrologic cycle. See Chapter 4 for additional discussion of water consumption.

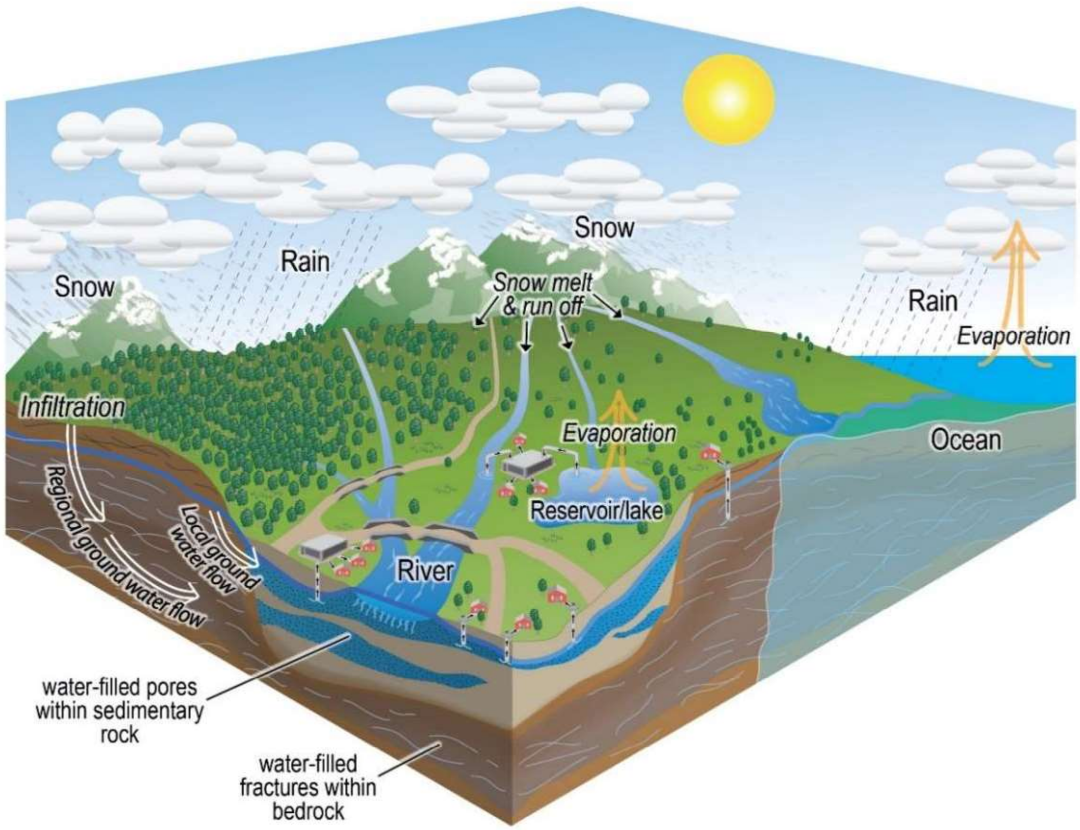
Text Box 2-1. The Hydrologic Cycle.

The finite amount of water and its movement on earth is often called the hydrologic cycle, depicted below. The three basic, and repeating, stages of this cycle include:

1. Rainfall transfers water from the atmosphere into oceans or onto land,

2. Water on land moves among surface water bodies and groundwater, and

3. Evaporation from land and the oceans returns water to the atmosphere.



Rainwater and melted snow collect into rivers, lakes or other water bodies to become surface water, or infiltrates into the ground to become groundwater. Humans drink fresh surface and groundwater, and in some locations, ocean water treated by desalination. Water resides on land or in the ground for varying amounts of time before moving into another of stage of the hydrologic cycle. Residence times for water found in different land locations can range from days to millions of years, depending on the path water takes. Residence time affects water quality on land or in the ground because water dissolves natural earth salts when in contact with those materials. When water on or under land reaches the ocean, its salt content ultimately stays in the ocean because evaporation leaves behind dissolved salt creating freshwater vapor. Evaporation from land and the ocean contribute fresh water to the atmosphere where it can precipitate once again, thus completing a hydrologic cycle. As drawn in this depiction, evaporation includes the release of water vapor from plant leaves that originally entered plant root systems in a process known as transpiration.

2.2.1 Groundwater Resources

Groundwater can be found in the subsurface nearly everywhere, but it varies in quality and quantity. Groundwater exists in that part of the hydrologic cycle where surface water infiltrates through soil into subsurface cracks and voids in rock, creating and sustaining aquifers, a natural process known as groundwater recharge.[1] The opposite natural process from recharge is discharge, where groundwater flows to the surface at springs or through the bottoms of lakes and rivers. Groundwater also includes water trapped in the pores of sedimentary rocks as they were deposited.

The scale of groundwater flow systems can be local, regional, or something in between. Local groundwater flows may be small enough to be measured in the tens of feet while regional groundwater flows may be large enough to be measured in hundreds of miles (Alley et al., 1999). Groundwater movement is related to the rate of groundwater recharge, gravity's effect on the groundwater, and the permeability of the rock through which groundwater flows. Localized groundwater flow tends to occur along shallower flow paths with shorter overall residence times, whereas regional groundwater flow tends to occur along deeper flow paths with longer residence times (Winter et al., 1998). Text Box 2-1 depicts differences between local and regional flow regimes.

The U.S. Geological Survey (USGS) has mapped and described more than 60 principal aquifers in the United States, although these aquifers are not the only occurrences of groundwater (USGS, 2009).[2] Although the depth to the water table can vary from ground surface to a few tens of feet below ground surface, the depth to the base of groundwater can be tens of thousands of feet below ground.[3] The depth to the base of individual principal aquifers can be a relatively uniform or may vary by thousands of feet across the aquifer's areal extent due to sloping geologic formations and/or changes in topography.

2.2.1.1 Groundwater Quality

The quality of groundwater often correlates with its age, which ranges from days to millions of years (Alley et al., 1999; Freeze and Cherry, 1979a; Chebotarev, 1955).[4] As explained in Text Box 2-1, groundwater salinity tends to increase with increasing residence time due to gradual dissolution of contacted earth materials. Some groundwater can become very saline. These waters can result from exposure to soluble sedimentary rocks and/or concentration of salt content due to evaporation of liquid water in the subsurface (Zolfaghari et al., 2016; Levorsen, 1965). It is also possible that sea water was trapped in sediments during deposition in ancient oceans, which were subsequently buried over geologic time. There are instances where groundwater is found at great

[1] An aquifer is a water-bearing geologic formation, group of formations, or part of a formation. Groundwater is the water in an aquifer.

[2] Principal aquifers are defined as a regionally extensive aquifer or aquifer system that has the potential to be used to supply potable water. Principal aquifers in Puerto Rico and the U.S. Virgin Islands are included.

[3] The water table refers to the top, or uppermost surface, of groundwater. Below the water table, the ground is saturated with water.

[4] Groundwater age used here refers to how long the water has been in the ground.

depths but is relatively fresh. This can be caused by groundwater moving from the surface to deep locations relatively quickly with little time to pick up dissolved solids and become saline. This phenomenon is more pronounced in mountains where rainwater or melted snow in upland areas supply groundwater that moves downward through steeply dipping, permeable sedimentary rock layers to reach great depths. Chemicals occurring naturally in groundwater include both inorganic (e.g., salts, metals) and organic (carbon-based) types.

Salinity variation. Salinity is often the principal characteristic used to describe the overall quality of groundwater. The term "fresh" groundwater often means groundwater containing no more than 1,000 milligrams per liter of total dissolved solids (mg/L TDS) but it is sometimes used to refer to groundwater containing no more than 3,000 mg/L TDS (Maupin et al., 2014; U.S. EPA, 2012e; Freeze and Cherry, 1979a). When characterizing groundwater quality, scientists generally consider the relative abundance of sodium, calcium, potassium, magnesium, chloride, bicarbonate, and sulfate to account for the bulk of dissolved constituents (Freeze and Cherry, 1979a). Natural salinity ranges from less than 100 mg/L to over 300,000 mg/L TDS (Lauer et al., 2016; Clark and Veil, 2009). Higher salinity groundwater can contribute to palatability problems, and in the very high salinity ranges, causes water to be unhealthful for human consumption (Ellis, 1997). People have a range of reactions to drinking water salinity. Some people object to the taste of drinking water having comparatively lower salinity levels while other people reach this objection threshold at higher salinity levels (Burlingame and Waer, 2002). Desalinating water containing salinity values of 10,000 mg/L TDS to render it potable is technically and economically feasible (Esser et al., 2015).[1] As a result, groundwater with salinity values up to 10,000 mg/L TDS is often defined as a protected groundwater resource under several laws, including the regulations implementing the federal Safe Drinking Water Act (SDWA) and the U.S. Bureau of Land Management (BLM) Onshore Order #2. The complete basis and standards for defining a protected groundwater in all locations within the United States is beyond the scope of this report. Additional information about protections given to groundwater is described in Chapter 1 in Text Box 1-1.

Groundwater suitable for drinking is found within a large range of depths around the United States. The groundwater quality profile with depth varies around the United States. Feth (1965) described patterns in the relationship of depth to groundwater containing salinity ranging from 1,000 to 3,000 mg/L TDS.[2] The patterns include: (1) large portions of the Southeast and middle Midwest have at least 1,000 ft (300 m) of separation between the land surface and groundwater containing 1,000-3,000 mg/L TDS, and (2) significant portions of the Northeast, northern Midwest, and parts of the West have less than 500 ft (200 m) separating the land surface from groundwater containing 1,000-3,000 mg/L TDS. The report does not contain information about the base or thickness of groundwater having certain quality. As a result, these depths represent minimum distances between the land surface and bottom depth of groundwater having this salinity range.

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[1] For instance, desalination of sea water (approximately 35,000 mg/L TDS) now occurs in Florida, California, and Texas.

[2] Salinity and total dissolved solids are frequently interchangeable terms. The vast majority of dissolved constituents in natural water are inorganic salts, although a minor fraction of dissolved constituents can be organic matter. Feth (1965) maps groundwater found at ranges of depth with spans of salinity. Singular depth and salinity values are not present on the map.

Methane in groundwater. Methane can be found naturally at detectable levels in groundwater (Kappel and Nystrom, 2012; Eltschlager et al., 2001; Coleman et al., 1988). There are different origins of methane in groundwater. Biogenic methane is produced at comparatively low temperature and pressure from biologic decay of carbon-bearing matter, while thermogenic methane is formed over geologic time when carbon-bearing matter is exposed to elevated pressure and temperature conditions typically associated with deep burial (Baldassare et al., 2014). Given the buoyancy of natural gas, if a pathway exists or enough time is available, it can move upward and accumulate at shallower depths. Natural gas found in small, uneconomic quantities in shallow zones may have originated in place or may have migrated upward, and is often referred to as stray gas. For more discussion about the issue of stray gas, see Text Box 6-3 in Chapter 6. When consumed in drinking water, methane does not generally have human health effects,[1] however, it is an explosive gas if it comprises between 5% and 15% of a volume of air (Astle and Weast, 1984). If methane from well water enters the atmosphere within a confined space under conditions that allow it to concentrate, it can pose an explosive threat if it reaches this threshold.

2.2.1.2 Groundwater Quantity

Groundwater quantity can be characterized as the total subsurface water available, although a practical limiting property is the rate at which groundwater can be withdrawn from the subsurface, a property known as yield (Freeze and Cherry, 1979a). If rock formations in the subsurface contain water within exceedingly small or poorly connected pore spaces, then the low yield may preclude its practical use as a source of drinking water.

When recharge and discharge are in balance, the volume of groundwater existing in the subsurface remains the same. Recharge and discharge also occur in connection with human-caused activity. Groundwater recharge increases due to irrigation, underground injection wells, surface impoundments, and dammed reservoirs, while groundwater discharge increases through well withdrawals for irrigation, household use, etc. (Winter et al., 1998). These activities can locally affect the natural balance between groundwater recharge and discharge. Climatic variation that changes precipitation rates also affects groundwater recharge rates, which in turn leads to changes in subsurface groundwater volume (Winter et al., 1998).

When an aquifer consistently yields water at rates suitable for human use, and the water is of good enough quality to drink or be treated for drinking, it can serve as a source of drinking water.

2.2.2 Surface Water Resources

Surface water is that part of the hydrologic cycle that occurs on land surface and includes water in the ocean as well as rainwater or meltwater. Surface water collects into depressions or along channels in sufficient volume to create standing or running water all or much of the time. Non-ocean surface water has often had little time to become saline, because much of it is not in direct contact with anything other than more water in the surrounding surface water body. Non-ocean surface water can quickly move into the next phase of the hydrological cycle, either evaporating

[1] There is no enforceable drinking water standard established for dissolved methane in drinking water.

into the atmosphere or infiltrating the subsurface. Because surface water is open to the atmosphere and is generally located at the lowest points on a landscape, it is susceptible to contamination. Contamination sources include atmospheric deposition, and run-off from urban land areas or lands used for agricultural or industrial activities (Winter et al., 1998). Many non-ocean surface water bodies in the United States have a set of water quality standards based on their designated use, which can include recreation, drinking water, supportive of aquatic life, fishery, industrial supply, and other uses. In turn, National Discharge Pollution Elimination (NPDES) permits governing point source discharge into the surface water bodies are issued under the Clean Water Act and contain limits on pollutants designed to achieve these water quality standards.[1] When taken together, these permits are meant to ensure that the surface water achieves a water quality consistent with the designated use.

2.2.2.1 Surface Water Quality

Studies conducted in connection with the National Water Quality Assessment Program show the presence of human-made chemicals at low concentrations in the streams surveyed (Kingsbury et al., 2008).[2] Based on dissolved solids alone, sampled streams range from less than 100 mg/L TDS to more than 500 mg/L TDS (Anning and Flynn, 2014). Large lakes can range in salinity from less than 500 mg/L TDS to more than 200,000 mg/L. By comparison, ocean water has a salinity of about 35,000 mg/L TDS. Considering the vast array of possible chemical, biological, and radiological content in surface water, it is beyond the scope of this report to describe in detail the surface water qualities that exist in the United States.

2.2.2.2 Surface Water Quantity

About 7% of the surface area of the United States is covered by surface water, but it is not uniformly distributed. The portion of the United States located east of the Mississippi River comprises about 25% of the total area, yet it contains about 42% of the total land area covered by surface water (USGS, 2016; U.S. Census Bureau, 2012). The Great Lakes alone, located in the eastern half of the United States, contain about one-fifth of the world's surface fresh water (Government of Canada and U.S. EPA, 1995).[3] In contrast, the western part of the United States has a lower proportion of land covered by surface water with streams that tend to be more intermittent in nature.[4] For instance, 81 percent of the streams in Arizona, New Mexico, Nevada, Utah, Colorado, and California are not permanent streams (Levick et al., 2008). Certain parts of the western U.S. are presently experiencing less surface water availability as indicated by declining water reservoir levels with some reservoirs in the southwest currently below 50% of their capacity.[5] For example, according to

[1] Title 40, United States Code of Federal Regulations, Part 131, as of May 25, 2016.

[2] See USGS (2012) for more information about this program.

[3] Including the portion of the Great Lakes lying within Canada.

[4] Not all western states follow this trend. Hawaii and Alaska, for instance, have a significantly higher percentage of land mass covered by surface water (41% and 14%, respectively) than the national average.

[5] See for instance U.S. DOI (2016b), California Department of Water Resources (2016), and SRP (2016).

the U.S. Department of the Interior (DOI), the largest capacity reservoir in the United States, Lake Mead, holds about 37% of its volume capacity as of the fall of 2016 (U.S. DOI, 2016a).

2.3 Current Drinking Water Sources

Drinking water is supplied to households and businesses by either public water systems (PWSs) or non-public systems (non-PWSs).[1] In 2010, approximately 270 million people (86% of the population) in the United States relied on PWSs to supply their homes with drinking water (Maupin et al., 2014; U.S. EPA, 2013b). These PWSs provided households with nearly 24 billion gal (91 billion L) of water per day (Maupin et al., 2014).[2] In areas without service by PWSs, approximately 45 million people (14% of the population) obtain drinking water from non-PWSs, using mostly water wells. Non-PWSs account for about 3.6 billion gal (14 billion L) of daily water withdrawals (Maupin et al., 2014).[3]

Both groundwater and surface water serve as drinking water sources in the United States. Surface water accounts for about 58% of all drinking water withdrawals and groundwater supplies the remaining 42%. Table 2-1 portrays the relative abundance of surface water and groundwater as sources for both publicly and non-publicly supplied drinking water.

Of the population receiving water supplied by PWSs, the relative importance of surface and groundwater sources for supplying drinking water varies geographically (Figure 2-1). Most larger PWSs rely on surface water and are located in urban areas (U.S. EPA, 2011c), whereas most smaller PWSs rely on groundwater and are located in rural areas (U.S. EPA, 2014h, 2013b). More than 95% of households in rural areas obtain their drinking water from groundwater (U.S. EPA, 2011c).

PWSs are subject to routine monitoring and testing requirements required under the National Primary Drinking Water Standards regulations, whereas no such monitoring or testing is required for non-PWSs.[4] The required monitoring and testing at PWSs ensures that the public has information regarding the extent to which delivered water meets drinking water standards, whereas users of non-PWSs (e.g., private water wells) make individual, voluntary decisions about how often they monitor and test their water. Lack of monitoring may make non-PWS users more vulnerable to contamination, if present, than PWS users.

[1] PWSs provide water for human consumption from surface water 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 (U.S. EPA, 2012g). The EPA categorizes PWSs as either community water systems, which supply water to the same population year-round, or non-community water systems, which supply water to at least 25 of the same people at least six months per year, but not year-round. Non-public water systems (non-PWSs) have fewer than 15 service connections and serve fewer than 25 individuals (U.S. EPA, 1991). Non-PWSs are often private water wells supplying drinking water to a singular residence.

[2] The USGS compiles data in cooperation with local, state, and federal environmental agencies to produce water-use information aggregated at the county, state, and national levels. Every five years, data at the county level are compiled into a national water use census and state-level data are published. The most recent USGS water use report was released in 2014, and contains water use estimates from 2010. Water withdrawals are distinguished from and are greater than water deliveries due to water loss during the process of delivering finished water (Maupin et al., 2014; USGS, 2014b).

[3] A withdrawal means the volume of water taken from its source regardless of how much of that volume is either returned to the local hydrologic cycle or is consumed without being returned to the local hydrologic cycle.

[4] See Title 40 of the Code of Federal Regulations, Part 141, promulgated pursuant to the SDWA.

Table 2-1. Summary of drinking water sources in the United States in 2010.
The volume and percentages of daily domestic water withdrawals in the United States are shown by public and non-public water systems, total withdrawal, and whether the source is surface water or groundwater. Volume is in billions of gallons per day (Bgal/day) and percentages are of either water supply type or total volume withdrawn, as indicated in italics. Some figures shown are rounded values. Source of data: Maupin et al. (2014).

Drinking water source	Public water supply	Non-public water supply	Total volume withdrawn
Surface Water			
Daily volume withdrawn (billion gallons)	26.3	0.1	26.4
Percent of water supply type	63	2	58
Groundwater			
Daily volume withdrawn (billion gallons)	15.7	3.5	19.2
Percent of water supply type	37	98	42
Total			
Daily volume withdrawn (billion gallons)	42.0	3.6	45.6
Percent of water supply type	92	8	100

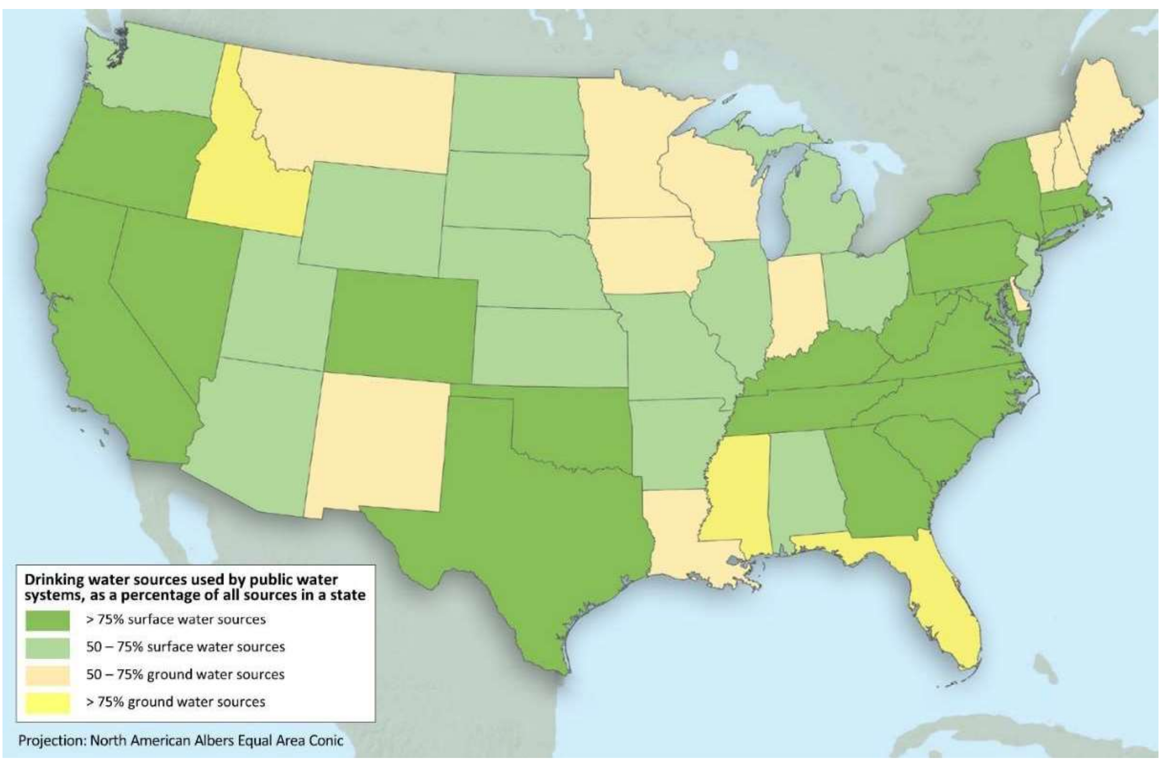

Figure 2-1. Geographic variability in drinking water sources for public water systems.
The relative importance of surface and groundwater as sources for public water systems varies by state. The public water system sources used in this analysis include infiltration galleries, intakes, reservoirs, springs, and wells. Sources: ESRI (2010), U.S. Census Bureau (2013), and U.S. EPA (2013b).

2.3.1 Factors Affecting How Water Becomes a Drinking Water Source

The most common source of drinking water in the world, including in the United States, is fresh water (see Section 2.2.1.1). There can be exceptions to the use of fresh water as a drinking water source. For instance, projects in California, Florida, Arizona and Texas desalinate sea water or brackish groundwater to produce drinking water.[1] The principle of supply and demand that affects availability of commercial products in the marketplace is also applicable to drinking water resources. Water not considered a practical drinking water source under one demand condition may become desirable as a drinking water source under different demand conditions. Text Box 2-2 presents El Paso, Texas as such an example.

Text Box 2-2. El Paso's Use of Higher Salinity Water for Drinking Water.

The El Paso Water Utility (EPWU) provides drinking water to over 600,000 people in the City of El Paso, Texas and surrounding communities. Historically, the EPWU has withdrawn surface water from the Rio Grande River and groundwater to meet water needs. Salinity from the freshwater aquifers typically ranges between 300 and 1,000 mg/L TDS. With increases in population and periodic drought conditions stressing the water supply, the EPWU instituted a number of different measures to diversify its water supply portfolio. Components of the EPWU water supply portfolio include water conservation, surface water, groundwater and, more recently, desalinating saline groundwater. Continued long-term pumping of fresh groundwater allowed higher salinity groundwater to enter into one of EPWU's well fields from more saline parts of the aquifer. This well field is now used as the source for the Kay Bailey Desalination Plant, which began operation in 2007 and desalinates groundwater with salinity ranging from 1,000 and 5,000 mg/L TDS (El Paso Water Utilities, 2016). The plant uses reverse osmosis technology to remove the high salt content thereby creating additional fresh water supplies. Use of this higher salinity water supply has added approximately 25% more water availability, decreasing the stress on the original fresh water supplies available to the EPWU and highlights the potential value of groundwater that had not formerly been considered a drinking water source.

2.3.1.1 General Considerations Applicable to All Water as Source of Drinking Water

Factors to consider when assessing a possible source of drinking water include availability, contaminants in the water, and the cost to obtain and treat water. Surface water in streams, lakes, or reservoirs is almost always considered to be a source for drinking water, because they contain fresh, readily accessible water. Groundwater is a critically important drinking water source in many parts of the United States, especially where surface water is less abundant. Challenges for use as drinking water exist for both surface and groundwater. Surface water may not suffice as a drinking water source when it exists only temporarily or cannot supply the volume demand. Both surface water and groundwater may have contaminant levels that require expensive treatment technology. For instance, in an extensive report, the USGS describes how human activities cause unnaturally fast and deep groundwater movement, which degrades water quality over long periods in the

[1] Brackish water is often a general term used for water having a salinity content intermediate between fresh water and sea water, although it may also have a more specific definition, such as the 1,000 – 10,000 mg/L TDS value used in some USGS publications.

nation's principal aquifers (DeSimone et al., 2014). Despite these challenges, changes in the demand for water affect the consideration of sources of water for drinking purposes.

2.3.1.2 Considerations Applicable to Groundwater as a Drinking Water Source

Determining what groundwater is eligible for use as a drinking water source can include additional challenges. Groundwater may be located at significant depth or within low-yield aquifers, requiring additional engineering solutions to make them practical and/or cost effective as a drinking water source. Aquifers, or parts of aquifers, not in use today for drinking water purposes may nonetheless eventually be considered a drinking water source. The future viability of currently unused aquifers depends on the definition of what constitutes a drinking water resource and knowledge of the physical and chemical characteristics of the aquifers. The extent of knowledge about what exists in the subsurface depends on extrapolation from limited subsurface data (e.g., water samples collected from wells in, or passing through, aquifers). Although salinity is a common criterion for designating an aquifer as a drinking water resource (see Section 2.2.1.4), there is not a uniform threshold value for making that determination. The Groundwater Protection Council (GWPC) notes:

> There is a great deal of variation between states with respect to defining protected groundwater. The reasons for these variations relate to factors such as the quality of water, the depth of Underground Sources of Drinking Water, the availability of groundwater, and the actual use of groundwater (GWPC, 2009).[1]

In addition to variation in applicable water quality criteria, the availability of information regarding groundwater that meets an applicable criterion (if one exists) is also variable. For instance, the bottom depth of aquifers or parts of aquifers that may be defined as a drinking water resource are not always readily publicly available. In some locations, such as the State of Texas, estimates of the bottom depth of groundwater meeting certain regulatory threshold criteria are made public on a website.[2] In other parts of the United States the depth of identified protected subsurface drinking water resources may not be publicly available. No centralized compilation of groundwater depth and quality exists for all locations in the United States, nor does such a reference exist for depths to protected groundwater resources. The depths to protected groundwater resources can vary. In one example, the EPA described the reported bottom depths of protected groundwater resources as ranging from just below ground surface to 8,000 ft (2,000 m) (U.S. EPA, 2015n).[3]

Even in regions where the bottom depth of protected groundwater resources are generally known, there can remain uncertainty regarding precise depths at specific locations. Examples include the states of Indiana and Michigan according to the EPA Region 5 Underground Injection Control (UIC)

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[1] An underground source of drinking water (USDW) is defined in the federal regulations that implement the UIC program. A USDW is generally considered to be any aquifer, or its portion, that currently serves as a source for a public water system; or which contains enough groundwater to supply a public drinking water system, and either now supplies water for human consumption, or contains fewer than 10,000 mg/L TDS. See Title 40 of the Code of Federal Regulation, Section 144.3.

[2] See http://www.beg.utexas.edu/sce/index.html.

[3] This reference provided 1,000-foot (305 meters) depth resolution for the reported base of protected groundwater.

program, the State of Utah according to the Utah Geological Survey, and the State of California according to the California State Water Resources Board (Esser et al., 2015; Anderson et al., 2012; U.S. EPA, 2012e). In these examples, the depth to groundwater meeting the salinity threshold necessary for decision-making is stated not to be known with precision, and collection of additional groundwater quality information is advised.[1]

2.4 Future Drinking Water Sources

The future availability of fresh drinking water sources in the United States (Section 2.2.1.1) will likely be affected by changes in climate and water use (Georgakakos et al., 2014). 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 (National Drought Mitigation Center, 2015; U.S. EPA, 2015p). Declines in surface water resources have already led to increased withdrawals and cumulative net depletions of groundwater in some areas (Castle et al., 2014; Georgakakos et al., 2014; Konikow, 2013; Famiglietti et al., 2011). Loss of approximately 240 mi^3 (1,000 km^3) of groundwater between 1900 and 2008 has been documented by the USGS. USGS reports that about 20% of that loss occurred in the final eight years of that timeframe and that depletion is greater in the arid and semi-arid western states than in the more humid eastern states (Konikow, 2013). Other sources of water that might not be considered fresh, such as wastewater from sewage treatment plants, brackish and saline surface and groundwater, as well as sea water, are also increasingly being used to meet water demand. Through treatment or desalination, these water sources can reduce the use of high-quality, potable fresh water for industrial processes, irrigation, recreation, and toilet flushing (i.e., non-potable uses). In addition, in 2010, approximately 355 million gal per day (1.3 billion L per day) of treated wastewater was reclaimed through potable reuse projects (NRC, 2012). Such projects use reclaimed wastewater to augment surface drinking water sources or to recharge aquifers that supply drinking water to PWSs (NRC, 2012; Sheng, 2005). In 2007, among approximately 13,000 desalination plants worldwide, there existed the capacity to produce about 14.7 billion gal (55.6 billion L) of fresh water each day. In 2005, the United States had approximately 11 % of that volume capacity (Gleick, 2008; Cooley et al., 2006).

An increasing number of states are developing new water supplies to augment existing drinking water sources through reuse of reclaimed water, recycling of storm water, and desalination (U.S. GAO, 2014). Most desalination programs currently use brackish water as a source, although plans are underway to expand the use of sea water. States with the highest installed capacity for desalination include Florida, California, Arizona, and Texas (Cooley et al., 2006). It is likely that various water treatment technologies will continue to expand drinking water sources beyond those that are currently being considered. In addition to treatment technologies, there are efforts by public water systems to alleviate demand on drinking water supplies such as encouraging more modest consumer water usage and repairing leaks in water infrastructure.

[1] Decisions dependent on knowledge of threshold salinity values in groundwater can include permitting injection wells and oil and gas production well construction design approvals.

2.5 Proximity of Drinking Water Resources to Hydraulic Fracturing Operations

Hydraulic fracturing in oil and gas production wells necessarily takes place where oil and gas resources are located. The relative locations of drinking water resources influences the degree to which they may be affected by activities in the hydraulic fracturing water cycle. With increased proximity, hydraulic fracturing activities have a greater potential to affect surface and subsurface sources of current and future drinking water (Vengosh et al., 2014; Entrekin et al., 2011). To estimate potentially vulnerability populations that use drinking water resources, the EPA performed an analysis of the number of hydraulically fractured production wells that are located within 1 mi (1.6 km) of a PWS source. The EPA also presents subsurface separation distances between the depths of drinking water resources and hydraulic fracturing in production wells.

2.5.1 Lateral Distance between Public Water System Sources and Hydraulic Fracturing

The EPA analyzed the locations of the approximately 275,000 oil and gas wells that were assumed to be hydraulically fractured in 25 states between 2000 and 2013 (Chapter 3) to determine the number of fractured wells within a 1-mile radius of facilities that withdraw water for a PWS.[1,2,3] Based on 2000–2013 DrillingInfo data, the lateral distance from the nearest facility that withdraws water for PWS to a hydraulically fractured well ranged from 0.01 to 41 mi (0.02 to 66 km), with an average distance of 6.2 mi (10.0 km) and a median distance of 4.8 mi (7.7 km) (DrillingInfo, 2014a; U.S. EPA, 2014h). Of the approximately 275,000 wells that were estimated to have been hydraulically fractured in 25 states between 2000 and 2013, an estimated 21,900 (8%) were within 1 mile of at least one PWS groundwater well or surface water intake. Most of these approximately 6,800 individual facilities that withdraw water for a PWS were located in Colorado, Louisiana, Michigan, North Dakota, Ohio, Oklahoma, Pennsylvania, Texas, and Wyoming (Figure 2-2). These facilities that withdraw water for a PWS had an average of seven hydraulically fractured production wells and a maximum of 144 such production wells within a 1-mile radius. These water sources supplied water to 3,924 PWSs—1,609 of which are community water systems—that served more than 8.6 million people year-round in 2013 (U.S. EPA, 2014h; U.S. Census Bureau, 2013; U.S. EPA, 2013b).[4]

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[1] The EPA estimated the number of oil and gas production wells hydraulically fractured between 2000 and 2013. To do this, EPA assumed that all horizontal wells were hydraulically fractured in the year they started producing and assumed that all wells within a shale, coalbed, or low-permeability formation, regardless of well orientation, were hydraulically fractured in the year they started producing. More details are provided in U.S. EPA (2013c). Not all coalbed methane wells are hydraulically fractured, but coalbed methane wells represent production wells that sometimes uses hydraulic fracturing. Given that there were 15% of coalbed methane wells relative to all hydraulically fractured wells and the lack of data that distinguishes whether or not coalbed wells are hydraulically fractured, EPA included coalbed wells into all counts of wells that are hydraulically fractured.

[2] The selected 1-mile distance used in this analysis provides a consistent approach. Local topographic conditions could support the use of a different analysis at any specific site.

[3] A facility that withdraws water for a PWS includes water intakes, water wells, springs, infiltration galleries, and reservoirs. It is common for a PWS to operate multiple individual facilities to withdraw the cumulative water supplied by the PWS.

[4] All PWS types were included in the locational analyses performed. However, only community water systems were used to calculate the number of customers obtaining water from a PWS with at least one source within 1 mile of a hydraulically

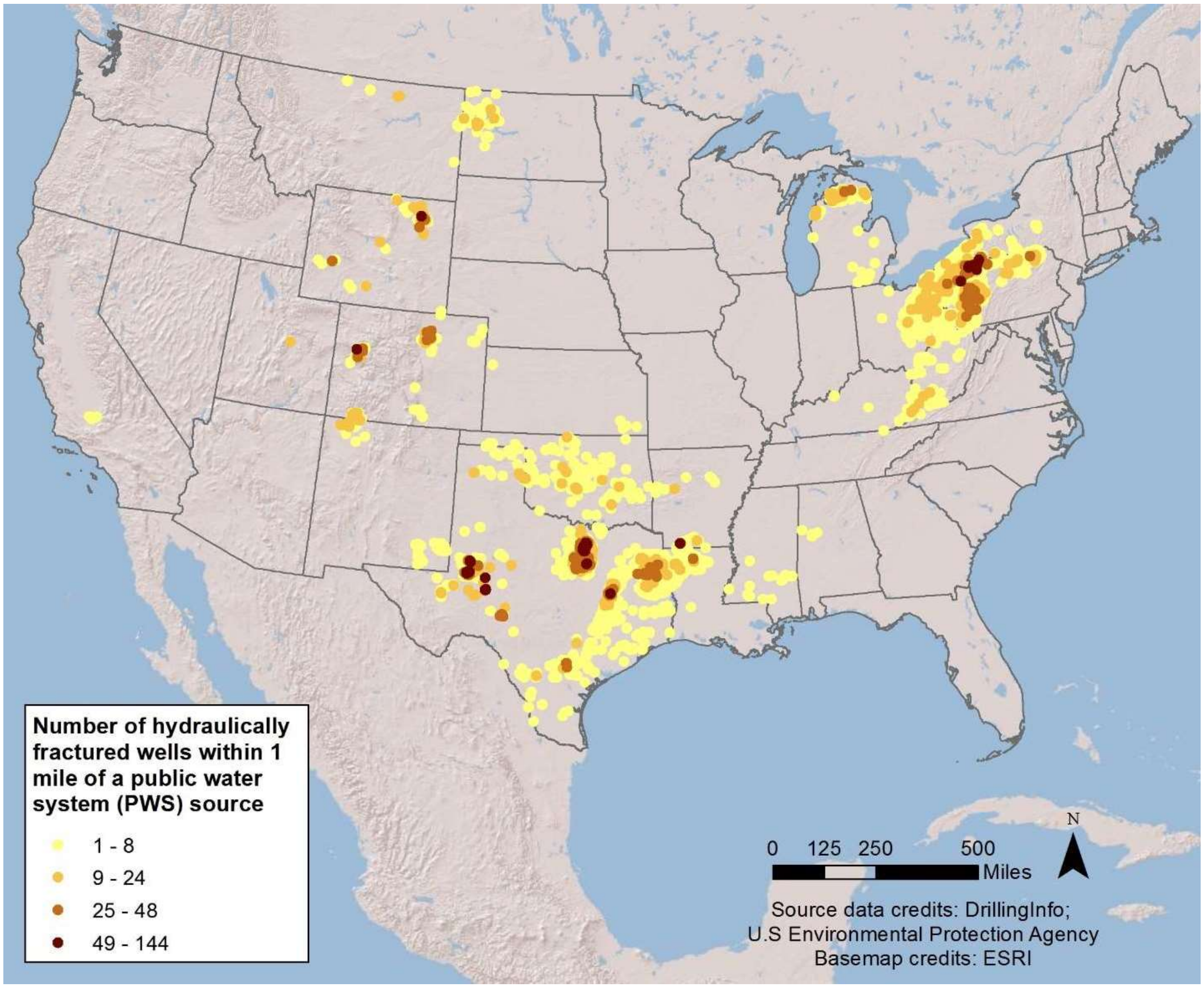


Figure 2-2. The location of public water system sources having hydraulically fractured wells within 1 mile.

Points indicate the location of public water system (PWS) sources; point color indicates the number of hydraulically fractured wells within 1 mile of each PWS source. The estimates of wells hydraulically fractured from 2000 to 2013 developed from the DrillingInfo data were based on assumptions described in Chapter 3. Sources: DrillingInfo (2014), U.S. EPA (2013b), and ESRI (2010).

The EPA also analyzed the location of hydraulically fractured wells relative to populations where a high proportion (≥30%, or at least twice the national average) obtain drinking water from non-PWSs (mostly private groundwater wells).[1] Based on DrillingInfo well location data and USGS drinking water data, between 2000 and 2013, approximately 3.6 million people live in counties

fractured well. If non-community water systems are included, the estimated number of customers increases by 533,000 people (U.S. EPA, 2012g). A community water system is a PWS which serves at least 15 service connections used by year-round residents or regularly serves at least 25 year-round residents.

[1] There is no national data set of non-PWSs. In Maupin et al. (2014), the USGS estimates the proportion of the population reliant on non-PWSs, referred to as the "self-supplied population," by county, based on estimates of the population without connections to a public water system. The USGS estimates were used for this analysis.

with at least one hydraulically fractured well and where at least 30% of the population relies on non-PWSs for drinking water (DrillingInfo, 2014a; USGS, 2014b). The population changes to approximately 740,000 people living in counties with more than 400 hydraulically fractured wells and at least 30% of the population relies on non-PWSs for drinking water (DrillingInfo, 2014a; USGS, 2014b).[1] The counties having more than 400 hydraulically fractured wells and at least 30% of the population relying on non-PWSs for drinking water were located in Colorado, Kentucky, Michigan, Montana, New Mexico, New York, Oklahoma, Pennsylvania, Texas, and Wyoming.

As described in Chapter 1, this assessment defines five stages in the hydraulic fracturing water cycle. The lateral distance analysis presented here relates to the wellhead locations of hydraulically fractured production wells, and therefore addresses three stages that take place near production wellheads, evaluated in Chapters 5, 6, and 7, respectively (chemical mixing, well injection, and produced water handling).[2] A lateral distance analysis was not possible for the other two stages (water acquisition, wastewater disposal and reuse) because there is a lack information about where water is acquired for hydraulic fracturing and where the wastewater from any given hydraulically fractured well is disposed or treated.

2.5.2 Vertical Distance between Drinking Water Resources and Hydraulic Fracturing

The depth at which hydraulic fracturing takes place varies depending on the depth to the targeted production zone. For instance, in a study of wells representing approximately 23,000 production wells hydraulically fractured by nine service companies during 2009 and 2010, the EPA found that, when measured vertically from the surface to total depth, well depths ranged from less than 2,000 ft (600 m) to more than 11,000 ft (3,000 m) (U.S. EPA, 2015n). Similarly, based on more than 38,000 hydraulic fracturing disclosures to the FracFocus registry website, the middle 90% of these well disclosures had vertical depths between 2,900 and 13,000 ft (880 and 4,000 m) with a median value of about 8,100 ft (2,500 m) (U.S. EPA, 2015a). Hydraulic fracturing can occur at or near the bottom of a production well or it may take place at different intermediate depths depending on the location of economically producible oil and gas, and thus the total vertical depth of a production well does not necessarily correlate to the depth at which hydraulic fracturing occurs (Chapter 6). Hydraulic fracturing has been conducted at depths ranging from less than 1,000 ft (300 m) to greater than 10,000 ft (3,000 m) depth (U.S. EPA, 2015n; NETL, 2013). The distance from the base of the drinking water resource to the shallowest hydraulic fracturing initiation point in a production well serves as a separation distance.[3] The EPA reports separation distances in depth measured along the well ranging from no separation distance (where hydraulic fracturing took

[1] Approximately 14% of the U.S. population is self-supplied by non-PWSs (Maupin et al., 2014). This analysis considers only counties in which more than double the national average—that is, at least 30% of the county's population—was supplied by non-PWSs.

[2] Chapter 7 (Produced Water Handling) examines potential effects on drinking water resources at hydraulically fractured wellhead locations, as well as away from wellhead locations.

[3] If measured vertically from the shallowest hydraulic fracturing initiation point to the bottom of the drinking water resource, this is referred to as a vertical separation distance. If measured along a borehole from the shallowest hydraulic fracturing initiation point to the bottom of the drinking water resource, this is referred to as a separation distance in measured depth.

place at depths shallower than the reported base of the drinking water resource) to more than 10,000 ft (3,000 m) (U.S. EPA, 2015n).

In a given setting, it is the geologic and hydrologic history that determines the depths to potential oil and gas and/or subsurface drinking water resources. In some settings, rock formations bearing economic quantities of oil or gas also contain groundwater that, based on salinity value alone, qualifies it as a drinking water resource. Large distances vertically separate these two resources in other settings. Figure 2-3 depicts two different types of these settings.

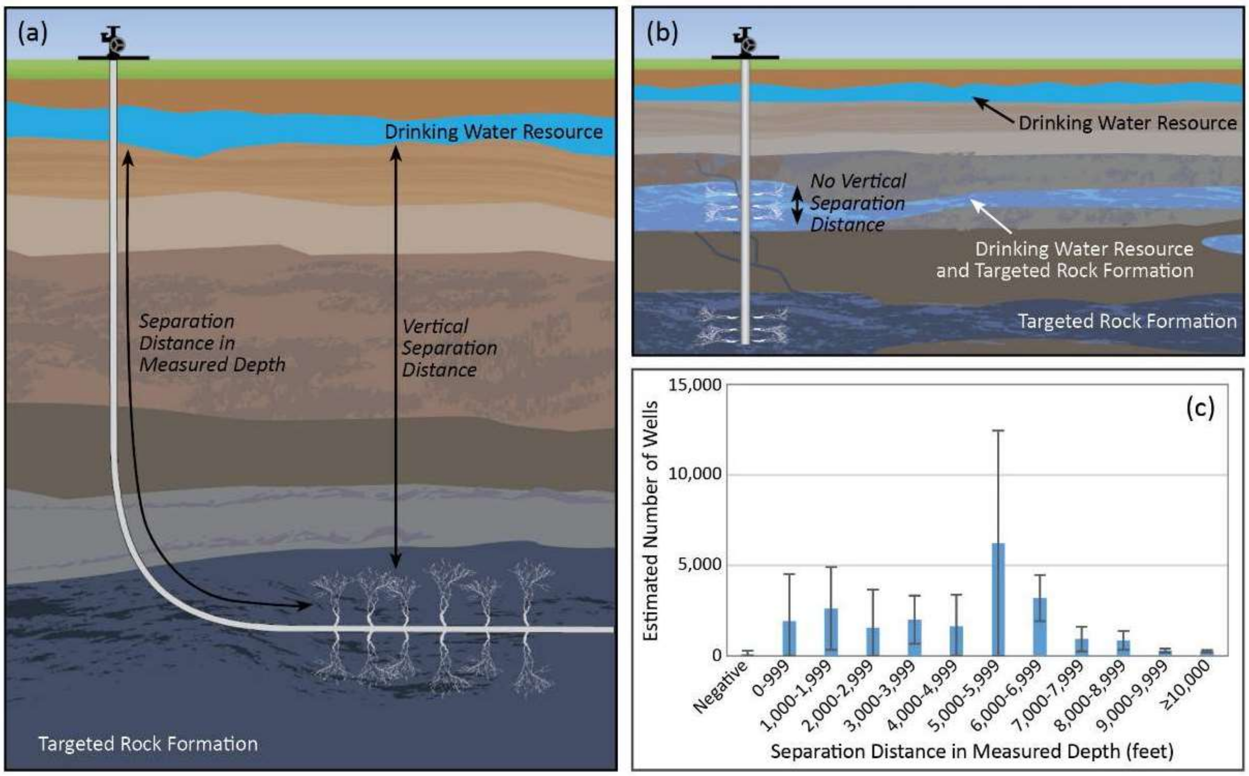


Figure 2-3. Separation distance between drinking water resources and hydraulically fractured intervals in wells

Schematic examples showing a relatively large separation distance (panel a) and the absence of any separation distance (panel b) between the shallowest fracture initiation depth in a well to the base of the protected drinking water resource. Distances may be presented as vertical or as a measured distance along a non-vertical well. Panel c shows result from wells studied representing approximately 23,000 production wells hydraulically fractured between 2009 and 2010 (U.S. EPA, 2015n). Error bars in panel c display 95% confidence intervals.

In Figure 2-3, panel (a), the hydraulically fractured oil- and gas-bearing zone is much deeper than drinking water resources, therefore separation distance is large. In panel (b), the hydraulically fractured oil- and gas-bearing zone is at the same depth as drinking water resources and there is no separation. The lack of separation distance can be due to the oil- and gas-bearing zone being shallow and/or the drinking water resource being deep. Panel (c) illustrates the distribution of separation distances in measured depth for study wells representing approximately 23,000 oil and gas production wells hydraulically fractured by nine service companies between 2009 and 2010, as reported in U.S. EPA (2015n). The calculation of 95% confidence intervals shown in panel (c) is described in the EPA report and was affected by the number of companies in the study and the well file selection methods.

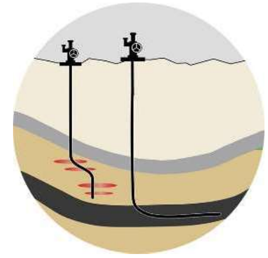
2.6 Conclusions

Drinking water resources provide the water humans consume, cook with, bathe in, and need for other purposes. An estimated 86% of the United States population derives its household drinking water from PWSs that serve at least 25 people. The remaining 14% self-supply their homes with drinking water from non-PWSs, which are largely private water wells. Publicly supplied drinking water is subject to monitoring and testing to determine compliance with drinking water standards while no such monitoring and testing is required at non-PWSs. Surface water is the source for an estimated 58% of the volume needed to supply drinking water and groundwater is the source for the remaining 42%.

The existing distribution and abundance of the drinking water resources in the United States may not be sufficient in some locations to meet future demand. The future availability of sources of drinking water that are considered fresh will likely be affected by changes in climate and water use. Since at least 2000, many areas of the United States have experienced significant drought, which often correlate with diminishment of ground and surface water supplies in these areas. Locally, measures are now being implemented to prolong use of current drinking water sources such as encouraging more modest drinking water use and using treated wastewater or other non-potable water sources to help meet demand.

Between 2000 and 2013, the EPA estimates there were approximately 275,000 oil and gas production wells hydraulically fractured in 25 states. To produce a consistent measure of proximity between these hydraulically fractured oil and gas production wells and drinking water resources during this time frame, the EPA counted the number hydraulically fractured oil and gas production wells located within 1 mile of public drinking water sources, and performed a count of the counties with a relatively high reliance on self-supplied drinking water that also contain one or more of these hydraulically fractured production wells. Between 2000 and 2013, approximately 3,900 public water systems had between one and 144 wells hydraulically fractured within 1 mile of their water source; these public water systems served more than 8.6 million people year-round in 2013. An additional 740,000 people between 2000 and 2013 self-supplied their drinking water in counties where at least 30% of the population relies on groundwater and having at least 400 hydraulically fractured wells.

Depending on the nature of the geologic setting, hydraulically fractured oil and gas production wells can be located near where people get their drinking water. Depths to hydraulically fractured oil and gas resources can range from less than 1,000 ft (300 f) to more than 10,000 ft (3,000 m) while drinking water resources may be found between a few tens of feet to as much as 8,000 ft (2,000 m) below the surface. There is limited publicly available information to determine the vertical distance separating the shallowest hydraulic fracturing initiation point in a production well from the deepest drinking water resource. The EPA found, among 323 wells studied statistically representing more than 23,000 production wells hydraulically fractured by nine service companies between 2009 and 2010, the distance along the wells between these two resources ranged from none to more than 10,000 ft (3,000 m).



Chapter 3. Hydraulic Fracturing for Oil and Gas in the United States

Abstract

This chapter provides a general description of the practice of hydraulic fracturing, where it is conducted, how prevalent it is, and how hydraulic fracturing-based oil and gas production fits into the context of energy production in the United States. Some of the information in this chapter also serves as an introduction to the more in-depth technical chapters in the assessment.

Hydraulic fracturing is a technique used to increase oil and gas production from underground oil- and/or gas-bearing rock formations (reservoirs). The technique involves the injection of hydraulic fracturing fluids through the production well and into the reservoir under pressures great enough to fracture the reservoir rock. Hydraulic fracturing fluids typically consist mainly of water, a "proppant" (typically sand) that props open the created fractures, and additives (usually chemicals) that modify the properties of the fluid for fracturing. Fractures created during hydraulic fracturing enable better flow of oil and gas from the reservoir into the production well. Water that naturally occurs in the oil and gas reservoirs also typically flows into and through the production well to the surface as a byproduct of the oil and gas production process.

Since the mid-2000s, the combination of modern hydraulic fracturing and directional drilling has become widespread and significantly contributed to a surge in oil and gas production in the United States. Slightly more than 50% of oil production and nearly 70% of gas production in 2015 is estimated to have occurred using hydraulic fracturing. Hydraulic fracturing is widely used in unconventional (low permeability) oil and gas reservoirs that include shales, so-called tight oil and tight gas formations, and coalbeds, but it is also used in conventional reservoirs.

There is no comprehensive national database of wells that are hydraulically fractured in the United States. Using data from several commercial and public sources, the EPA estimates that 25,000 to 30,000 new wells were drilled and hydraulically fractured in the United States annually between 2011 and 2014. These hydraulic fracturing wells are geographically concentrated; in 2011 and 2012 almost half of hydraulic fracturing wells were located in Texas, and a little more than a quarter were located in the four states of Colorado, Pennsylvania, North Dakota, and Oklahoma.

New drilling activity for hydraulic fracturing wells is generally linked with oil and gas prices, and those peaked in the United States between 2005 and 2008 for gas and between 2011 and 2014 for oil. Following price declines, the number of new hydraulically fractured wells in 2015 decreased to about 20,000. Despite recent declines in prices and new drilling, U.S. gas and oil production continues at levels above those in recent decades, and production for both is predicted to continue growing in the long term, led by hydraulic fracture-based production from unconventional reservoirs.

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3. Hydraulic Fracturing for Oil and Gas in the United States

3.1 Introduction

This chapter provides general background information on hydraulic fracturing and will help the reader understand the in-depth technical chapters that follow. We describe the purpose and process of hydraulic fracturing and the situations and settings in which it is used (Section 3.1). Then we provide a general description of activities at a hydraulic fracturing well site including assessing and preparing the well site, well drilling and construction, the hydraulic fracturing event, the oil and gas production phase, and eventual site closure (Section 3.3). A characterization of the prevalence of hydraulic fracturing in the United States is then presented (Section 3.4), followed by a review of its current and future importance in the oil and gas industry and its role in the U.S. energy sector (Section 3.5), and a brief conclusion (Section 3.6).

3.2 What is Hydraulic Fracturing?

Hydraulic fracturing is a technique used to increase oil and gas production from underground oil- or gas-bearing rock formations (reservoirs).[1] The technique involves the injection of hydraulic fracturing fluids through the production well and into the reservoir under pressures great enough to fracture the reservoir rock. The injected hydraulic fracturing fluid carries "proppant" (typically sand) into the fractures so that they remain propped open after the pressurized injection is stopped. In addition to water, which typically makes up most of the injected fracturing fluid, the fluid also contains chemical additives (additives) that serve a variety of purposes. These additives, for example, can increase the fluid viscosity (how "thick" the fluid is) so that it carries the proppant into the fractures more effectively, can help control well corrosion, can help minimize microbial growth in the well, and so on (King and Durham, 2015; Gupta and Valkó, 2007). The resulting fractures enable better flow of oil and gas from the reservoir into the production well. Water that naturally occurs in the reservoirs also typically flows into and through the production well to the surface as a byproduct of the production process.

Although hydraulic fracturing is not new, how and where it is employed has changed (Text Box 3-1). For about a half-century after its introduction in the late 1940s, it was used to increase production from vertical wells in conventional oil and gas reservoirs. Conventional reservoirs develop over geologic time (many millions of years) when naturally buoyant oil and gas very slowly migrate upward from the shale rock formations in which they formed until they are trapped by geologic formations or structures and accumulate under a confining layer (Figure 3-1). As the oil and gas accumulate, the pressure may increase. If the reservoir is under enough pressure and has

[1] A version of hydraulic fracturing, sometimes called hydrofracturing or hydrofracking, can be used to increase water yields from water wells and is typically done by injecting only water under pressure. This application of hydraulic fracturing is out of the scope of this assessment.

Text Box 3-1. Hydraulic Fracturing: Not New, but Different and Still Changing.

From the mid-1800s to the 1940s, operators of oil and gas wells occasionally tried to increase production by pumping fluids or sometimes dropping explosives into wells. In the late 1940s, a fracturing technique to increase production was patented by the Stanolind Oil and Gas Company and licensed to the Halliburton Oil Well Cementing Company (Montgomery and Smith, 2010). Close to 1 million wells were hydraulically fractured from the late 1940s to about 2000 (IOGCC, 2002). The typical well design and hydraulic fracturing operations during most of that time, though, were very different from today's modern hydraulic fracturing operations.

The groundwork for the transformation to modern hydraulic fracturing was laid in the 1970s and early 1980s. Public-private research and development (R&D) partnerships that included industry, the Department of Energy, and the Gas Research Institute were established because large amounts of natural gas were known to occur in some shale rock formations yet traditional production well technology was not able to recover much of the gas (Avila, 1976). These R&D programs played a key role in advancing technologies such as deep horizontal drilling and fracturing with higher water volumes that ultimately enabled production from shales and other unconventional sources of gas and oil (DOE, 2015; NRC: Committee on Benefits of DOE R&D on Energy Efficiency and Fossil Energy, 2001). During this period, the U.S. Congress began offering tax incentives for producers to use the developing technologies in the field (Wang and Krupnick, 2013; EIA, 2011a; Yergin, 2011). Advances in directional drilling technologies led to the first horizontal wells being drilled in the mid-1980s in the Austin Chalk oil-bearing rock formation in Texas (Pearson, 2011; Haymond, 1991). Directional drilling and other technologies matured in the late 1990s. In 2001, the Mitchell Energy company developed a cost-effective technique to fracture the Barnett Shale in Texas. The company was bought by Devon Energy, a company with advanced experience in directional and horizontal drilling, that, in 2002, drilled seven wells and developed in the Barnett Shale using the combination of horizontal drilling and hydraulic fracturing; fifty-five more wells were completed in 2003 (Yergin, 2011). The techniques were rapidly adopted and further developed by others (DOE, 2011b; Montgomery and Smith, 2010). By 2005, the techniques were being used in unconventional (low-permeability) oil and gas reservoirs outside of Texas. Modern hydraulic fracturing quickly became the industry standard, driving a surge in U.S. production of oil and natural gas.

Hydraulic fracturing techniques and technologies continue to evolve. Wells are being drilled with longer horizontal sections and are more closely spaced. Multiple, horizontal sections extending from a single vertical well enable production from larger subsurface areas from a single well pad on the land's surface. These historic and continuing technological developments enable production from previously unused oil and gas-bearing geologic formations, altering and expanding the geographic range of oil and gas production activities.

Left: Early hydraulic fracturing site, late 1940s (source: Halliburton, used with permission). Right: Contemporary hydraulic fracturing operation, late 2000s (source: NYSDEC (2015), used with permission).

adequate natural permeability, the economic extraction of oil and/or gas may only require using a drilled well to bring the oil or gas to the surface.[1]

If the natural pressure is not high enough for the oil and gas to readily flow to the surface, various pumping and "lift" techniques can be used to help the oil and gas move up the well to the surface (Hyne, 2012). In other situations, operators may pump water or a mix of water and carbon dioxide (or other similar mixtures) into the reservoir through injection wells to help move and enhance the extraction of oil and gas through nearby production wells. These techniques address pressure and fluid characteristics in the reservoir, are not designed to fracture the reservoir rock, and therefore are production-increasing techniques that are distinct from hydraulic fracturing. The discussions in the remainder of this chapter focus on hydraulic fracturing in unconventional reservoirs.

Hydraulic fracturing is now combined with directional drilling technologies to access oil and gas in unconventional reservoirs (although hydraulic fracturing is still used in conventional reservoirs, too).[2] Unconventional reservoirs have a very low natural permeability, which prevents oil and gas from flowing through the rock into wells in economic amounts. Production from unconventional reservoirs becomes economically feasible when wells, typically horizontal or deviated, are drilled and hydraulically fractured through long portions of the production zone (the targeted oil- and gas-bearing zones within a reservoir). See Figure 3-1 for a diagram of horizontal and other well types and the reservoir types from which they can produce. Text Box 3-2 provides a brief discussion on the use of the terms conventional and unconventional.

More details about the geologic formations that can be unconventional reservoirs are presented below:

- ***Shales.*** Some organic-rich black shales serve as the source of oil and gas found in conventional resources when, over geologic time, the lighter and more buoyant oil and gas migrate upward from these shales and become trapped under impermeable confining layers (Figure 3-1). Shales have very low permeability and the oil and gas are contained in poorly connected pore space in the shale rock. With hydraulic fracturing and directional drilling now enabling oil and gas production from very low permeability formations, some of these shale source rocks are now unconventional reservoirs in addition to being sources. Some shales produce predominantly gas and others predominantly oil; often there will be some co-production of gas from oil wells and co-production of liquid oil from gas wells (USGS, 2013a; EIA, 2011a).
- ***Tight formations.*** Some oil- and gas-bearing sandstone, siltstone, and carbonate formations can be referred to as "tight" formations (for example, "tight sands") because of their relatively low permeability and the fact that oil and gas are contained in small, poorly connected pore spaces. Given a range of permeabilities, some tight formations require

[1] Permeability in rocks is the ability of fluids, including oil and gas, to flow through well-connected pores or small openings in the rock.

[2] Directional drilling is the practice of controlling the direction and deviation (angle) of a borehole during drilling to extend the borehole in a predetermined orientation and to a targeted area in the subsurface. Directional drilling is required for drilling a deviated or horizontal well and is common in unconventional reservoirs. The terms deviated wells and directional wells are often used interchangeably.

hydraulic fracturing for economic production and some do not. In the literature, "tight gas" generally refers to gas in tight sands and is distinguished from "shale gas." Oil resources from shale and other tight formations, in contrast, are frequently referred together under the label "shale oil" or "tight oil" (Schlumberger, 2014; USGS, 2014a).

- ***Coalbeds.*** Organic-rich coal, found in coalbeds, can be a source of methane (natural gas). The gas primarily adheres to the coal surface rather than being contained in pore space or structurally trapped in the formation. A range of techniques can be used to extract methane from coalbeds and these techniques sometimes, but not always, employ hydraulic fracturing. A key component of all coalbed methane production is the need to "dewater" the coalbeds (pumping out naturally occurring or injected water) to reduce the pressure in the coal allowing the methane to be released and flow from the coal into the production well (Palmer, 2010; Al-Jubori et al., 2009; USGS, 2000).

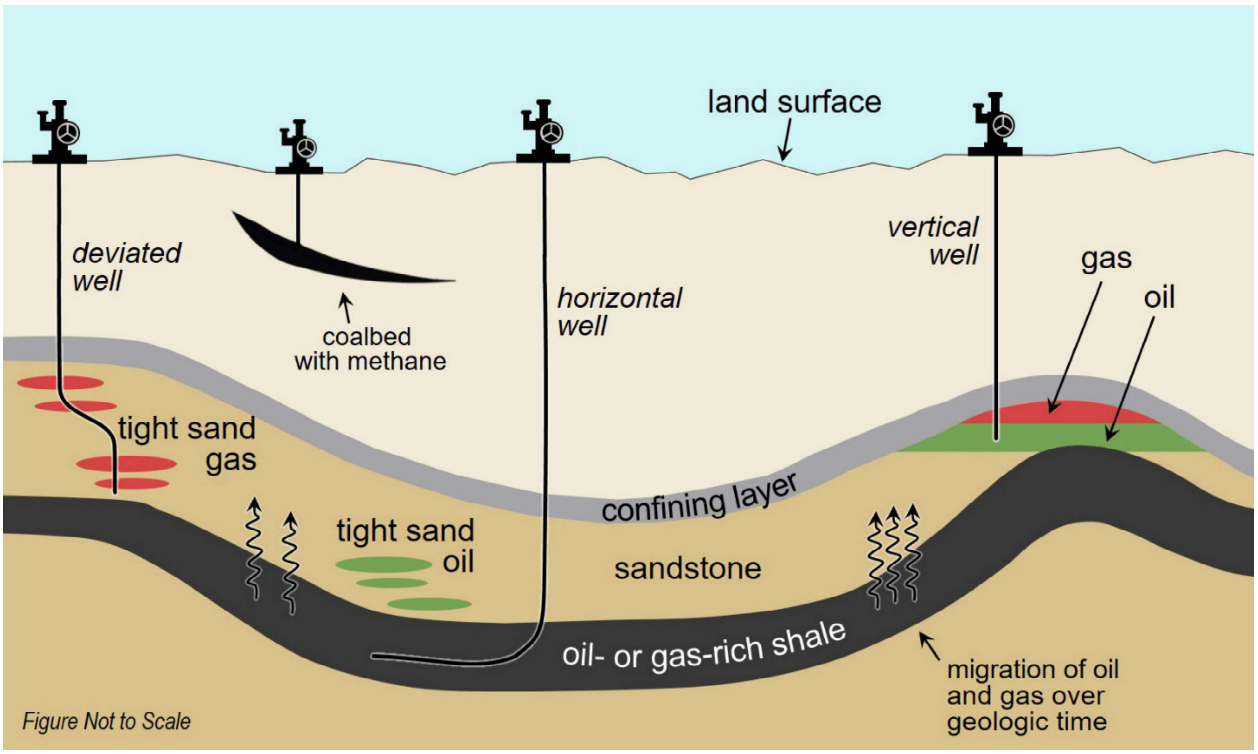

Figure 3-1. Conceptual illustration of the types of oil and gas reservoirs and production wells used in hydraulic fracturing.

A vertical well is producing from a conventional oil and gas reservoir (right). The impermeable gray confining layer (sometimes called a cap rock) traps the lighter and more buoyant gas (red) and oil (green) as it migrates up from the deeper oil- or gas-rich shale source rock. Also shown are wells producing from unconventional reservoirs: a horizontal well producing from a deep shale (center); a vertical well producing methane (gas) from coalbeds (second from left); and a deviated well producing from a tight sand reservoir (left). Multiple deviated or horizontal wells can be constructed and operated from a single well site. Note that the oil- or gas-rich shale serves as both a source and a reservoir. Modified from Schenk and Pollastro (2002) and Newell (2011).

Text Box 3-2. "Conventional" Versus "Unconventional."

The terms "conventional" and "unconventional" are widely used in articles and reports to distinguish types of oil and gas reservoirs, wells, production techniques, and more. In this report, the terms are mainly used to distinguish different types of oil and gas reservoirs: "conventional" reservoirs are those that can support the economically feasible production of oil and gas using long-established technologies, and "unconventional" reservoirs are those in which production has become economical only with the advances that have occurred in hydraulic fracturing (often combined with directional drilling) in recent years.

Note that as hydraulic fracturing has increasingly become a standard industry technique, the word "unconventional" is less apt than it once was to describe these oil and gas reservoirs. In a sense, "the unconventional has become the new conventional" (NETL, 2013).

The following three maps show the locations of major shale gas and oil resources, tight gas resources, and coalbed methane resources, respectively, in the contiguous United States (Figure 3-2, Figure 3-3, and Figure 3-4). To explain the terminology used in the maps: a group of known or possible oil and gas accumulations in the same region and with similar geologic characteristics can be referred to as a *play* (Schlumberger, 2014). Plays can sometimes be geologically layered atop one another (or "stacked") and are located in broad depressions filled with sedimentary rock formations in the earth's continental crust known as *basins*. A group of similar coalbed methane (gas) reservoirs can be referred to as coalbed methane *fields* (rather than plays) and are also found in basins. The plays and fields in the maps below represent unconventional reservoirs that are being exploited now or could be exploited in the future using hydraulic fracturing.

There is a wide range of depths at which hydraulic fracturing occurs across the country. For example, approximate average depths for some of the largest gas-producing reservoirs are as deep as 6,000 ft (2,000 m) in the Marcellus Shale in Pennsylvania and West Virginia, 7,500 ft (2,300 m) in the Barnett Shale in Texas, and 12,000 ft (3,700 m) for the Haynesville-Bossier Shale in Louisiana and Texas (NETL, 2013).[1] A few other, smaller plays are shallower, with depths less than 2,000 ft (600 m) in parts of the Antrim (Michigan), Fayetteville (Arkansas), and New Albany (Indiana and Kentucky) shale plays (NETL, 2013; GWPC and ALL Consulting, 2009). Coal seams that can be drilled to produce gas (coalbed methane) range in depth from less than 600 ft (200 m) to more than 6,000 ft (2,000 m) with production often occurring at depths between 1,000 and 3,000 ft (300 and 900 m) (U.S. EPA, 2006; ALL Consulting, 2004). Coalbed methane production occurs in the San Juan Basin in New Mexico, the Powder River Basin in Wyoming and Montana, and the Black Warrior Basin in Alabama and Mississippi. See Chapter 6 for more information on the general locations and depths of formations being hydraulically fractured.

[1] These are approximate average depths; hydraulic fracturing occurs in shallower and deeper zones in all these plays.

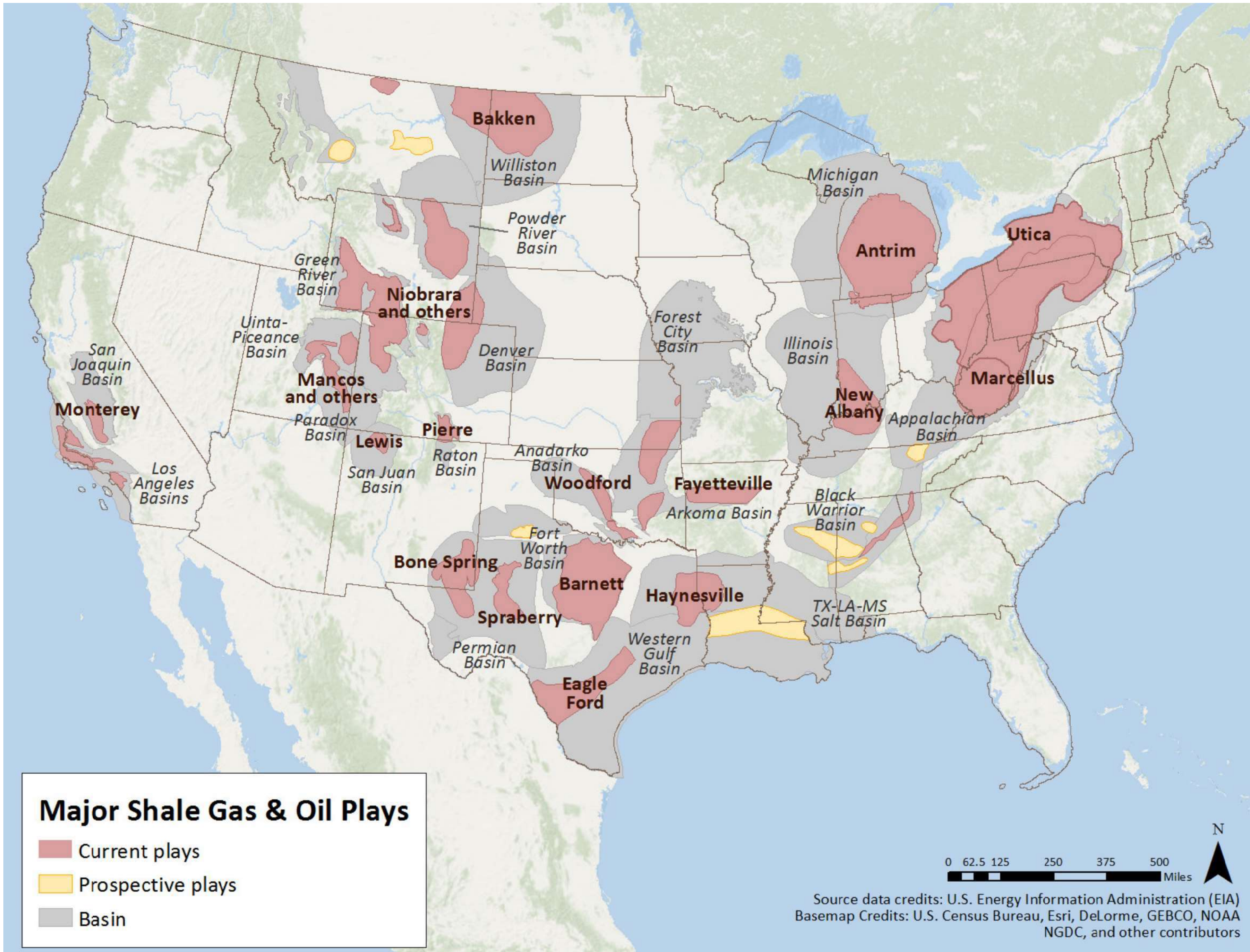

Figure 3-2. Major shale gas and oil plays in the contiguous United States.
The plays represent geologically similar accumulations of oil and gas that are or could be developed. Adapted from EIA (2015).

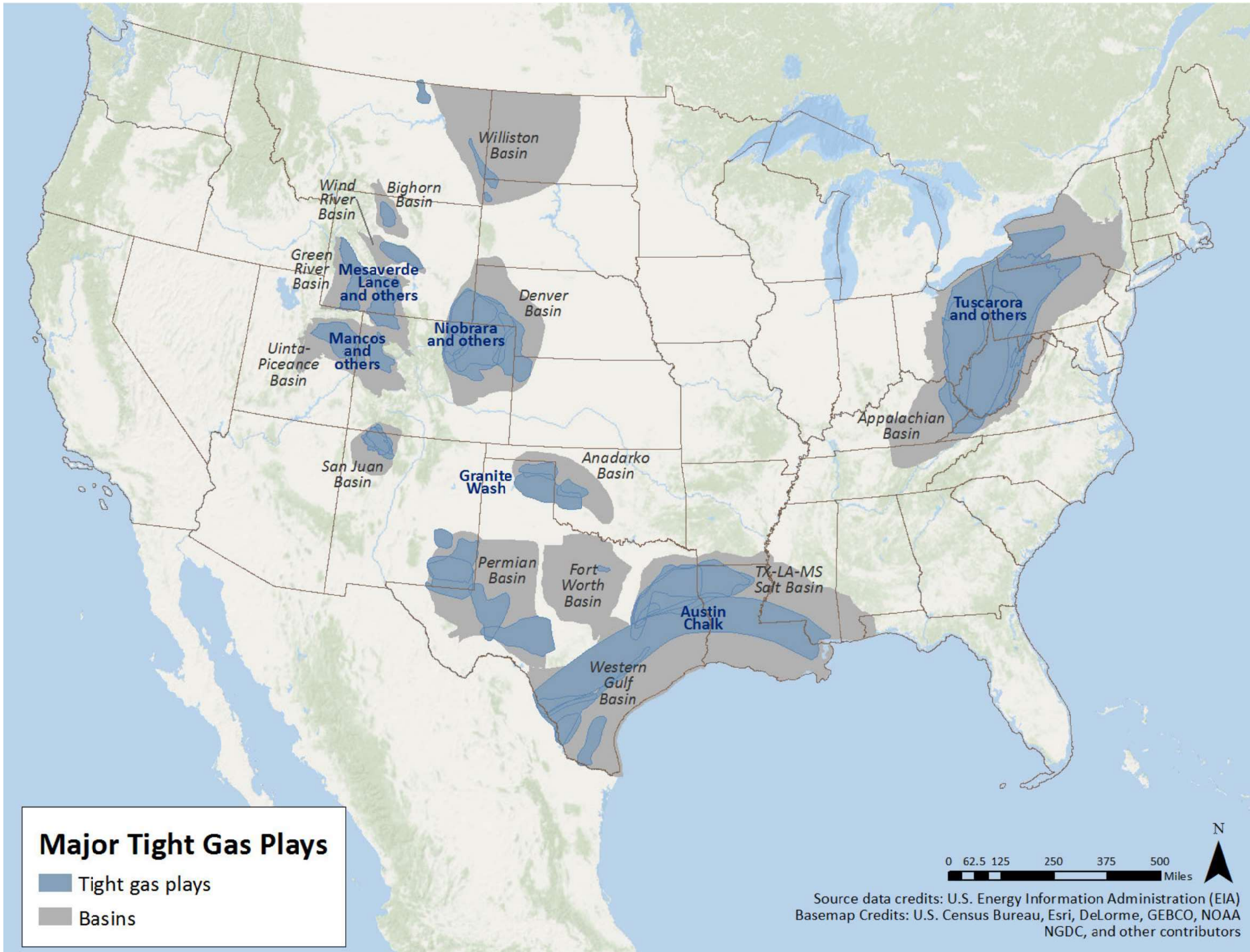

Figure 3-3. Major tight gas plays in the contiguous United States.
The plays represent geologically similar accumulations of gas that are or could be developed. Adapted from EIA (2011b).

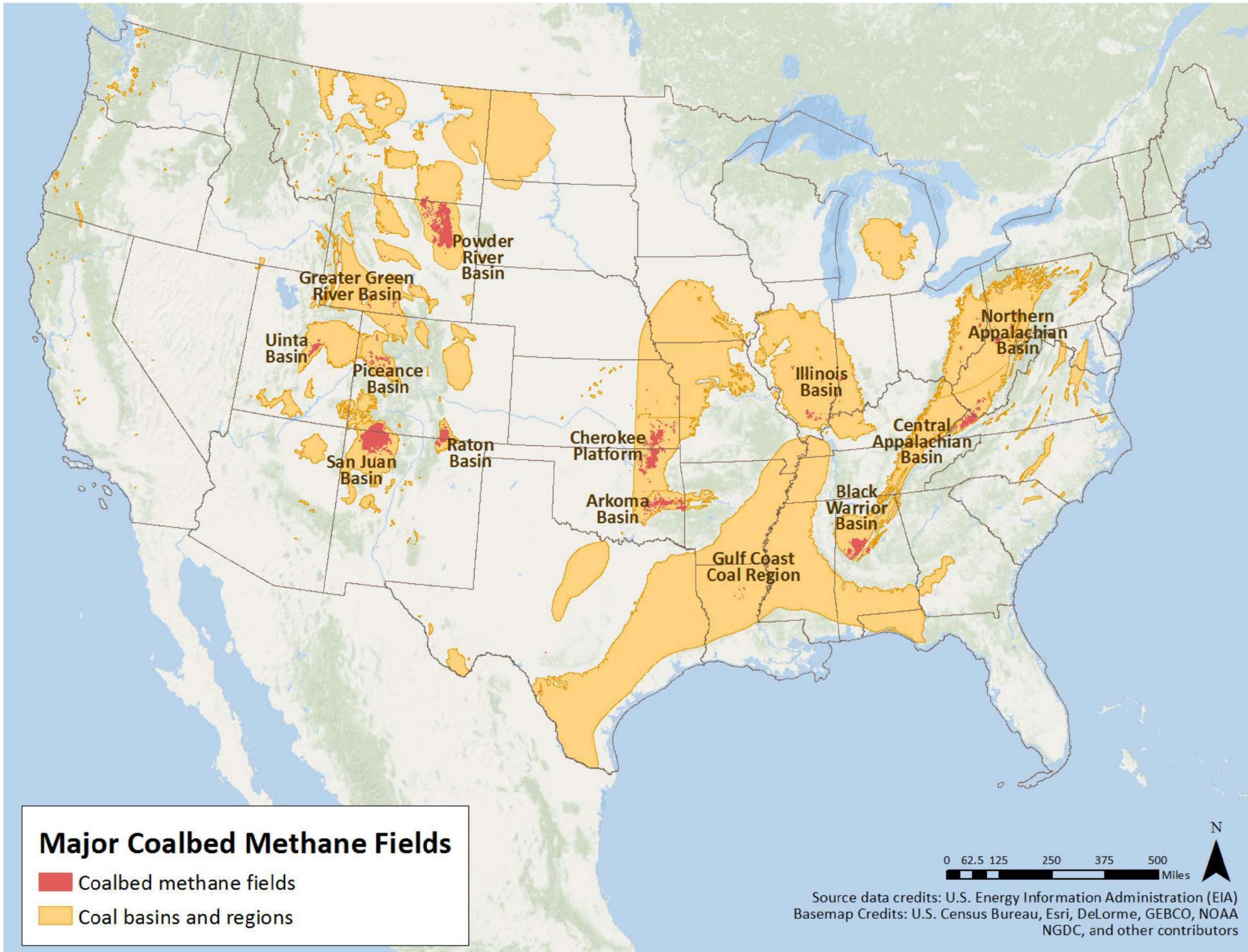

Figure 3-4. Coalbed methane fields and coal basins in the contiguous United States.
The fields represent gas-bearing coal deposits that are or could be developed. Adapted from EIA (2011b).

How a hydraulic fracturing operation is conducted depends on the characteristics of the oil- or gas-bearing formation (such as the geology, depth, and other factors). Hydraulic fracturing operations in shales, such as the Marcellus and Haynesville, require that relatively large volumes of water and proppant to be pumped at high pressures through deep wells with long horizontal sections in the production zone. In some tight formations, such as in the Permian Basin, hydraulic fracturing can be conducted with smaller water volumes and using less pressure in shorter vertical or deviated wells (Gallegos and Varela, 2015). Hydraulic fracturing technologies can be applied to coalbed methane production in various ways, for example, with much smaller water volumes and no proppant, or with water-based gels or foams and proppant. Coalbed methane production sometimes involves no hydraulic fracturing, with only pumping of the naturally occurring formation water out of the coalbeds to enable the release and production of the trapped methane.[1]

3.3 Hydraulic Fracturing and the Life of a Well

A variety of activities take place at a well site over the course of the operational life of a hydraulically fractured oil and gas production well. Not all of these activities are within the scope of this assessment (that includes water acquisition, chemical mixing, well injection, produced water handling, and wastewater disposal and reuse). However, in this chapter we include some information on a wider range of activities related to the well site to provide context for the reader.

The overview of well operations presented in this section is broad, illustrates common activities, and describes some specific operational details. The details of well preparation, hydraulic fracturing and production operations, and closure can vary between companies, reservoirs, and states, and even from well to well. The activities involved in well development and operations may be conducted by the well owner and/or operator, their representatives, and/or service companies working for the well owner.

Figure 3-5 shows the general sequence and duration of activities at a hydraulic fracturing well site, including the activities that comprise the five stages of the hydraulic fracturing water cycle (noted above and defined in Chapter 1). The hydraulic fracturing event itself is the period of the most operational activity during the life of a well and is short in duration compared to the other well site activities. The hydraulic fracturing activity typically lasts from about a day to several weeks (U.S. EPA, 2016c; Halliburton, 2013; NYSDEC, 2011). The subsequent phase of oil and gas production, during which produced water also flows from the well, is the longest phase during the life of the well and can last decades (King and Durham, 2015).[2]

[1] Some subsurface geologic formations, including coalbeds and oil and gas reservoirs, can contain naturally occurring water that is commonly referred to as "formation water," "native water," or (if salty) "native brines."

[2] In general, produced water is water that flows from the subsurface through oil and gas wells to the surface as a by-product of oil and gas production. See Section 3.3.3 and Chapter 7 for more details.

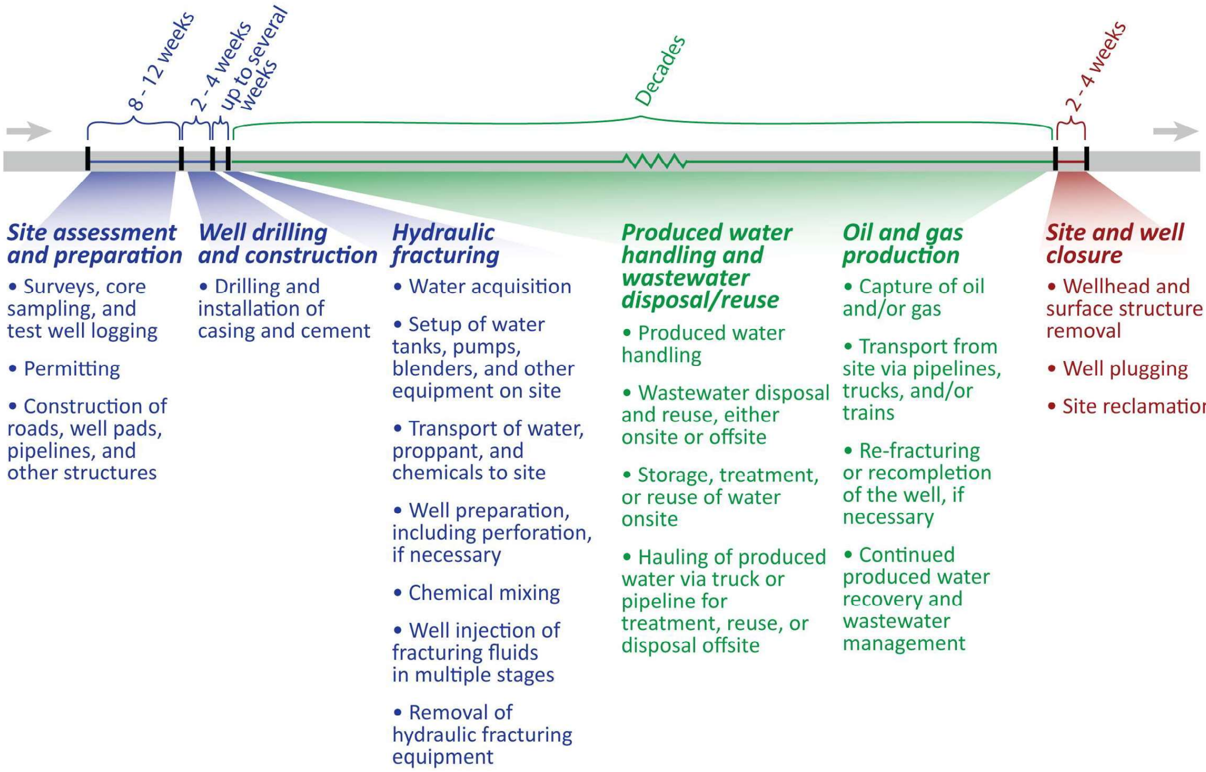

Figure 3-5. General timeline and summary of activities that take place during the preparation and through the operations of an oil or gas well site at which hydraulic fracturing is used.

3.3.1 Site Preparation and Well Construction

Before hydraulic fracturing and production can occur, preliminary steps include assessing and preparing the site, and drilling and constructing the production well.

3.3.1.1 Site Assessment and Preparation

Selecting a suitable well site requires an assessment of geologic (subsurface) and geographic (surface) factors. Geophysical surveys of the subsurface can be conducted using data gathering techniques from the land surface or subsurface, and rock samples may be gathered from outcrops or from exploratory or test wells. Other information is obtained by well logging in which geophysical instruments that collect data on subsurface conditions are lowered into or installed in a well (Kundert and Mullen, 2009).[1] Analyzing all of this information together enables operators to develop an understanding of the potential reservoir characteristics (such as permeability and the presence of natural fractures and water), the position of such formations in relation to other

[1] Well logging is used to obtain information on mechanical integrity, well performance, and reservoir properties that can affect oil and gas production. Well logging data from other wells in the nearby area also provides information on the reservoir. More information on well logging is found in Chapter 6 and Appendix D.

formations, including water-bearing zones, and details about the quantity and quality of the oil and gas resource.

Geographic factors involved in well site assessment include topography and land cover; proximity to roads, pipelines, water sources, other oil and gas wells, and abandoned oil or gas wells; possible well setback requirements; potential for site erosion; location relative to environmentally sensitive areas; and location relative to populated areas (Drohan and Brittingham, 2012; Arthur et al., 2009a).[1] Land ownership also plays an important role in well site selection. During site assessment and before site development and well drilling, the well owner/operator obtains a mineral rights lease, negotiates with landowners, and applies for necessary permits from the appropriate federal, state, and local authorities (Hyne, 2012). This initial site assessment phase of the process may take several months (King and Durham, 2015; King, 2012).

The site is typically surveyed to plan and finalize well site location and access. Sometimes an access road may need to be built to accommodate trucks delivering equipment and supplies to be used at the site (Hyne, 2012). The operator levels and grades the well site to manage drainage, complete access routes, and prepare the well pad. The well pad is a smaller area within the broader well site where the production well will be drilled and the hydraulic fracturing activities will be concentrated. Well pads can range in size from less than an acre to several acres depending on the scope of the operations (King, 2012; NYSDEC, 2011). Multiple wells can be located on a single well pad at a well site (King, 2012; NYSDEC, 2011)

To manage the various fluids that are used for or generated during operations, storage pits (sometimes referred to as impoundments) are excavated, graded and constructed on the well site, and/or steel tanks are installed. These are used to hold water and materials (such as drilling mud) related to the well-drilling activities, water used in the hydraulic fracturing process, or the produced water that is generated post-fracturing (Hyne, 2012). Pit construction is generally governed by local regulations. In some areas, regulations may prohibit the use of pits or require pits to be lined to prevent fluid seepage into the shallow subsurface. One alternative to constructing a pit for drilling fluids is the use of a closed loop drilling system that stores, partly treats, and recycles the drilling fluid (Astrella and Wiemers, 1996). Often piping is installed along the surface or in the shallow subsurface of the well site to deliver water for hydraulic fracturing, remove produced water, or transport the oil and gas once production begins (Arthur et al., 2009a).

Water may be acquired from local surface water or groundwater resources, or reused from other well sites. Water is required for the drilling phase as well as for hydraulic fracturing (Chapter 4). Figure 3-6 depicts the pumping of water for well site operation from a local surface water source.

After site and well pad preparation, drill rigs and associated equipment (including the drill rig platform, generators, well blowout preventer, fuel storage tanks, cement pumps, drill pipe, and casing) are brought onto the site.

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[1] Regarding well setbacks, some states and sometimes local city or county governments can have requirements that define how close an oil and gas well can be located to drinking water supplies or other water bodies.

Figure 3-6. Surface water being pumped for oil and gas development.
Photo credit: Arkansas Water Science Center (USGS).

3.3.1.2 Well Drilling and Construction

Wells are generally drilled and constructed by repeating several basic steps. The operator begins by using the drill rig (temporarily located on the well pad) to hoist a section of long drill pipe up and attaching a drill bit to the bottom of the drill pipe. The drill rig is then used to rotate and advance the drill pipe/drill bit combination (also known as the drill string) downward through the soil and rock. As the drill string continues moves downward, new sections of pipe are added at the surface, enabling the drilling to proceed deeper (Hyne, 2012). During drilling, a drilling fluid is pumped down through the center of the drill string to the drill bit to lubricate and cool it, and to help remove the drill cuttings from the well (King, 2012).[1]

Drilling is temporarily halted at certain pre-determined intervals, the drill string is removed from the wellbore (also called the borehole), and long sections of another type of steel pipe called casing are lowered into the wellbore and set in place.[2] Cement is then pumped into the space between the outside of the casing and the wellbore. This process is repeated, with the next interval of drilling

[1] Drilling fluids, sometimes called drilling mud, consist primarily of water, foam, oil or air, with the most common drilling mud consisting mainly of water and clay (Williamson, 2013). Drill cuttings are the small pieces of broken and ground-up rock generated during the drilling process.
[2] The wellbore is the drilled hole and can refer to both the open hole or an uncased portion of the well.

using a smaller diameter drill bit that fits inside the existing casing. The result can be multiple layers of casing and cement with surface casing and cement typically set below the groundwater resource to be protected. Figure 3-7 illustrates different types of casing as defined by their locations within the well, shows multiple casing and cement layers, and shows examples of two wells with differences in the extent of cement.[1]

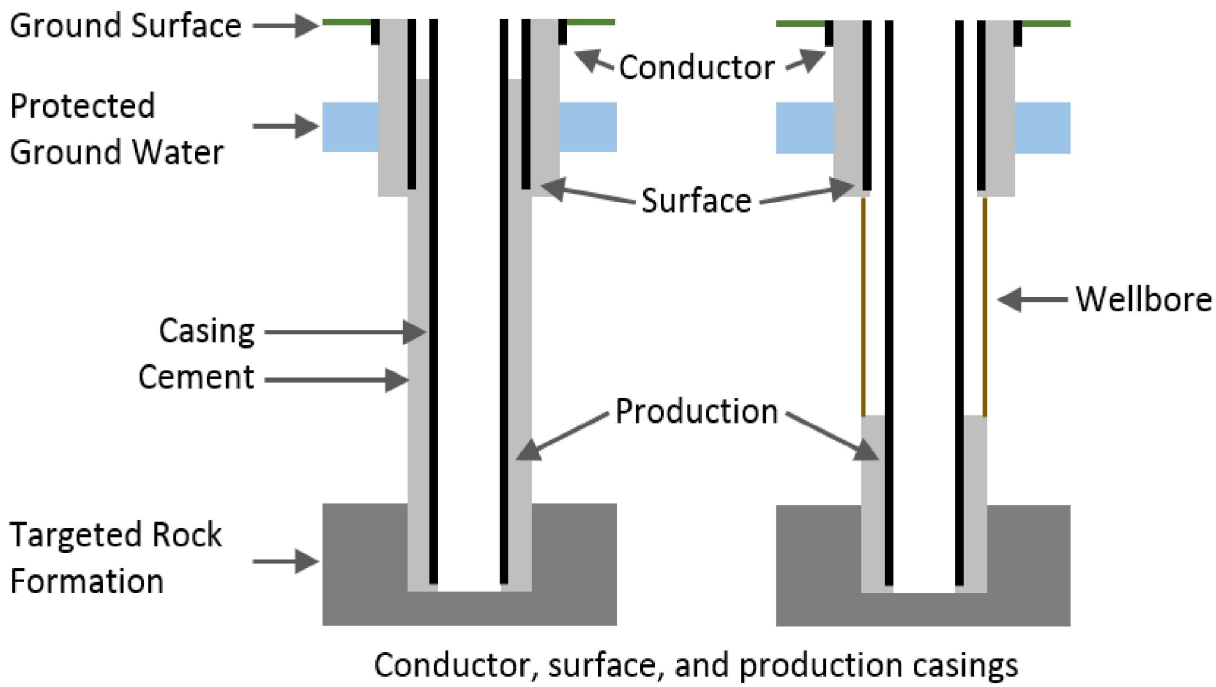

Figure 3-7. Illustration of well construction showing different types of casing and cement.

The well on the left is cemented continuously from the surface to the production zone and the well on the right has cement in sections, including sections cemented across protected groundwater.

The cement protects the casing from corrosion by formation water, helps physically support the casing in the borehole, and stabilizes the borehole against collapse or deformation (Renpu, 2011).[2] The casing and cement help to isolate geologic zones of high pressure, isolate water-bearing zones, and maintain the integrity of the production well for transporting oil and gas to the surface. Casing and cement provide important barriers that keep fluids within the well (oil, gas, hydraulic fracturing fluids) isolated and separated from fluids outside the well (formation water) (Hyne, 2012). Figure 3-8 shows sections of casing ready for installation.

[1] In different portions of the well, multiple concentric sections of casing of different diameters can be used as shown by the surface and production casings in Figure 3-7. The largest casing diameter can range between 30 in. (76 cm) to 42 in. (107 cm) with casing diameters typically larger in the shallower portions of a well and smaller in the deeper portions (Hyne, 2012). See Appendix D for details on well construction and casing diameters.

[2] Some naturally occurring formation water can be very saline (salty or briny), which can be corrosive to metal.

Figure 3-8. Sections of well casing ready for installation at a well site in Colorado.
Photo credit: Gregory Oberley (U.S. EPA).

Some wells are cemented continuously from the surface down to the production zone. Other wells are partially cemented with, for example, cement from the surface to some distance below the deepest protected groundwater zone and perhaps cement across high pressure or water- or oil-bearing zones. Sometimes there can be multiple casing and cement layers (Figure 3-7). There are advantages, in some situations, to not fully cementing the casing as long as high pressure or water- and oil-bearing zones are cemented. For example, some sections may not be cemented to allow monitoring of the pressure in the space between the casing and the borehole or to prevent damage to weak rock formations due to the weight of the cement[1] (King and Durham, 2015; API, 2009).

Although wells are initially drilled vertically (more or less straight down), the sections of the wells that are hydraulically fractured in the production zone of the reservoir can be vertical, deviated, or horizontal (Figure 3-1). The operator determines the well orientation that will provide the best access to the targeted zone(s) within a reservoir and that will align the production section of the well with natural fractures and other geologic structures in a way that helps improve production. Deviated wells may be "S" shaped or continuously slanted. So-called "horizontal wells" have one or more extensions or branches oriented approximately 90 degrees from the vertical portion of the well; these horizontal sections are often referred to as "laterals." The lengths of laterals can range from 2,000 to 10,000 ft (600 to 3,000 m) or more (Hyne, 2012; Miskimins, 2008; Bosworth et al., 1998). Multiple laterals can extend in different directions from a single well (and multiple wells can be located on a single well site). This allows access to more of the production zone with a higher well density in the subsurface, which can be required for unconventional reservoirs, while having fewer well sites on the land surface.

[1] The use of lighter cement or special cementing techniques can also prevent damage of weaker rock formations. See Chapter 6 and Appendix D for more details on well construction and cementing.

Once well construction is completed, the operator can move the drilling rig and related drilling equipment, install the wellhead (the top portion of the well), and prepare the well for hydraulic fracturing and subsequent production of oil and gas. Chapter 6 and Appendix D contain more details on well construction, casing, and cement.

Figure 3-9 (from northeastern Pennsylvania) and Figure 3-10 (from northwestern North Dakota) show, in the context of the local landscape, well sites during well drilling and construction prior to hydraulic fracturing activities.

Figure 3-9. Aerial photograph of two hydraulic fracturing well sites and a service road in Springville Township, Pennsylvania.
Photo credit: Image@J Henry Fair / Flights provided by LightHawk.

Figure 3-10. Aerial photograph of hydraulic fracturing well sites near Williston, North Dakota.
Photo credit: Image@J Henry Fair / Flights provided by LightHawk.

3.3.2 Hydraulic Fracturing

The hydraulic fracturing phase is an intense phase of work in the life of the well that involves complex operational activities at the well site. This phase of work is short in duration, compared to other work phases in the life of a well, and typically lasts less than two weeks per well. It consists of multiple activities, is typically a process done in repetitive stages, and requires a variety of equipment and materials. During this phase of work, the well is prepared for hydraulic fracturing, specialized equipment is hauled to the well site, the hydraulic fracturing fluid components –the water, proppant, and additives– are moved to the well site, and the hydraulic fracturing fluid is mixed and injected under pressure through the well and into the targeted production zone in the subsurface (Figure 3-11).

Figure 3-11. Well site with equipment (and pits in the background) in preparation for hydraulic fracturing in Troy, Pennsylvania.
Image from NYSDEC (2015). Reprinted with permission.

3.3.2.1 Injection Process

The section of well located in the production zone can be prepared for the injection and fracturing process in several different ways. One approach is used when the production casing and cement extend all the way into the production zone; this requires the use of focused explosive charges to perforate (blast holes in) the casing and cement in a segment of the well within the production zone. In another approach, known as a formation packer completion, only the casing, equipped with holes that can be opened and closed, is extended into the production zone. The resulting perforations or holes allow the injected hydraulic fracturing fluids to flow out of the well to fracture the reservoir rock and allow the oil and gas to flow into the well. Another technique is an open hole completion in which the casing is set and cemented just to the edge of the production zone, so the borehole extends open (with no casing or cement) into the production zone. In open hole completions, oil and gas flow directly into the borehole and eventually into the cased section of the well leading to the surface (Hyne, 2012; Cramer, 2008; Economides and Martin, 2007).

After the subsurface portion of the well is prepared for injection, a wellhead assembly is temporarily installed on the wellhead to which high pressure fluid lines are connected for injection of the fluids into the well. Figure 3-12 shows three wellheads with injection piping attached in preparation for hydraulic fracturing injection. Pressures required for fracturing can vary widely depending on depth, formation pressure, and rock type and can range from 2,000 psi to 12,000 psi (U.S. EPA, 2016c; Salehi and Ciezobka, 2013; Abou-Sayed et al., 2011; Thompson, 2010).

Figure 3-12. Three wellheads on a multi-well pad connected to the piping used for hydraulic fracturing injection.
Photo credit: DOE/NETL

The portion of the well to be fractured can sometimes be done all at once or done in multiple interval (U.S. EPA, 2016c; GWPC and ALL Consulting, 2009). When done in multiple intervals, shorter lengths or segments of the well are closed-off (using equipment inserted down into the well) and fractured independently in "stages" (Lee et al., 2011). Fluids are first injected to clean the well (removing any cement or debris). Then, for each stage fractured, a series of hydraulic fracturing fluid mixtures is injected to initiate fractures and carry the proppant into the fractures (Hyne, 2012; GWPC and ALL Consulting, 2009). The fracturing process can require moving millions of gallons of fluids around the well site through various hoses and lines, blending and mixing the fluids with proppant, and injecting the mixture at high pressures down the well. For more details on hydraulic fracturing chemical mixtures and stages, see Chapter 5.

The hydraulic fracturing produces propped-open fractures that extend into the production zone and create more flow paths that contact a greater volume of the oil- and gas-bearing rock within the production zone of the reservoir. This increase in flow paths and in the volume of the production zone accessed by the production well is how hydraulic fracturing increases production. In this regarding, hydraulic fracturing can be considered a production or well "stimulation" technique.

The process and the fracturing pressures during injection are closely monitored throughout the fracturing event. Microseismic monitoring (a geophysical survey technique) can be used to estimate the horizontal and vertical extent of the fractures created and, used with other monitoring and operational data, provides important information for designing subsequent fracture jobs (Cipolla et al., 2011). Engineers can design fracture systems using modeling software to help optimize the process. More details of injection, fracturing, and related monitoring are provided in Chapter 6 and Appendix D.

3.3.2.2 Fracturing Fluids

To conduct the chemical mixing and preparation of the hydraulic fracturing fluids, water- and chemical-filled tanks and other storage containers are transported and installed on site. The components that make up the hydraulic fracturing fluid for injection are commonly mixed on a truck-mounted blender on the well pad. Hoses and pipes are used to transfer the water, proppant, and chemicals from storage units to the mixing equipment and to the well into which the mixed hydraulic fracturing fluid will be injected. The injection process happens in stages with specific chemicals added at different times during each stage. The composition of the hydraulic fracturing fluid, therefore, can change over time during the process (Knappe and Fireline, 2012; Fink, 2003). See Chapter 5 for more details on mixing and staged injection.

Hydraulic fracturing fluids (sometimes referred to as "fluid systems") are generally either water-based or gel-based. Other fluid systems include foams or emulsions made with nitrogen, carbon dioxide, or hydrocarbons; acid-based fluids; and others (Montgomery, 2013; Saba et al., 2012; Gupta and Hlidek, 2009; Gupta and Valkó, 2007; Halliburton, 1988). Water-based systems are used more often with the most common type being "slickwater" formulations, which include polymers as friction reducers and are typically used in very low permeability reservoirs such as shales (Barati and Liang, 2014). Because slickwater fluids are thinner (have lower viscosity) they do not as easily carry sand proppant into fractures, so larger volumes of water and greater pumping pressures are required to effectively transport proppants into fractures. In contrast, gelled fluids (used in "gel fracs") are more viscous, and more proppant can be transported with less water as compared to slickwater fractures (Brannon et al., 2009). Gel fracs are generally used in reservoirs with higher permeability (Barati and Liang, 2014).

The composition of a typical water-based hydraulic fracturing fluid by volume is 90% to 97% water, 2% to 10% proppant, and 2% or less additives (U.S. EPA, 2015a; OSHA, 2014a, b; Carter et al., 2013; Knappe and Fireline, 2012; Spellman, 2012; Sjolander et al., 2011; SWN, 2011). In a detailed study, the EPA analysis of FracFocus 1.0 data for nearly 39,000 wells nationally in 2011 and 2012 indicates that the fracturing fluid injected into a well consists of nearly 90% water, 10% proppant, and less than 1% additives (on a mass basis) (U.S. EPA, 2015a). The proportions of water, proppant, and additives in the fracturing fluid, and the specific additives used, can vary depending on a number of factors, including the rock type and the chemistry of the reservoir, whether oil or gas is being produced, operator preference, and to some degree on local or regional availability of chemicals (Arthur et al., 2014; Spellman, 2012; GWPC and ALL Consulting, 2009; Gupta and Valkó, 2007). Hydraulic fracturing fluid composition and chemical use changes as processes are tested and refined by companies and operators. These changes are driven by economics, scientific and technological developments, and concerns about environmental and health impacts. Further detail on hydraulic fracturing fluid systems is presented in Chapter 5.

Sources of water for hydraulic fracturing fluid include groundwater, surface water, and reused wastewater (URS Corporation, 2011; Blauch, 2010; Kargbo et al., 2010). The water may be brought to the production well from an offsite regional source via trucks or piping, or it may be more locally sourced (for example, pumped from a nearby river or a groundwater well). Selection of water source depends upon availability, cost, water quality needs, and the logistics of delivering it to the site. Figure 3-13 shows a row of water tankers storing water on a well site. Chapter 4 provides additional details on water acquisition and the amounts of water used for hydraulic fracturing.

Figure 3-13. Water tanks (blue, foreground) lined up for hydraulic fracturing at a well site in central Arkansas.
Photo credit: Martha Roberts (U.S. EPA).

Proppants are most commonly silicate minerals, primarily quartz sand (GWPC and ALL Consulting, 2009). Sand proppants can be coated with resins that make them more durable. Ceramic materials are also sometimes used as proppants due to their high strength and resistance to crushing and deformation (Beckwith, 2011).

Additives generally constitute less than 2.0% of hydraulic fracturing fluids (Carter et al., 2013; Knappe and Fireline, 2012; GWPC and ALL Consulting, 2009). The EPA analyzed additive data in the EPA FracFocus 1.0 project database and estimated that chemicals used as additives were about 0.43% (the median value by mass) of the total amount of fluid injected for hydraulic fracturing (U.S. EPA, 2015a). Given the total volume of hydraulic fracturing fluid, these small percentages of chemicals in the fluid mean that a typical hydraulic fracturing job can handle, mix, and inject tens of thousands of gallons of chemicals. Chapter 5 includes details on the number, types, and estimated quantities of chemicals typically used in hydraulic fracturing.

3.3.3 Fluid Recovery, Handling, and Disposal or Reuse

At the end of the hydraulic fracturing process, the pressurized injection is stopped and the direction of fluid flow reverses. Initially, the fluid flowing back into the well and to the surface is mostly the injected fracturing fluid (sometimes referred to as flowback). The composition of the fluid changes over time, though, and after the first few weeks or months the proportion of hydraulic fracturing fluid flowing back into the well decreases and the proportion of formation water flowing into the well and to the surface increases (NYSDEC, 2011). In this assessment, the water that flows from the subsurface through oil and gas wells to the surface as a by-product of oil and gas production is referred to as produced water. The amount of produced oil or gas flowing into the well gradually increases until it is the primary constituent of the fluid emerging from the well at the surface. Produced water continues to flow from the production well along with the oil or gas throughout the operating life of the production well (Barbot et al., 2013). See Chapter 7 for details, descriptions, and discussions of the chemical composition and quantities of produced water recovered.

Produced water is sometimes referred to as hydraulic fracturing wastewater. Along with other liquid waste collected from the well pad (such as rainwater runoff), it is typically stored temporarily on-site in pits (Figure 3-14) or tanks. This wastewater can be moved offsite via truck or pipelines for treatment and reuse or for disposal. Most hydraulic fracturing wastewater in the United States is disposed of by injection into deep, porous geologic rock formations, often located away from the production well site. This disposal-by-injection occurs not through oil and gas production wells, but through wastewater injection wells regulated by EPA Underground Injection Control (UIC) programs under the Safe Drinking Water Act.[1] See Chapter 8 for a brief discussion of wastewater injection.

Figure 3-14. A pit on the site of a hydraulic fracturing operation in central Arkansas.
Photo credit: Caroline E. Ridley (U.S. EPA).

[1] States may be given federal EPA approval to run a UIC program under the Safe Drinking Water Act. Most oil- and gas-related UIC programs are implemented by the states although some are implemented by the EPA.

Other wastewater handling options include discharge to surface water bodies either with or without treatment, evaporation or percolation pits, or reuse for subsequent fracturing operations either with or without treatment (U.S. EPA, 2012h; U.S. GAO, 2012). Decisions regarding wastewater handling are driven by factors such as cost (including costs of temporary storage and transportation), availability of facilities for treatment, reuse, or disposal, and regulations (Rassenfoss, 2011). Chapter 8 contains details of the treatment, reuse, and disposal of wastewater.

3.3.4 Oil and Gas Production

After the hydraulic fracturing activity is completed, the fracturing-related equipment is removed and operators drain, fill in with soil, and regrade pits that are no longer needed unless multiple wells are drilled and fractured on the same pad. The well pad size is reduced as the operation moves toward the production phase (NYSDEC, 2011). Prior to and during production, the operator runs production tests to determine the maximum flow rate that the well can sustain and to determine optimum equipment settings (Hyne, 2012; Schlumberger, 2006). During production, monitoring of mechanical integrity and performance (with pressure tests, corrosion monitoring, etc.) can be conducted to ensure that the well is performing as intended. Such well tests and monitoring may be required by state regulations.

Produced gas typically flows from the well through a pipe to a "separator" that separates the gas from water and any liquid oil and gas (NYSDEC, 2011). The finished gas is typically piped to a compressor station where it is pressurized and then piped to a main pipeline for sale (Hyne, 2012). Production at oil wells proceeds similarly, although oil/water or oil/water/gas separation typically occurs on the well pad, no compressor is needed, and the oil can be hauled by truck or train, or piped from the well pad to offsite storage and sale facilities.[1]

During the life of the well it may be necessary to repair components of the well and replace old equipment. Sometimes the well is re-fractured to boost production.[2] Routine maintenance activities, often referred to as "workovers," may be done with the well still in production (Vesterkjaer, 2002) or sometimes require stopping production and removing the wellhead to clean out debris or repair components of the well (Hyne, 2012). More extensive re-workings of a well, sometimes referred to as "re-completions," can include making additional perforations in the well in new sections to produce oil and/or gas from another production zone, lengthening the borehole, or drilling new horizontal extensions (laterals) from an existing borehole.

3.3.4.1 Production Rates and Duration

The production life of a well depends on a number of factors, such as the amount of oil or gas in the reservoir, the reservoir pressure, the rate of production, and the economics of well operations, including the price of oil and gas. In hydraulically fractured wells in unconventional reservoirs,

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[1] In some oil production operations, the oil reservoir being tapped may include some natural gas that is extracted along with oil through the production wells. In cases where no facilities or pipelines are in place to handle the natural gas or move it to a market, the gas can be "flared" (ignited and burned at the well site) or vented into the atmosphere.

[2] Sometimes boosting or reinvigorating production in a well is referred to as "well stimulation." In some cases, well stimulation can refer to either the initial well hydraulic fracturing event or the re-fracturing of a well.

initial high production is typically followed by a rapid drop and then a slower decline in production (Patzek et al., 2013). The production phase may be 40 to 60 years in tight gas reservoirs (Ross and King, 2007) or range from 5 to 70 years in a gas- or liquids-rich shale (King and Durham, 2015). However, because the current hydraulic fracturing-led production surge is less than a decade old with limited well production history, there is an incomplete picture of production declines and it is not known how much and for how long these wells will ultimately produce (Patzek et al., 2013).

3.3.5 Site and Well Closure

Once a well reaches the end of its useful life, it is removed from production and disconnected from any pipelines that transferred produced oil or gas offsite. The well is then sealed to prevent any movement of fluids inside or along the borehole. This is done by removing the wellhead, cutting the casing off below ground surface, and then sealing portions of the well with one or more cement or mechanical plugs placed permanently in sections of the well. Spaces between plugs may be filled with a thick clay (bentonite) or drilling mud (NPC, 2011b). State regulations identify plugging locations within the borehole and the materials for plugging (Calvert and Smith, 1994). After plugging and cementing, a steel plate is welded on top of the well casing to provide a complete seal (API, 2010). Permanently closing a well like this is called "plugging" a well. Some states require formal notification of the location of these plugged wells. Proper plugging prevents fluids at the surface from seeping down the borehole and migration of fluids through the borehole (NPC, 2011b). See Chapter 6 for more details regarding fluid movement in wells and through the borehole.

To complete site closure, any remaining production-related equipment is removed and the site land cover and topography are restored to pre-well pad conditions to the extent possible. Some surface structures from the former operations may be left in place for subsequent reuse.

3.4 How Widespread is Hydraulic Fracturing?

There is no national database or complete national registry of wells that have been hydraulically fractured. However, hydraulic fracturing activity for oil and gas production in the United States is substantial based on various reports and data sources. According to the Interstate Oil and Gas Compact Commission (IOGCC), close to 1 million wells had been hydraulically fractured in the United States by the early 2000s (IOGCC, 2002). A recent U.S. Geological Survey report estimated approximately 1 million wells with 1.8 million hydraulic fracturing treatment records from 1947 to 2010 (more than one fracturing event, or treatment, can be conducted on a single well) (Gallegos and Varela, 2015). Roughly a third of these 1 million wells were drilled and hydraulically fractured between 2000 and 2013/2014 based on estimates from FracFocus (2016); Baker Hughes (2015); Gallegos et al. (2015); DrillingInfo (2014a); IHS Inc. (2014). This timeframe marks the beginning of modern hydraulic fracturing (refer to Text Box 3-1). Figure 3-15 shows the location of the approximately 275,000 oil and gas wells that were drilled and hydraulically fractured between 2000 and 2013 across the United States based on well and locational data from DrillingInfo (DrillingInfo, 2014a).

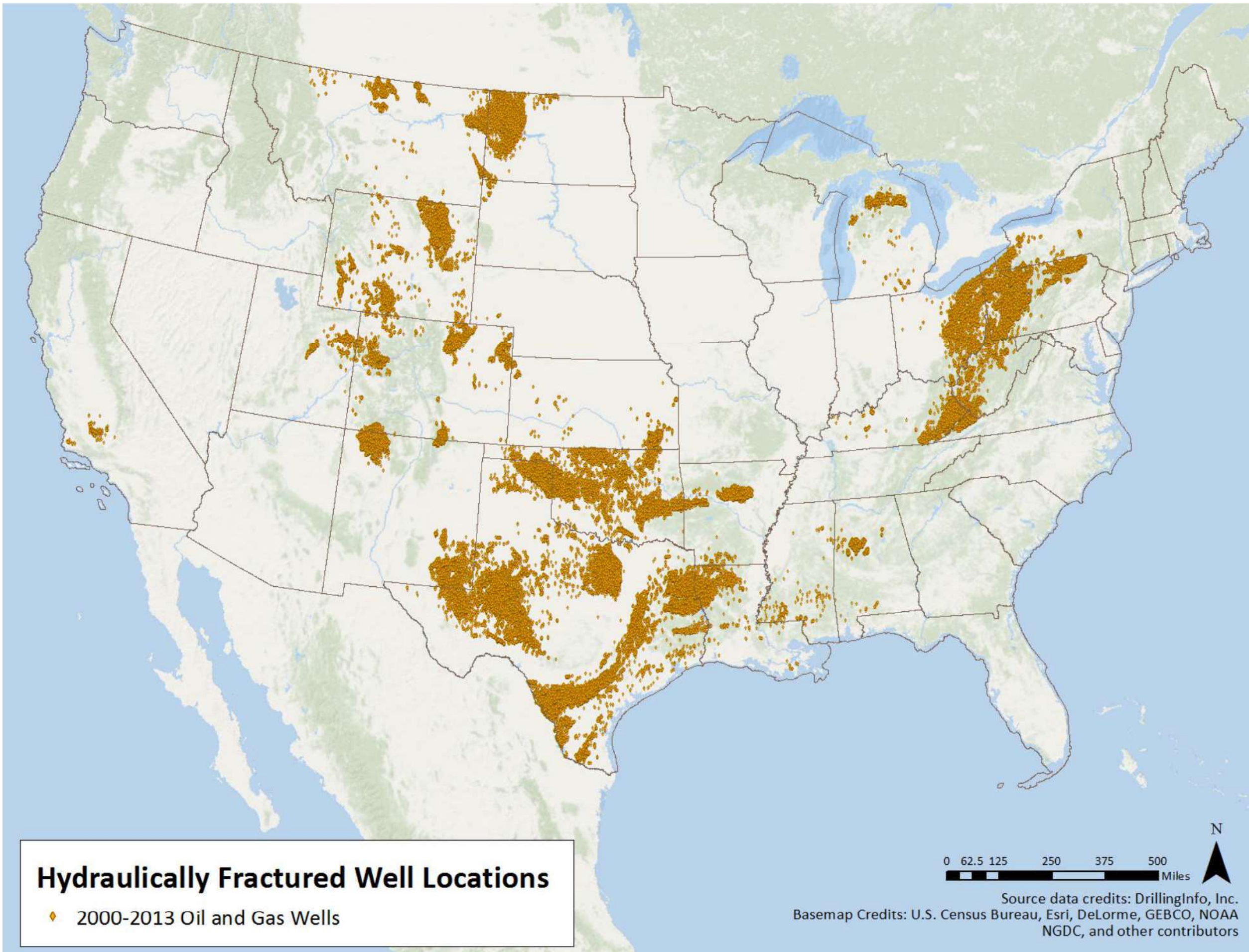

Figure 3-15. Locations of the approximately 275,000 wells drilled and hydraulically fractured between 2000 and 2013.
Based on data from the DrillingInfo Database.

The following two satellite photographs show hydraulic fracturing well sites in a regional context. These Landsat images show the locations, number, and density of hydraulic fracturing well sites across landscapes in northwest Louisiana (Figure 3-16) and western Wyoming (Figure 3-17). The orange circles around some of the well sites identify them as operations for which well information was reported to the FracFocus 1.0 registry and included in the EPA FracFocus 1.0 project database (U.S. EPA, 2015c). Note that some of the well sites in the Landsat images, taken in 2014, are for wells that were constructed after the development of the EPA FracFocus 1.0 project database.

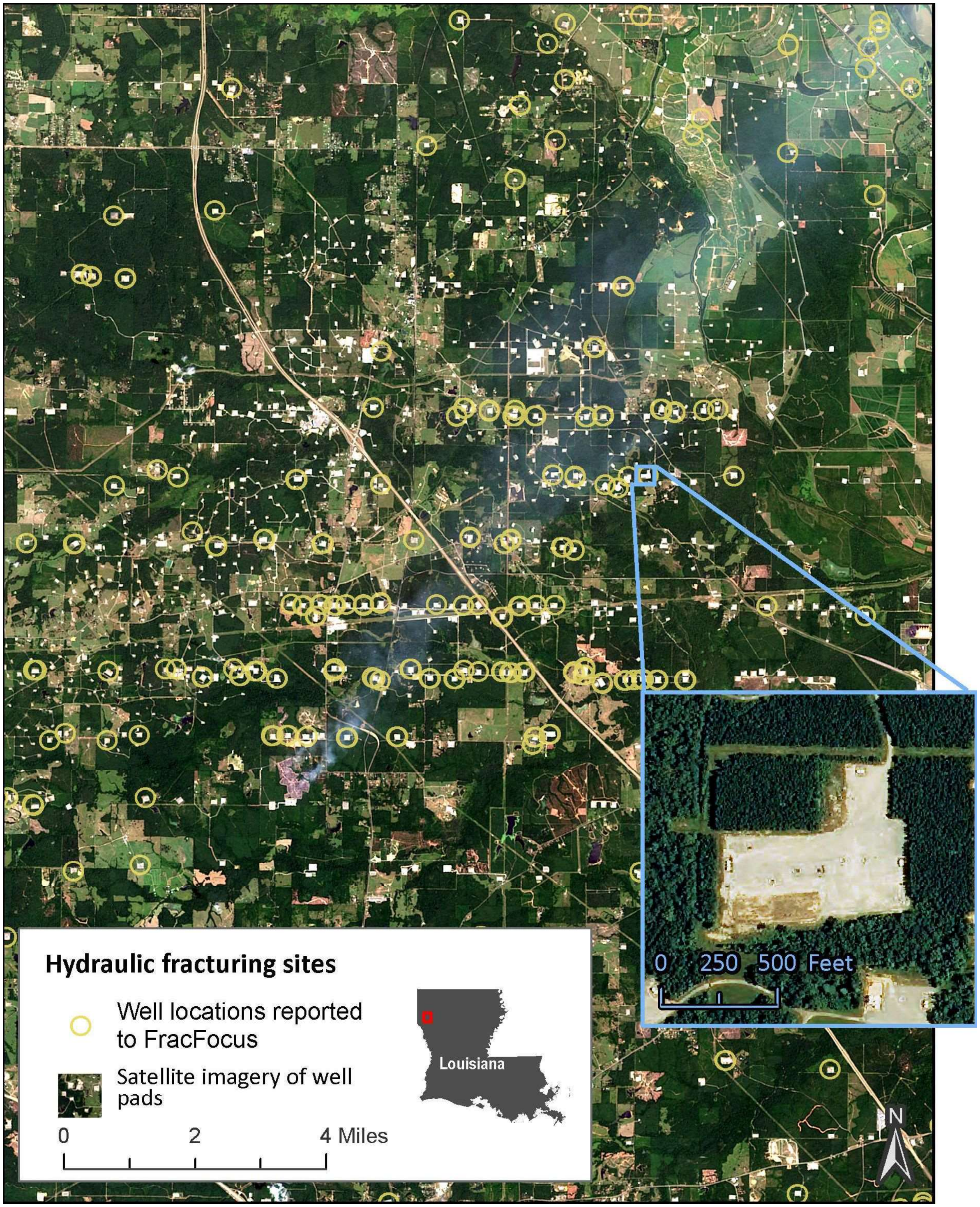

Figure 3-16. Landsat photo showing hydraulic fracturing well sites near Frierson, Louisiana. Imagery from USGS Earth Resources Observation and Science, Landsat 8 Operational Land Imager (scene LC80250382014232LGN00) captured 8/20/2014, accessed 5/1/2015 from USGS's EarthExplorer (http://earthexplorer.usgs.gov/). Inset imagery from United States Department of Agriculture National Agriculture Imagery Program (entity M 3209351_NE 15_1_20130703_20131107) captured 7/3/2013, accessed 5/1/2015 from USGS's EarthExplorer (http://earthexplorer.usgs.gov/). FracFocus well locations are from the EPA FracFocus 1.0 project database (U.S. EPA, 2015c).

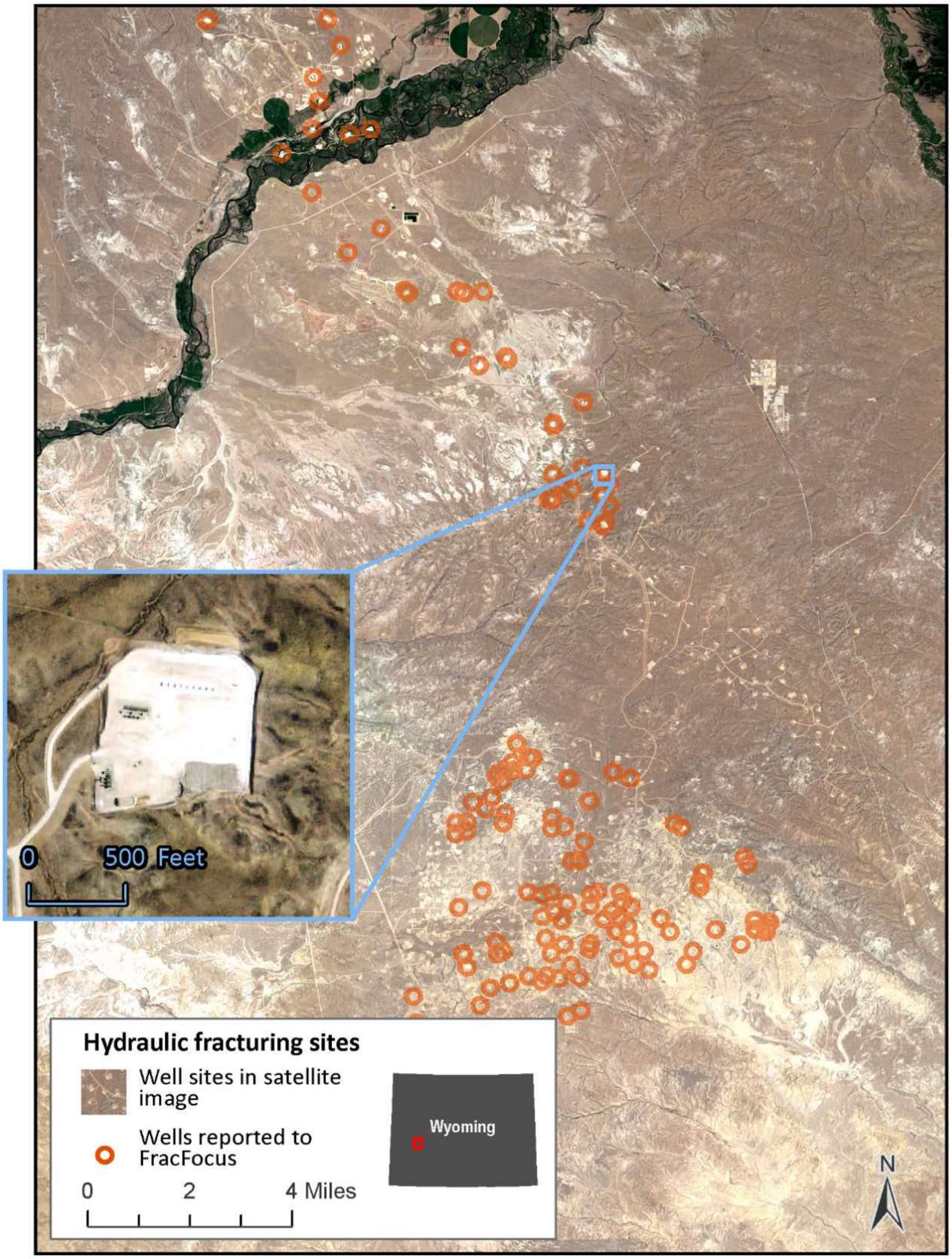

Figure 3-17. Landsat photo showing hydraulic fracturing well sites near Pinedale, Wyoming.
Imagery from USGS Earth Resources Observation and Science, Landsat 8 Operational Land Imager (scene LC80370302014188LGN00) captured 7/7/2014, accessed 5/1/2015 from USGS's EarthExplorer (http://earthexplorer.usgs.gov/). Inset imagery from United States Department of Agriculture National Agriculture Imagery Program (entity M 4210927_NW 12_1_20120623_20121004) captured 6/23/2012, accessed 5/1/2015 from USGS's EarthExplorer (http://earthexplorer.usgs.gov/). FracFocus well locations are from the EPA FracFocus 1.0 project database (U.S. EPA, 2015c).

3.4.1 Number of Wells Fractured per Year

Approximately 25,000 to 30,000 new oil and gas wells were hydraulically fractured each year in the United States between 2011 and 2014 based on data from several commercial data sets and publicly available data from organizations that track drilling and hydraulic fracturing activities (Table 3-1). These estimates do not include fracturing activity in older, existing wells (wells more than one-year old that may or may not have been hydraulically fractured in the past). Likely following the decline in oil prices (starting in about 2014) and gas prices (in about 2008), the estimated number of new hydraulically fractured wells declined to about 20,000 in 2015 according to well information submitted to FracFocus (FracFocus, 2016). Future drilling activity and the annual number of new wells will be influenced by future oil and gas prices.

Table 3-1. Estimated number of new wells hydraulically fractured nationally by year from various sources.

Data from FracFocus (2016); Baker Hughes (2015); DrillingInfo (2014a); IHS Inc. (2014) as provided in Gallegos et al. (2015).

Data Source	2011	2012	2013	2014
IHS	29,650	31,073	29,114	11,980 [a]
DrillingInfo	23,144	22,865	15,903 [b]	NA
Baker Hughes	NA	24,948	25,368	26,548
FracFocus [c]	14,025	22,471	26,400	28,285

[a] The IHS well count for 2014 is incomplete as it represents data only for 8 months (January through August).

[b] The DrillingInfo well count for 2013 is incomplete because some months are missing from some state data sets.

[c] The FracFocus 2011 and 2012 counts are underestimates because reporting well information to FracFocus was voluntary when it began in 2011. The number of states requiring reporting to FracFocus has increased over time. See FracFocus discussion below. The FracFocus well counts for 2011 and 2012 are from the EPA FracFocus 1.0 project database (U.S. EPA, 2015c) developed from the FracFocus national registry, and the FracFocus counts for 2013 and 2014 are from (FracFocus, 2016).

The Information Handling Services (IHS) annual well count estimates presented in Table 3-1 are from IHS data made available in a U.S. Geological Survey publication that evaluated well data from 2000 to 2014 (Gallegos et al., 2015). The IHS data are compiled from a variety of public and private sources and are commercially available from IHS Energy. A well is identified as a hydraulic fracturing well apparently based on well operational information. Gallegos et al. (2015) estimated, based on the IHS data, that approximately 371,000 wells were hydraulically fractured between January 2000 and August 2014.

DrillingInfo, another commercial database, is developed using data obtained from individual state oil and gas agencies (DrillingInfo, 2014a). Because DrillingInfo data does not identify whether a well has been hydraulically fractured, EPA relied on information about well orientation and the oil- or gas-producing rock formation type to infer which wells were likely hydraulically fractured. This is a similar approach to that used by the EPA for estimating oil and gas well counts for its greenhouse gas inventory work (U.S. EPA, 2013c).[1] Using this approach, we estimate from the DrillingInfo data the annual numbers presented in Table 3-1 above and also estimate that a total of approximately 275,000 oil and gas wells were drilled and hydraulically fractured between 2000 and 2013.[2]

Well counts tracked by Baker Hughes provide another estimate of new wells fractured annually. This field service company compiles new-well information based on its extensive field work in oil and gas producing areas and through state agencies. Baker Hughes started compiling this publicly available well count data in 2012, but stopped in 2014. The well count data are categorized into 14 basins containing reservoirs that are mostly unconventional (and, therefore, likely hydraulically fractured wells) and one "other" category (Baker Hughes, 2015). The well count estimates in the table above are for the 14 basins and, therefore, are considered estimates of new wells hydraulically fractured in each year.

FracFocus is a national registry for operators of hydraulically fractured oil and gas wells to report information about well location and depth, date of operations, and water and chemical use. The registry, publicly accessible online (www.fracfocus.org), was developed by the Groundwater Protection Council and the Interstate Oil and Gas Compact Commission. Submission of information to FracFocus was initially voluntary (starting in January 2011), but many states now require reporting of hydraulic fracturing well activities to FracFocus. As of May 2015, 23 states required reporting to FracFocus (Konschnik and Dayalu, 2016). The annual well counts in the table above are from the EPA FracFocus 1.0 project database for 2011 and 2012 (U.S. EPA, 2015c) and from the FracFocus 2016 Quarterly Report for 2013 and 2014 (FracFocus, 2016). The well counts in the earliest years are underestimates because not all states required oil and gas well operators to submit hydraulic fracturing data to FracFocus.[3] The FracFocus registry has undergone several updates since its launch in 2011. For more details on FracFocus, see FracFocus (2016), Konschnik and Dayalu (2016), U.S. EPA (2015a), U.S. EPA (2015c), and DOE (2014a).[4]

In addition to these new well counts, some portion of existing wells are also re-fractured. Several studies indicate that re-fracturing occurs in less than 2% of wells. Shires and Lev-On (2012)

[1] Using the DrillingInfo data, EPA assumed that all horizontal wells were hydraulically fractured in the year they started producing and assumed that all wells within a shale, coalbed, or low-permeability formation, regardless of well orientation, were hydraulically fractured in the year they started producing. More details are provided in (U.S. EPA, 2013c). Not all coalbed methane wells are hydraulically fractured, but coalbed methane wells represent gas production that sometimes uses hydraulic fracturing. Given the small percent of coalbed methane wells relative to all hydraulically fractured wells and the lack of data that distinguishes whether or not coalbed wells are hydraulically fractured, EPA included coalbed production wells into all counts of wells that are hydraulically fractured.

[2] The different well count totals from IHS and DrillingInfo are likely due to different sources of data, different approaches for defining hydraulically fractured wells in those sources, and somewhat different timeframes. The higher IHS count likely includes hydraulically fractured vertical and deviated wells in conventional reservoirs (the DrillingInfo estimate does not) and covers a time period that is a year or more longer.

[3] We compared state records of hydraulic fracturing wells in North Dakota, Pennsylvania, and West Virginia in 2011 and 2012 to those reported to FracFocus during those same years and found the FracFocus wells counts underestimated the number of fracturing jobs in those states by approximately 30% on average. See Chapter 4, Text Box 4-1.

[4] Analyses of the FracFocus data based on the EPA FracFocus 1.0 project database (U.S. EPA, 2015c) are presented in Chapter 4 regarding water volumes and in Chapter 5 regarding chemical use.

suggested that the rate of re-fracturing in natural gas wells is about 1.6% whereas analysis for the EPA's 2012 Oil and Gas Sector New Source Performance Standards indicated a re-fracture rate of 1% for gas wells (U.S. EPA, 2012f). The percentage of hydraulically fractured producing gas wells that were re-fractured in a given year ranged from 0.3% to 1% across the 1990-2013 period according to the EPA's Inventory of U.S. Greenhouse Gas Emissions and Sinks (U.S. EPA, 2015h).

The above rates are calculated by comparing the number of re-fractured wells in a single year to all hydraulically fractured wells cumulatively over a multi-year time period. However, when calculating the rates of wells that conduct re-fracturing in a given year compared to the total number of wells in that same year, the re-fracturing rate is higher. Data provided to the EPA's Greenhouse Gas Reporting Program (GHGRP) for 2011 to 2013 suggest that 9-14% of the gas wells hydraulically fractured *in each year* were pre-existing wells undergoing re-fracturing (U.S. EPA, 2014b).[1] Another rate presenting a somewhat different measure (estimated by an EPA review of well records from 2009 to 2010) found that 16% of the surveyed wells had been re-fractured at least once (U.S. EPA, 2016c).[2]

In summary, a complete count of the number of hydraulically fractured wells in the United States is hampered by a lack of a definitive and readily accessible source of information, and the fact that existing well and drilling databases and registries track information differently and therefore are not entirely comparable. There is also uncertainty about whether existing information sources are representative of the nation (or parts of the nation), whether they include data for all production well types, and to what degree they include activities in both conventional and unconventional reservoirs. Taking these limitations into account, however, it is reasonable to conclude that between approximately 25,000 and 30,000 new wells (and, likely, additional pre-existing wells) were hydraulically fractured each year in the United States from about 2011 to 2014, and approximately 20,000 wells were hydraulically fractured in 2015.

3.4.2 Hydraulic Fracturing Rates

Estimates of hydraulic fracturing rates, or the proportion of all oil and gas production wells that are hydraulically fractured, also indicate widespread use of the practice. Data from IHS Inc. (2014) indicate that approximately 62% of all new oil and gas wells in 2013 were hydraulically fractured. Data from DrillingInfo (2014a), indicate a similar rate of 64% of all new production wells in 2012. Estimates of hydraulic fracturing rates reported by states in response to an IOGCC survey tended to be considerably higher. Of eleven oil and gas producing states that responded to the survey, ten (Arkansas, Colorado, New Mexico, North Dakota, Ohio, Oklahoma, Pennsylvania, Texas, Utah, and West Virginia) estimated that 78% to 99% of new wells in their states were hydraulically fractured in 2012. Louisiana was the one exception, reporting a fracturing rate of 3.9% (IOGCC, 2015).

Hydraulic fracturing may be more prevalent in gas wells than in oil wells. A 2010 to 2011 survey of 20 natural gas production companies reported that 94% of the gas wells that they operated were

[1] The GHGRP reporting category that covers re-fracturing is "workovers with hydraulic fracturing." This re-fracturing data is for gas wells only (and does not include oil wells).

[2] This EPA report is based on a statistical survey so there is some uncertainty and a margin of error regarding the 16% re-fracturing rate. This rate includes both oil and gas wells. For more details, see Chapter 6 and U.S. EPA (2016).

fractured (Shires and Lev-On, 2012), a rate that is higher than many of the reported statistics for oil and gas together (presented in the previous paragraph). Recent EIA data on the portion of oil and gas production attributable to hydraulically fractured wells also suggest possibly higher rates of hydraulic fracturing for gas. In 2015, production from hydraulically fractured wells accounted for an estimated 67% of natural gas production (EIA, 2016d) and 51% of oil production (EIA, 2016c).

3.5 Trends and Outlook for the Future

Future oil and gas drilling and production activities, including hydraulic fracturing, will be primarily affected by the cost of well operation (partly driven by technology) and the price of oil and gas. Scenarios of increasing, stable, and decreasing hydraulic fracturing activity all appear to be possible (Weijermars, 2014). The section below provides some discussion on trends and future prospects for production quantities and locations.

Fossil fuels–oil, gas, and coal–have been dominant energy sources in the United States over the last half century (Figure 3-18). The relative importance of oil, gas, and coal has changed several times, with a significant recent shift starting in the mid-2000s as hydraulic fracturing transformed oil and gas production. Coal, the leading fossil fuel from the mid-1980s to the mid-2000s, has experienced a large decrease in production, dropping from approximately 33% of U.S. energy production in 2007 to approximately 20% (about 18 quadrillion Btus) by the end of 2015 (EIA, 2016a).[1] In contrast, natural gas production has risen to unprecedented levels, and oil production has resurged to levels not seen since the 1980s. Oil accounted for 15% of U.S. energy production in 2007 and increased to approximately 23% (about 20 quadrillion Btus) by the end of 2015, and natural gas as a portion of domestic energy production went from 31% to 37% (about 33 quadrillion Btus) (EIA, 2016a).

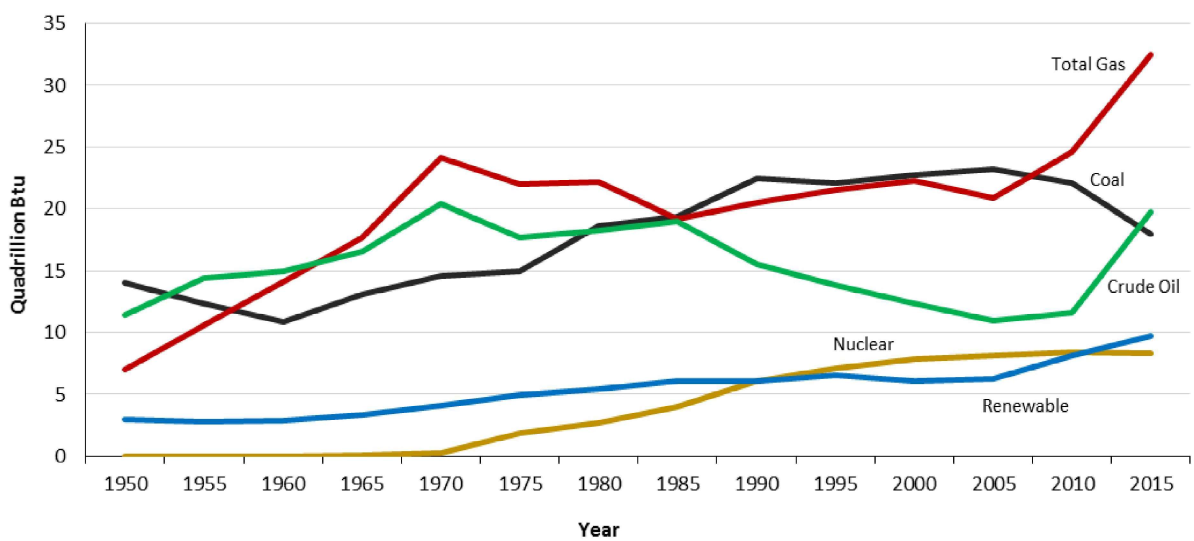

Figure 3-18. Primary U.S. energy production by source, 1950 to 2015.
Source: EIA (2016a).

[1] A Btu, or British thermal unit, is a measure of the heat (or energy) content of fuels. At the scale of national U.S. production, the graph in Figure 3-18 presents Btus in quadrillions, or a thousand million million (which is 10^{15}, or a 1 with 15 zeros).

The surge in both oil and gas production started in the mid- to late-2000s and was driven by market forces (supply and demand) and the related developments in and expanded use of hydraulic fracturing. Figure 3-19 focuses on the years 2000 to 2015 and presents data showing the steady increase in the portion of oil and gas production coming from hydraulically fractured wells. Oil and gas production associated with hydraulic fracturing was insignificant in 2000, but by 2015 it accounted for an estimated 51% of US oil production and 67% of US gas production (Figure 3-19).

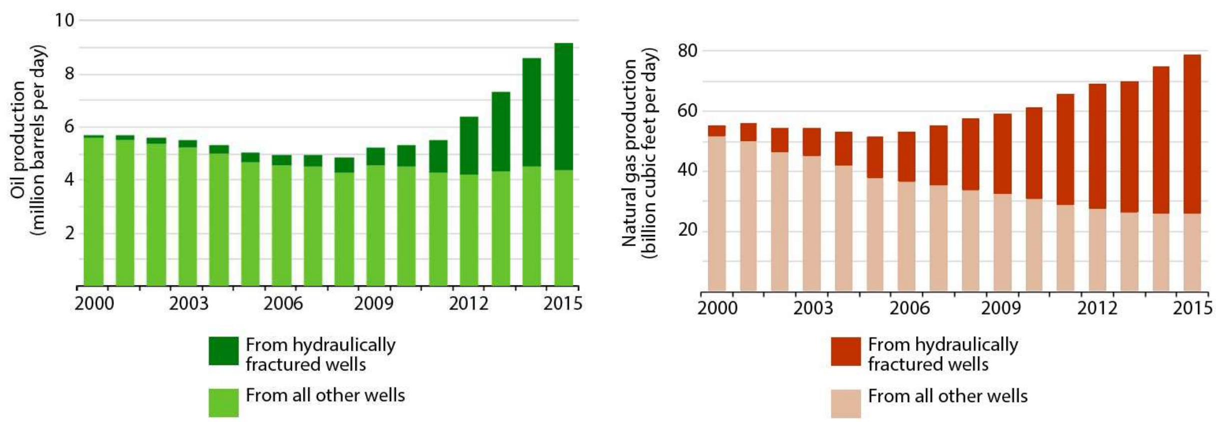

Figure 3-19. U.S. production of oil (left) and gas (right) from hydraulically fractured wells from 2000 to 2015.
Source: EIA (2016c) (oil) and EIA (2016d) (gas), based on IHS Global Insight and DrillingInfo, Inc.

Hydraulic fracturing activities are concentrated geographically in the United States. In 2011 and 2012 about half of hydraulic fracturing wells were located in Texas with another quarter located in the four states of Colorado, Pennsylvania, North Dakota, and Oklahoma (U.S. EPA, 2015c). The maps in Figure 3-20 show changes starting in 2000 in the national geography of oil and gas production through the increased use of horizontal drilling, which frequently is associated with hydraulic fracturing. Some traditional oil- and gas-producing parts of the country, such as Texas, have seen an expansion of historical production activity as a result of modern hydraulic fracturing. Pennsylvania, a leading oil- and gas-producing state a century ago, has seen a resurgence in oil and gas activity. Other states that experienced a steep increase in production, such as North Dakota, Arkansas, and Montana, have historically produced less oil and gas.

3.5.1 Natural Gas

Drilling of new natural gas wells declined markedly as natural gas prices fell in 2008 (Figure 3-21). Nevertheless, over the coming decades natural gas production is expected to increase and that increase will be associated significantly with wells that are hydraulically fractured. Projections by EIA indicate that gas production from shale (and tight oil reservoirs) will almost double from 2015 to 2040 when it will constitute nearly 70% of total natural gas production (EIA, 2016d). Slight increases are projected for production from tight gas reservoirs and coalbed methane production is expected to continue fairly steady at relatively low levels (EIA, 2016a) (Figure 3-22). These projections are dependent on estimated future prices of natural gas and other assumptions, and