EPA/600/D-11/001/February 2011/www.epa.gov/research

EPA
United States
Environmental Protection
Agency

Draft Plan to Study the Potential Impacts of Hydraulic Fracturing on Drinking Water Resources

United States Environmental Protection Agency
Office of Research and Development

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U.S. Environmental Protection Agency

Washington, D.C.

February 7, 2011

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List of Acronyms and Abbreviations

AOE	area of evaluation
API	American Petroleum Institute
DBP	disinfection byproducts
DOE	United States Department of Energy
EIA	United States Energy Information Administration
EPA	United States Environmental Protection Agency
g/mile	gram per mile
GIS	geospatial information systems
GWPC	Ground Water Protection Council
IOGCC	Interstate Oil and Gas Compact Commission
mcf/d	thousand cubic feet per day
mmcf/d	million cubic feet per day
NETL	National Energy Technology Laboratory
NGO	non-governmental organization
NIOSH	National Institute for Occupational Safety and Health
NPS	National Park Service
NYS dSGEIS	New York State Draft Supplemental Generic Environmental Impact Statement
ORD	Office of Research and Development
POTW	publicly owned treatment works
PPRTV	Provisional Peer Reviewed Toxicity Value
QA	quality assurance
QAPP	Quality Assurance Project Plan
QSAR	quantitative structure-activity relationship
SAB	Science Advisory Board
STAR	Science To Achieve Results
TDS	total dissolved solids
UIC	underground injection control
U.S.	United States
USACE	United States Army Corps of Engineers
USDW	underground source of drinking water
USGS	United States Geological Survey
VOC	volatile organic compound

EXECUTIVE SUMMARY

As natural gas production has increased, so have concerns about the potential environmental and human health impacts of hydraulic fracturing in the United States. Hydraulic fracturing, which involves the pressurized injection of water, chemical additives, and proppants into a geologic formation, induces fractures in the formation that stimulate the flow of natural gas or oil, thus increasing the volume of gas or oil that can be recovered from coalbeds, shales, and tight sands—the so-called "unconventional" reservoirs. Many concerns about hydraulic fracturing center on potential risks to drinking water resources, although other issues have been raised. In response to public concern, Congress directed the United States Environmental Protection Agency (EPA) to conduct research to examine the relationship between hydraulic fracturing and drinking water resources. This document presents the plan for the EPA study.

The overall purpose of this study is to understand the relationship between hydraulic fracturing and drinking water resources. More specifically, the study is designed to examine the conditions that may be associated with the potential contamination of drinking water resources, and to identify the factors that may lead to human exposure and risks. The scope of the proposed research includes the full lifecycle of water in hydraulic fracturing, from water acquisition through the mixing of chemicals and actual fracturing to the post-fracturing stage, including the management of flowback and produced water and its ultimate treatment and/or disposal. Figure 1 illustrates the hydraulic fracturing water lifecycle and the key research questions EPA will address through this study.

The research identified in this study plan has been designed to answer the questions listed in Figure 1 and will require a broad range of expertise, including petroleum engineering, fate and transport modeling, ground water hydrology, and toxicology. EPA will use case studies and generalized scenario evaluations as organizing constructs for the research identified in this plan.

Retrospective case studies will focus on investigating reported instances of drinking water resource contamination or other impacts in areas where hydraulic fracturing has already occurred. EPA will conduct retrospective case studies at three to five sites across the United States. The sites will be illustrative of the types of problems that have been reported to EPA during stakeholder meetings, and will provide EPA with information regarding key factors that may be associated with drinking water contamination. These studies will use existing data and possibly field sampling, modeling, and/or parallel laboratory investigations to determine the potential relationship between reported impacts and hydraulic fracturing activities.

Prospective case studies will involve sites where hydraulic fracturing will occur after the research is initiated. These case studies allow sampling and characterization of the site before, during, and after water extraction, drilling, hydraulic fracturing fluid injection, flowback, and gas production. EPA will work with industry and other stakeholders to conduct two to three prospective case studies in different regions of the United States. The data collected during prospective case studies will allow EPA to gain an understanding of hydraulic fracturing practices, evaluate changes in water quality over time, and assess the fate and transport of potential chemical contaminants.

Generalized scenario evaluations will allow EPA to explore hypothetical scenarios relating to hydraulic fracturing activities, and to identify scenarios under which hydraulic fracturing may adversely impact drinking water resources based on current understanding and available data.

To better understand potential human health effects, EPA plans to summarize the available data on the toxicity of chemicals used in or released by hydraulic fracturing, and to identify and prioritize data gaps for further investigation. The substances to be investigated include chemicals used in hydraulic fracturing fluids, their degradates and/or reaction products, and naturally occurring substances that may be released or mobilized as a result of hydraulic fracturing.

The research projects identified for this study are organized according to the hydraulic fracturing water lifecycle shown in Figure 1 and are summarized in Appendix A (p. 70). EPA is working with other federal agencies to collaborate on some aspects of the research described in this study plan. Additionally, EPA will announce requests for applications for extramural research projects related to this study as the study plan is finalized. These projects will be conducted through EPA's Science To Achieve Results (STAR) program.

All research activities associated with this study will be conducted in accordance with EPA's Quality Assurance Program for environmental data. EPA will provide periodic updates on the progress of various projects as the research is being conducted. The results of individual research projects will be made available after undergoing a quality assurance review. Early results may indicate the need for EPA to conduct further investigations to identify the key factors that may impact drinking water resources. It is expected that a report of interim research results will be completed in 2012. This interim report will contain a synthesis of EPA's research to date and will include results from retrospective case studies and initial results from scenario evaluations. However, certain portions of the work described here, including prospective case studies and work performed under STAR grants, are long-term projects that are not likely to be finished at that time. Additional reports of study findings will be published as these long-term projects progress, with a follow-up report on the study in 2014.

EPA recognizes that there are important potential research areas related to hydraulic fracturing other than those involving drinking water resources, including effects on air quality, aquatic and terrestrial ecosystem impacts, seismic risks, public safety concerns, occupational risks, and economic impacts. These topics are outside the scope of the current study, but should be examined in the future.

This draft study plan will be submitted to EPA's Science Advisory Board (SAB) for review before being finalized. Consistent with the operating procedures of the SAB, stakeholders and the public will have an opportunity to provide comments for the SAB to take into account during the review.

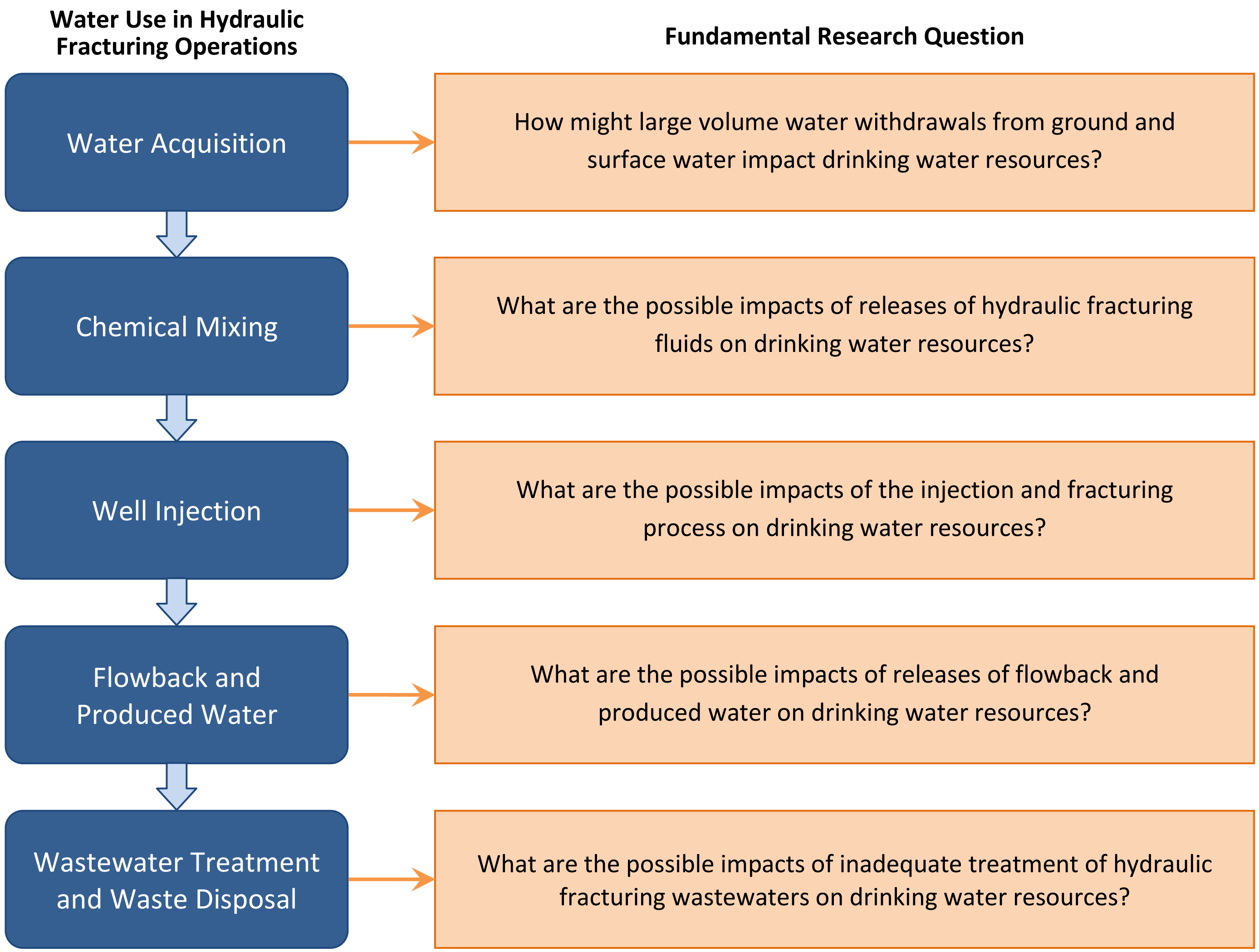


FIGURE 1. FUNDAMENTAL RESEARCH QUESTIONS POSED FOR EACH STAGE OF THE HYDRAULIC FRACTURING WATER LIFECYCLE

1 INTRODUCTION AND PURPOSE OF STUDY

Hydraulic fracturing is an important means of accessing one of the nation's most vital energy resources, natural gas. Advances in technology, along with economic and energy policy developments, have spurred a dramatic growth in the use of hydraulic fracturing across a wide range of geographic regions and geologic formations in the United States. As the use of hydraulic fracturing has increased, so have concerns about its potential impact on human health and the environment, especially with regard to possible effects on drinking water resources. These concerns have intensified as hydraulic fracturing has spread from the South and West to other settings, such as the Marcellus Shale, which extends from the southern tier of New York through parts of Pennsylvania, West Virginia, eastern Ohio, and western Maryland.

In Fiscal Year 2010, the U.S. Congress' Appropriation Conference Committee directed EPA to conduct research to examine the relationship between hydraulic fracturing and drinking water resources:

> *The conferees urge the Agency to carry out a study on the relationship between hydraulic fracturing and drinking water, using a credible approach that relies on the best available science, as well as independent sources of information. The conferees expect the study to be conducted through a transparent, peer-reviewed process that will ensure the validity and accuracy of the data. The Agency shall consult with other Federal agencies as well as appropriate State and interstate regulatory agencies in carrying out the study, which should be prepared in accordance with the Agency's quality assurance principles.*

This document presents a draft plan for EPA's research on hydraulic fracturing and drinking water resources and responds to both the request of Congress and concerns expressed by the public. For this study, EPA defines "drinking water resources" to be any body of water, ground or surface, that could currently, or in the future, produce an appropriate quantity and flow rate of water to serve as a source of drinking water for public or private water supplies. This includes both underground sources of drinking water (USDWs) and surface waters.

The overarching goal of this research is to answer the following questions:

- Can hydraulic fracturing impact drinking water resources?
- If so, what are the conditions associated with the potential impacts on drinking water resources due to hydraulic fracturing activities?

To answer these questions, EPA has identified a set of proposed research activities associated with each stage of the hydraulic fracturing water lifecycle, from water acquisition through the mixing of chemicals and actual fracturing to post-fracturing production, including the management of flowback and produced water and ultimate treatment and disposal. These research activities will identify potential sources and pathways of exposure and will provide information about the toxicity of contaminants of concern. This information can then be used to assess the potential risks to drinking water resources from hydraulic fracturing activities. Ultimately, the results of this study will provide policymakers at all levels with sound scientific knowledge that can be used in decision-making processes.

The study plan is organized as follows:

- Chapter 2 details the process for developing the study plan and the criteria for prioritizing the proposed research.
- Chapter 3 provides a brief overview of the natural gas production process.
- Chapter 4 outlines the hydraulic fracturing water lifecycle and the research questions associated with each stage of the lifecycle.
- Chapter 5 briefly describes the research approach.
- Chapter 6 provides background information on each stage of the hydraulic fracturing water lifecycle, and proposes research specific to each stage.
- Chapter 7 summarizes EPA's case study approach, which is a central component of the research plan.
- Chapter 8 describes proposed studies to characterize the toxicity and potential human health effects of substances associated with hydraulic fracturing.
- Chapter 9 presents a brief discussion of hydraulic fracturing in the context of environmental justice.
- Chapter 10 provides a short summary of how the proposed studies will address the research questions posed for each stage of the water lifecycle.
- Chapter 11 identifies additional areas of concern relating to hydraulic fracturing that are outside the scope of this study plan.

2 Process for Study Plan Development

2.1 Initial Science Advisory Board Review of the Study Plan Scope

In early Fiscal Year 2010, EPA's Office of Research and Development (ORD) developed a document that presented a proposed scope and initial design of the study (USEPA, 2010a). The document was submitted to the EPA Science Advisory Board's (SAB's) Environmental Engineering Committee for review in March 2010. The SAB is a public advisory committee that provides a balanced, expert assessment of scientific matters relevant to EPA. In its response to EPA in June 2010 (USEPA, 2010c), the SAB recommended that (1) initial research be focused on potential impacts to drinking water resources with later research investigating more general impacts on water resources, (2) engagement with stakeholders occur throughout the research process, and (3) 5 to 10 in-depth case studies at "locations selected to represent the full range of regional variability of hydraulic fracturing across the nation" be part of the research plan.

The SAB cautioned EPA against studying all aspects of oil and gas production, stating that the study should "emphasize human health and environmental concerns specific to, or significantly influenced by, hydraulic fracturing rather than on concerns common to all oil and gas production activities." This research plan, therefore, focuses on features of oil and gas production that are particular to—or closely associated with—hydraulic fracturing, and their impacts on drinking water resources.

2.2 Stakeholder Input

Stakeholder input has played, and will continue to play, an important role in the development of the hydraulic fracturing study plan and the research it will involve. EPA has implemented a strategy that engages stakeholders in dialogue and provides opportunities for input on the study scope and case study locations. The strategy also provides a means for exchanging information with experts on technical issues. EPA will continue to engage stakeholders as results from the study become available.

EPA has engaged stakeholders in the following ways:

Federal, state, and tribal partner consultations. Webinars were held with state partners in May 2010, with federal partners in June 2010, and with Indian tribes in August 2010. The state webinar included representatives from 21 states as well as representatives from the Association of State Drinking Water Administrators, the Association of State and Interstate Water Pollution Control Administrators, the Ground Water Protection Council (GWPC), and the Interstate Oil and Gas Compact Commission (IOGCC). The federal partners included the Bureau of Land Management, the U.S. Geological Survey (USGS), the U.S. Fish and Wildlife Service, the U.S. Forest Service, the U.S. Department of Energy (DOE), the U.S. Army Corps of Engineers (USACE), the National Park Service (NPS), and the Agency for Toxic Substances and Disease Registry. There were 36 registered participants for the tribal webinar representing 25 tribal governments; in addition, a meeting with the Haudenosaunee Environmental Task Force was held in August 2010 and included 20 representatives from the Onondaga, Mohawk, Tuscarora, Cayuga, and Tonawanda Seneca Nations. The purpose of these consultations was to discuss the study scope, data gaps, opportunities for sharing data and conducting joint studies, and current policies and practices for protecting drinking water resources.

Sector-specific meetings. Separate webinars were held in June 2010 with representatives from industry and non-governmental organizations (NGOs) to discuss the public engagement process, the scope of the study, coordination of data sharing, and other key issues. Overall, 176 people representing various natural gas production and service companies and industry associations participated in the webinars, as well as 64 people representing NGOs.

Informational public meetings. Public information meetings were held between July and September, 2010, in Fort Worth, Texas; Denver, Colorado; Canonsburg, Pennsylvania; and Binghamton, New York. At these meetings, EPA presented information on its reasons for studying hydraulic fracturing, an overview of what the study might include, and how stakeholders can be involved. Opportunities to present oral or written comments were provided, and EPA specifically asked for input on the following questions:

- What should be EPA's highest priorities?
- Where are the gaps in current knowledge?
- Are there data and information EPA should know about?

- Where do you recommend EPA conduct case studies?

Total attendance for all of the information public meetings exceeded 3,500 and more than 700 verbal comments were heard.

Summaries of all of the stakeholder meetings can be found at http://water.epa.gov/type/groundwater/uic/class2/hydraulicfracturing/wells_hydroout.cfm.

Other opportunities to comment. In addition to conducting the meetings listed above, EPA provided stakeholders with opportunities to submit electronic or written comments on the hydraulic fracturing study. EPA received over 5,000 comments, which are summarized in Appendix B.

2.3 Research Prioritization

In developing this proposed study plan, EPA considered the results of a review of the literature,[1] comments received from stakeholders, and input from meetings with interested parties, including other federal agencies, Indian tribes, state agencies, industry, and NGOs. EPA also considered recommendations from the initial SAB review of the study plan scope (USEPA, 2010c).

Based on stakeholder input and the expected growth in shale gas development, this study plan emphasizes hydraulic fracturing in shale formations. Portions of the proposed research, however, may provide information on hydraulic fracturing in coalbed methane reservoirs and tight sands, and EPA will pursue these research opportunities when possible.

As requested by Congress, EPA identified fundamental scientific research questions (summarized in Chapter 4) that will frame the research and help to evaluate the potential for hydraulic fracturing to impact drinking water resources. Following guidance from the SAB, EPA used a risk-based prioritization approach to identify research that addresses the most significant risks at each stage of the hydraulic fracturing water lifecycle. Other criteria considered in prioritizing proposed research activities include:

- *Relevance:* Only work that may directly inform an assessment of the potential impacts of hydraulic fracturing on drinking water resources was considered.
- *Precedence:* Work that needs to be completed before other work can be initiated received a higher priority.
- *Uniqueness of the contribution:* Relevant work already underway by others received a lower priority for investment by EPA.
- *Leverage:* Relevant work that EPA could leverage with co-investigators received a higher priority.

Application of the criteria listed above ensures that resources are provided for the areas that potentially pose the greatest risk to drinking water resources.

[1] The literature review includes information from more than 120 articles, reports, presentations, and other materials. Information resulting from this literature review is incorporated throughout this study plan.

2.4 Next Steps

The next steps in the development and implementation of the study plan are:

- The draft study plan will be sent to the SAB for peer review and made available to the public in February 2011. The SAB will have an opportunity to hear verbal comments and read written comments from stakeholders and the public during their March 2011 public meeting to review the draft study plan. EPA will respond to comments from the SAB, and will adjust the study plan as appropriate.
- EPA will conduct the research described in this plan, and plans to announce requests for applications for extramural research projects in the early part of 2011 for research that is related to this study. Additionally, it is likely that other federal agencies will cooperate with EPA on some aspects of the research.
- The research projects will begin in the early part of 2011 after EPA receives and responds to comments from the SAB.
- Periodic updates will be provided on the progress of the research projects.
- A study report providing interim research results is expected to be completed in 2012 and will be made available to the public.
- Additional study results will be published as individual research projects are completed, with an additional report expected to be published in 2014.

2.5 Interagency Cooperation

In a series of meetings, EPA consulted with several key state and federal agencies regarding research related to hydraulic fracturing. EPA met with representatives from DOE and DOE's National Energy Technology Laboratory (NETL), USGS, USACE, and IOGCC to learn about research that those agencies are involved in and to identify opportunities for collaboration and leverage. EPA also participated in a series of meetings in which a number of other federal agencies participated. As a result of those meetings, EPA has identified work underway by others that can inform its own study. EPA continues to discuss opportunities to collaborate on information gathering and research efforts with other agencies. In particular, the Agency plans to coordinate with DOE and USGS on existing and future research projects. Regular meetings between EPA and DOE will be set up to follow each agency's research on hydraulic fracturing and to exchange information among experts.

Federal agencies have also had an opportunity to provide comments on this draft study plan through an interagency review. EPA received comments from the Agency for Toxic Substances and Disease Registry, DOE, the Bureau of Land Management, USGS, the U.S. Fish and Wildlife Service, the Office of Management and Budget, the U.S. Energy Information Administration (EIA), the Occupational Safety and Health Administration, and the National Institute of Occupational Health and Safety. These comments have been reviewed and modifications to the study plan have been made where appropriate.

2.6 Quality Assurance

All EPA-funded research projects, both intramural and extramural, that generate or use environmental data to make conclusions or recommendations must comply with Agency Quality Assurance (QA) Program requirements (USEPA, 2002b). EPA recognizes the value of using a graded approach to QA such that QA requirements are based on the importance of the work to which the QA program applies. Given the significant national interest in the results of hydraulic fracturing related research, the following rigorous QA approach will be used:

- Research projects must comply with Agency requirements and guidance for quality assurance project plans (QAPPs), including the use of data quality objectives.
- Audits will be conducted as described in an audit plan and will include technical systems audits, audits of data quality, and data quality assessments.
- Performance evaluations of measurement systems will be conducted (if available).
- QA review of products[2] will occur.
- Reports must have a readily identifiable QA section.
- Research records will be managed according to EPA's record schedule for *Applied and Directed Scientific Research.*

All EPA organizations involved with the generation or use of environmental data are supported by QA professionals who oversee the implementation of the QA program for their organization. Given the cross-organizational nature of the proposed research, it is necessary to identify a Program Quality Assurance Manager who will coordinate the rigorous QA approach described above and oversee its implementation across all participating organizations. Typically, this person is associated with the organization that has the technical lead for the research program. The organizational complexity of the hydraulic fracturing research effort also demands that a quality management plan be written to define the QA-related policies, procedures, roles, responsibilities, and authorities for this research. The plan will document consistent QA procedures and practices that may otherwise vary between organizations.

3 Overview of Unconventional Natural Gas Production

Hydraulic fracturing is often used to stimulate the production of oil and gas from unconventional oil and gas deposits, which include shales, coalbeds, and tight sands.[3] Unconventional natural gas deposits generally contain a lower concentration of natural gas over broader areas that have a lower permeability than conventional gas reservoirs, which are typically porous and permeable and do not require additional stimulation for production (Vidas and Hugman, 2008). Similarly, hydraulic fracturing can make oil production from shale cost-effective.

[2] Applicable products may include reports, journal articles, symposium/conference papers, extended abstracts, computer products/software/models/databases, and scientific data.

[3] The use of hydraulic fracturing is not limited to natural gas production. It may also be used when drilling for oil (STRONGER, 2010), and has been used for other purposes, such as removing contaminants from soil and ground water at waste disposal sites, make geothermal wells more productive, and to complete water wells (Nemat-Nassar et al., 1983; New Hampshire Department of Environmental Services, 2010).

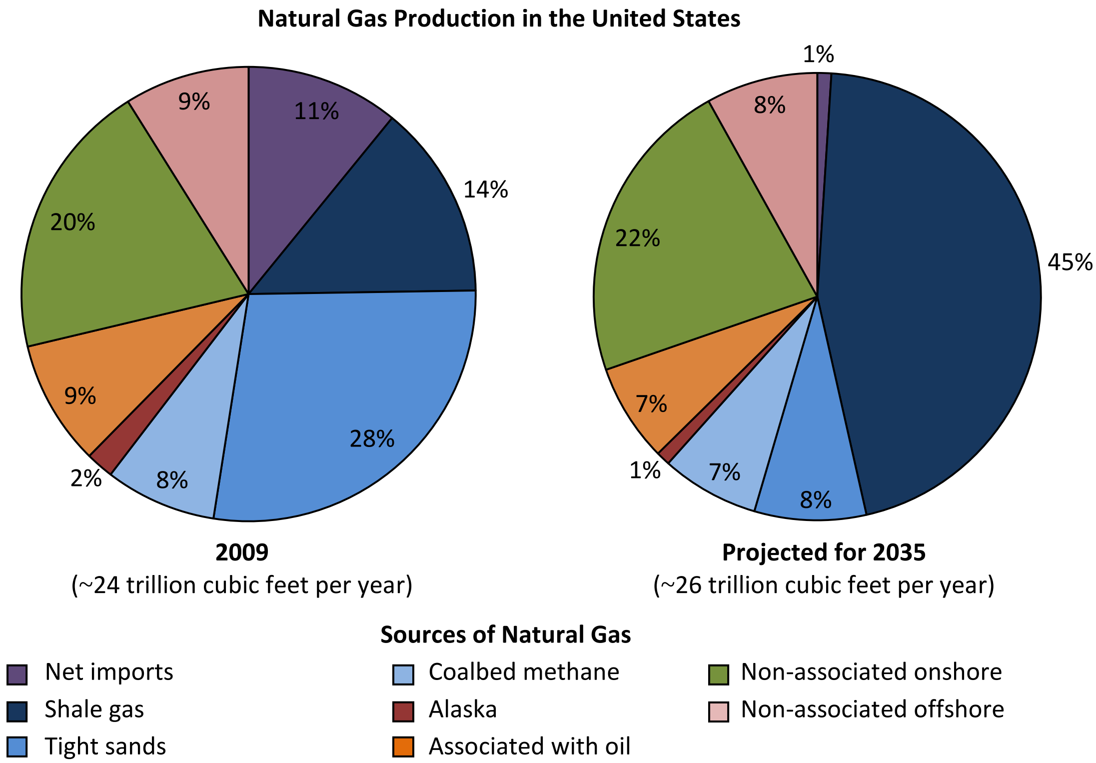
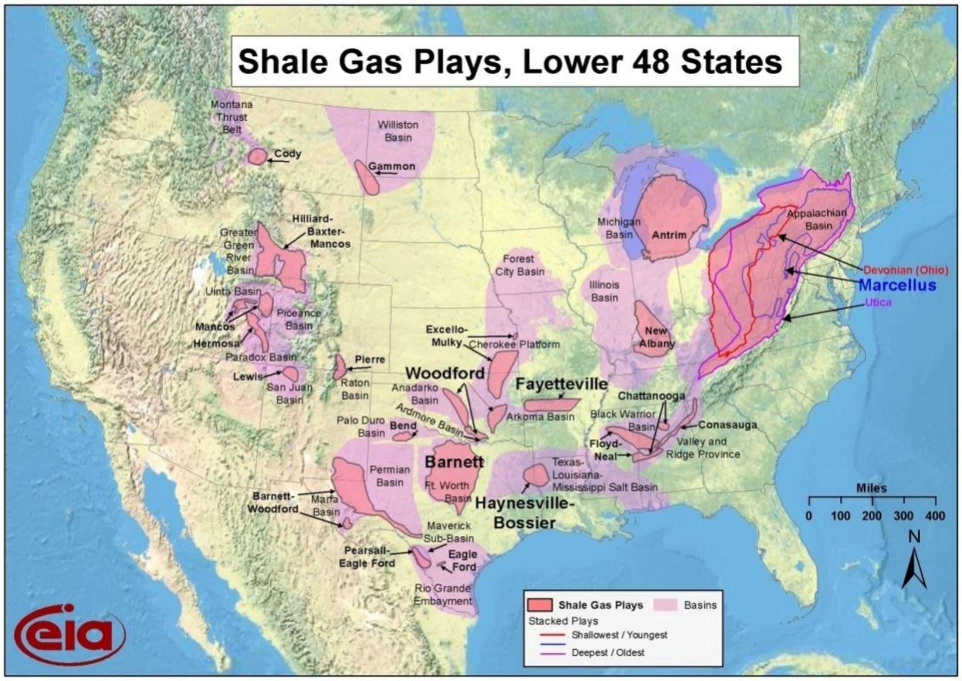


FIGURE 2. NATURAL GAS PRODUCTION IN THE UNITED STATES (DATA FROM USEIA, 2010)

Unconventional natural gas development has become an increasingly important source of natural gas in the United States in recent years. It accounted for 28 percent of total natural gas production in 1998 (Arthur et al., 2008). Figure 2 illustrates that this percentage has risen to 50 percent in 2009 and is projected to increase to 60 percent in 2035 (USEIA, 2010). This rise in hydraulic fracturing activities is also reflected in the number of drilling rigs operating in the United States; there were 603 horizontal gas rigs in June 2010, up 277 from the previous year (Baker Hughes, 2010). Most of these were involved in gas extraction via hydraulic fracturing.

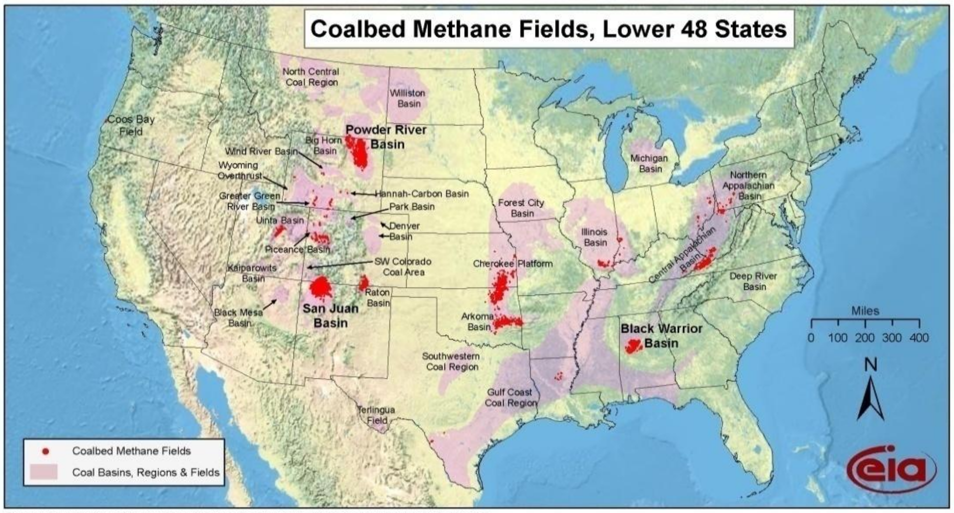


Source: Energy Information Administration based on data from various published studies.
Updated: March 10, 2010

FIGURE 3. SHALE GAS PLAYS IN THE CONTIGUOUS UNITED STATES

Shale gas extraction. Shale rock formations have become an important source of natural gas in the United States, and can be found in many locations across the country as shown in Figure 3. Depths for shale gas formations (commonly referring to as "plays") can range from 500 to 13,500 feet below the earth's surface (GWPC and ALL Consulting, 2009). At the end of 2009, the five most productive shale gas fields in the country—the Barnett, Haynesville, Fayetteville, Woodford, and Marcellus Shales—were producing 8.3 billion cubic feet of natural gas per day (Zoback et al., 2010). According to recent figures from EIA, shale gas constituted 14 percent of the total U.S. natural gas supply in 2009, and will constitute 45 percent of the U.S. gas supply in 2035 if current trends and policies persist (USEIA, 2010).

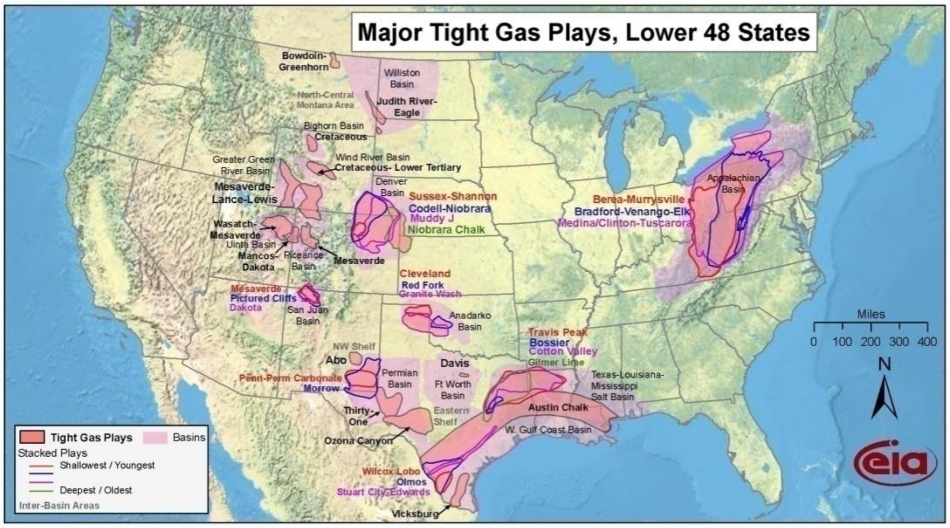
Oil production has similarly increased in oil-bearing shales following the increased use of hydraulic fracturing. Proven oil production from shales has concentrated primarily in the Williston Basin in North Dakota, although oil production is increasing in the Eagle Ford Shale in Texas and the Niobrara Shale in Colorado, Nebraska, and Wyoming (USEIA, 2010; OilShaleGas.com, 2010).



Source: Energy Information Administration based on data from USGS and various published studies
Updated: April 8, 2009

FIGURE 4. COALBED METHANE DEPOSITS IN THE CONTIGUOUS UNITED STATES

Production of coalbed methane. Coalbed methane is formed as part of the geological process of coal generation and is contained in varying quantities within all coal. Depths of coalbed methane formations range from 450 feet to greater than 10,000 feet (Rogers et al., 2007; National Research Council, 2010). At greater depths, however, the permeability decreases and production is lower. Below 7,000 feet, efficient production of coalbed methane can be challenging from a cost-effectiveness perspective (Rogers et al., 2007). Figure displays coalbed methane reservoirs in the contiguous United States. In 1984, there were very few coalbed methane wells in the United States; by 1990, there were almost 8,000, and in 2000, there were almost 14,000 (USEPA, 2004). In 2009, natural gas production from coalbed methane reservoirs made up 8 percent of the total U.S. natural gas production; this percentage would remain relatively constant over the next 20 years if current trends and policies persist (USEIA, 2010). Production of gas from coalbeds almost always requires hydraulic fracturing (USEPA, 2004), and many existing coalbed methane wells that have not been fractured are now being considered for hydraulic fracturing.



Source: Energy Information Administration based on data from various published studies
Updated: June 6, 2010

FIGURE 5. MAJOR TIGHT GAS PLAYS IN THE CONTIGUOUS UNITED STATES

Tight sands. Tight sands (gas-bearing, fine-grained sandstones or carbonates with a low permeability) accounted for 28 percent of total gas production in the United States in 2009 (USEIA, 2010), but may account for as much as 35 percent of the nation's recoverable gas reserves (Oil and Gas Investor, 2005). Figure 5 shows the locations of tight gas plays in the United States. Typical depths of tight sand formations range from 1,200 to 20,000 feet across the United States (Prouty, 2001). Almost all tight sand reservoirs require hydraulic fracturing to release gas unless natural fractures are present.

The following sections provide an overview of unconventional natural gas production, including site selection and preparation, well construction and development, hydraulic fracturing, and natural gas production. The current regulatory framework that governs hydraulic fracturing activities is briefly described in Section 3.5.

3.1 Site Selection and Preparation

The hydraulic fracturing process begins with exploring possible well sites, followed by selecting and preparing an appropriate site. In general, appropriate sites are those that are considered most likely to yield substantial quantities of natural gas at minimum cost. Other factors, however, may be considered in the selection process. These include proximity to buildings and other infrastructure, geologic considerations, and proximity to natural gas pipelines or the feasibility of installing new pipelines (Chesapeake Energy, 2009). Laws and regulations may also influence site selection. For example, applicants applying for a Marcellus Shale natural gas permit in Pennsylvania must provide information about proximity to coal seams and distances from surface waters and water supplies (PADEP, 2010a).

During site preparation, an area is cleared to provide space to accommodate one or more wellheads; pits for holding water, used drilling fluids, and other materials; and space for trucks and other equipment. At a typical shale gas production site, a 3- to 5-acre space is needed in addition to access roads for transporting materials to and from the well site. If not already present, both the site and access roads need to be built or improved to support heavy equipment.

3.2 Well Construction and Development

Current practices in drilling for natural gas include drilling vertical, horizontal, and directional (S-shaped) wells. Figure 6 depicts two different well completions, one in a typical deep shale gas-bearing formation like the Marcellus Shale (6a) and one in a shallower environment (6b) often encountered where coalbed methane or tight sand gas production takes place. The figures demonstrate a significant difference in the challenges posed for protecting underground drinking water resources. The deep shale gas environment shown in Figure 6a typically has several thousand feet of rock formation separating underground drinking water resources, while Figure 6b shows that gas production can take place at shallow depths that also contain underground sources of drinking water. The water well in Figure 6b illustrates the relative depths of a gas well and a water well.

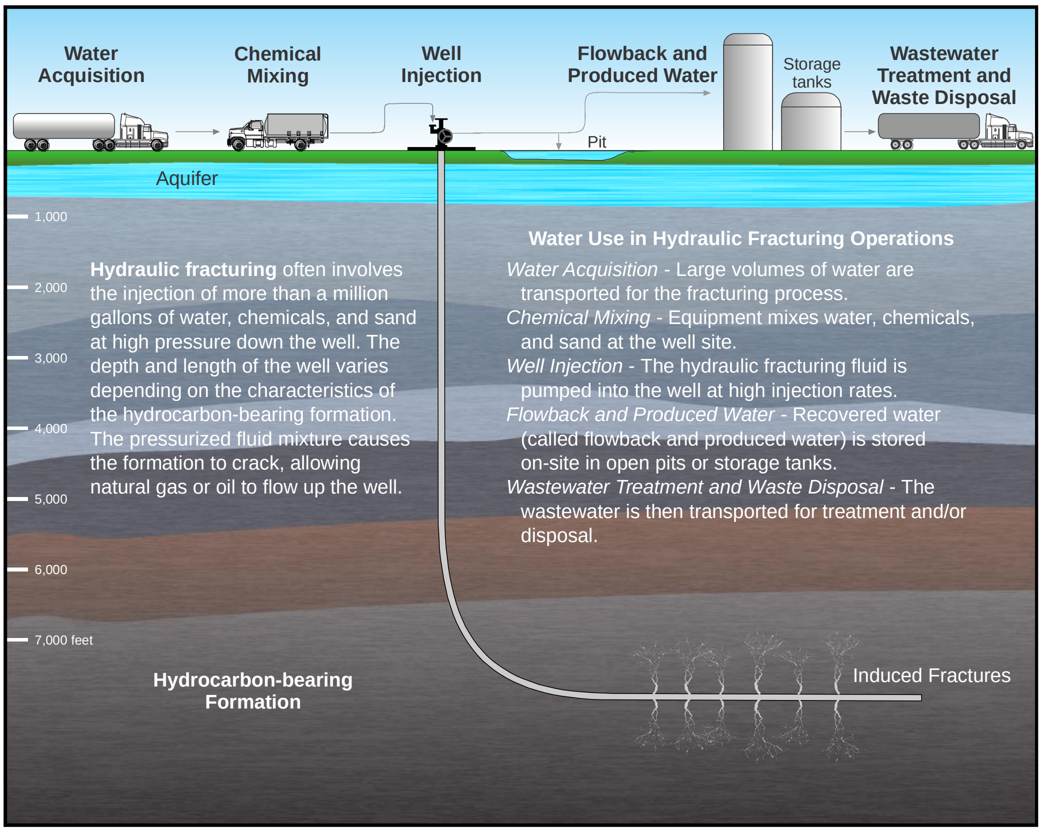


FIGURE 6a. ILLUSTRATION OF A HORIZONTAL WELL SHOWING THE WATER LIFECYCLE IN HYDRAULIC FRACTURING

Figure 6a depicts a horizontal well, which is composed of both vertical and horizontal legs. The depth and length of the well varies with the location and properties of the gas-containing formation. In unconventional cases, the well can extend more than a mile below the ground surface (Chesapeake Energy, 2010) while the "toe" of the horizontal leg can be almost 2 miles from the vertical leg (Zoback et al., 2010). Horizontal drilling provides more exposure to a formation than a vertical well does;

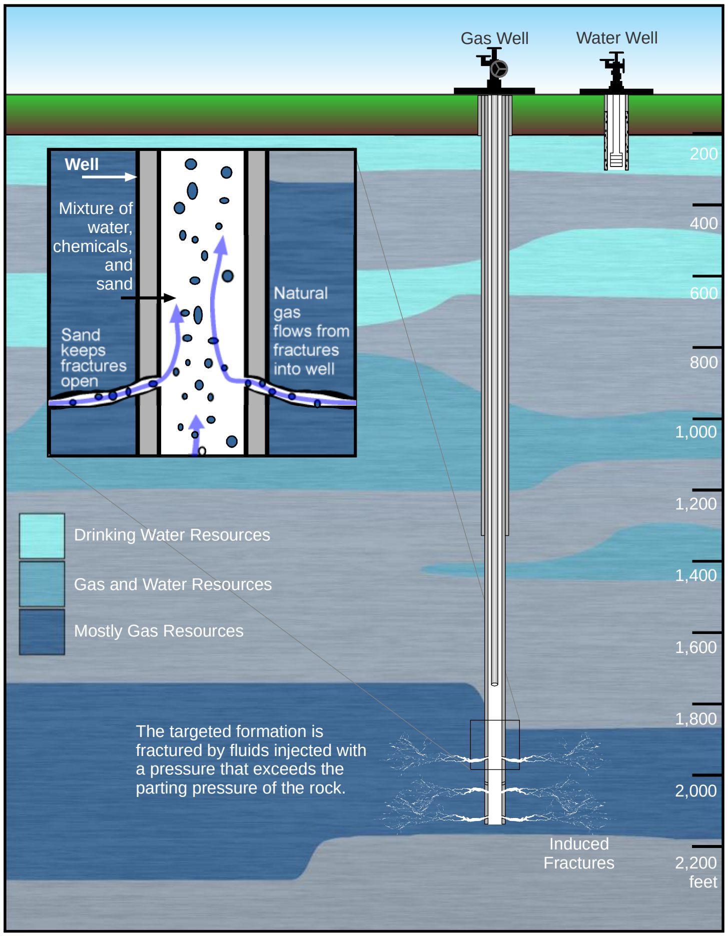


FIGURE 6b. ILLUSTRATION OF A VERTICAL WELL WHERE HYDRAULIC FRACTURING OCCURS NEAR AN UNDERGROUND SOURCE OF DRINKING WATER

therefore, it increases recovery of natural gas and makes drilling more economical. It may also have the advantage of limiting environmental disturbances on the surface because fewer wells are needed to access the natural gas resources in a particular area (GWPC and ALL Consulting, 2009).

The technique of multilateral drilling is becoming more prevalent in gas production in the Marcellus Shale region (Kargbo et al., 2010) and elsewhere. In multilateral drilling, two or more horizontal production holes are drilled from a single surface location (Ruszka, 2007) to create an arrangement resembling an upside-down tree, with the vertical portion of the well as the "trunk," and multiple "branches" extending out from it in different directions and at different depths.

In all wells, casing and cement are installed to contain the contents of the well in an effort to prevent contamination of the surrounding subsurface formations, especially USDWs. The high injection pressures associated with the hydraulic fracturing process, and the increased potential for aquifer contamination due to the close proximity of the aquifer to the well, make cementing and casing activities a crucial step in protecting ground water. The process of constructing a well is described in greater detail later in the study plan.

3.3 Hydraulic Fracturing

After the well is constructed and perforated, the targeted formation (shale, coalbed, or tight sands) is hydraulically fractured to stimulate natural gas production. As shown in Figure 6a, the hydraulic fracturing process requires large volumes of water that must be transported to the well site. Once on-site, the water is mixed with chemicals and a propping agent (called a proppant) such as sand, bauxite, or ceramic beads. The resulting hydraulic fracturing fluid is pumped down the well under high pressures, causing the targeted formation to fracture. As the injection pressure is reduced, the fluid is returned to the surface, leaving the proppant behind to keep the fractures open. The inset in Figure 6b illustrates how the resulting fractures create pathways in otherwise impermeable gas-containing formations, resulting in gas flow to the well for production. A portion of the injected fracturing fluid (water, chemical additives, and proppant), as well as naturally occurring substances released from the targeted formation, is then returned to the surface as flowback and produced water. These wastewaters are stored on-site in tanks or pits before being transported for treatment, disposal, land application, and/or discharge.

3.4 Well Production

Natural gas production rates can vary between basins as well as within a basin, depending on geologic factors and completion techniques. For example, the average well production rates for coalbed methane formations range from 50 to 500 thousand cubic feet per day (mcf/d) across the United States with maximum production rates reaching 20 million cubic feet per day (mmcf/d) in the San Juan basin and 1 mmcf/d in the Raton Basin (Rogers et al., 2007). The New York State Draft Supplemental Generic Environmental Impact Statement (NYS dSGEIS) for the Marcellus Shale cites industry estimates that a typical well will initially produce 2.8 mmcf/d; the production rate will decrease to 550 mcf/d after 5 years and 225 mcf/d after 10 years, after which it will drop approximately 3 percent a year (NYSDEC, 2009). A study of actual production rates in the Barnett Shale found that the average well produces about 800 mmcf during its lifetime, which averages about 7.5 years (Berman, 2009).

Refracturing is possible once an oil or gas well begins to approach the point where it is no longer cost-effectively producing hydrocarbons. Zoback et al. (2010) maintain that shale gas wells are rarely refractured. Berman (2009), however, claims that wells may be refractured once they are no longer profitable. The NYS dSGEIS estimates that wells may be refractured after roughly five years of service (NYSDEC, 2009).

3.5 Regulatory Framework

Hydraulic fracturing for oil and gas production wells is typically addressed by state oil and gas boards or equivalent state natural resource agencies. However, EPA retains authority to address many issues related to hydraulic fracturing under its environmental statutes. The major statutes include the Clean Air Act; the Resource Conservation and Recovery Act; the Clean Water Act; the Safe Drinking Water Act; the Comprehensive Environmental Response, Compensation and Liability Act; the Toxic Substances Control Act; and the National Environmental Policy Act. EPA does not expect to address the efficacy of the regulatory framework as part of this investigation. However, EPA may assess existing state regulations in a separate effort.

4 The Hydraulic Fracturing Water Lifecycle

Figure 7 illustrates the key stages of the hydraulic fracturing water lifecycle—from water acquisition to wastewater treatment and disposal—and the potential drinking water issues associated with each stage.

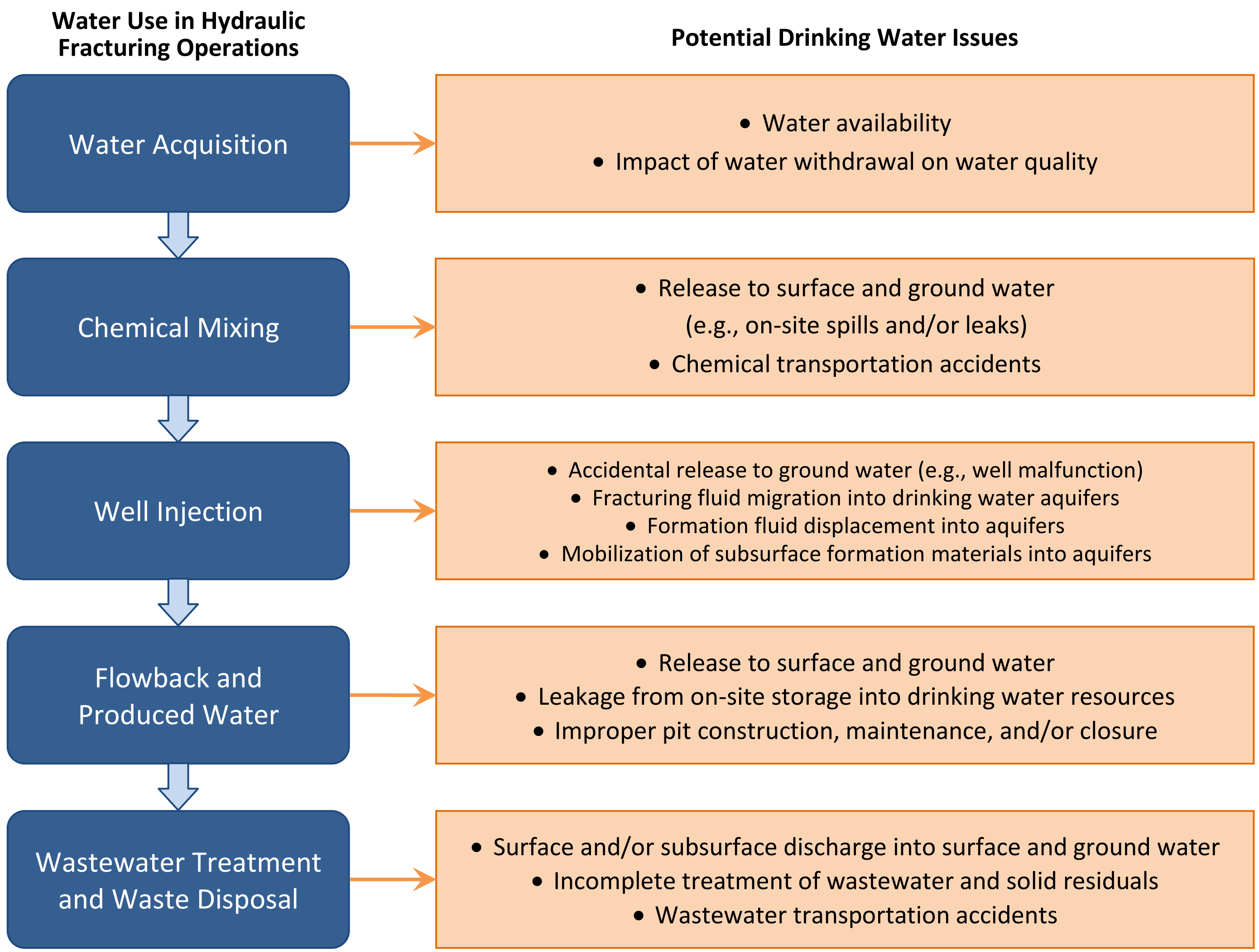


FIGURE 7. WATER USE IN HYDRAULIC FRACTURING OPERATIONS

Summarized below are the fundamental research questions EPA has identified for each stage of the hydraulic fracturing water lifecycle.

- *Water acquisition:* How might large volume water withdrawals from ground and surface water impact drinking water resources?
- *Chemical mixing:* What are the possible impacts of releases of hydraulic fracturing fluids on drinking water resources?
- *Well injection:* What are the possible impacts of the injection and fracturing process on drinking water resources?
- *Flowback and produced water:* What are the possible impacts of releases of flowback and produced water on drinking water resources?
- *Wastewater treatment and waste disposal:* What are the possible impacts of inadequate treatment of hydraulic fracturing wastewaters on drinking water resources?

The next chapter outlines the research approach and activities needed to answer these questions.

5 APPROACH

The highly complex nature of the problems to be studied will require a broad range of scientific expertise in environmental and petroleum engineering, ground water hydrology, fate and transport modeling, and toxicology, as well as many other areas. EPA will need to take a transdisciplinary research approach that integrates various types of expertise from inside and outside the EPA.

Case studies and *generalized scenario evaluations* provide organizing constructs for the research that will be used to address the key questions associated with each of the five water cycle stages of hydraulic fracturing. Table 1 shows the objectives for the case studies, both retrospective and prospective, and the scenario evaluations. Each of these approaches is briefly described below.

TABLE 1. RELATIONSHIP BETWEEN CASE STUDIES AND SCENARIO EVALUATIONS

Activity	**Objectives**
Case studies	
Retrospective	Perform a forensic analysis of sites with reported contamination to understand the underlying mechanisms and potential impacts on drinking water resources
Prospective	Develop understanding of hydraulic fracturing processes and their potential impacts on drinking water resources
Scenario evaluation	Assess the potential for hydraulic fracturing to impact drinking water resources based on knowledge developed

5.1 CASE STUDIES

Case studies are widely used to conduct in-depth investigations of complex topics and provide a systematic framework for investigating the relationship among relevant factors. In conjunction with other elements of the research program, case studies can help to determine whether drinking water resources are impacted by hydraulic fracturing, the extent and possible causes of any impacts, and what management practices are, or may be, used to avoid or mitigate such impacts. Additionally, case studies may provide data and model inputs to assess the fate and transport of fluids and contaminants in different regions and geologic settings.

Retrospective case studies are focused on investigating reported instances of drinking water resource contamination in areas where hydraulic fracturing events have already occurred. The goal is to determine whether or not the reported impacts are due to hydraulic fracturing activities. These studies will use existing data and will include environmental field sampling, modeling, and/or parallel laboratory investigations.

Prospective case studies involve sites where hydraulic fracturing will be implemented after the research is initiated. These cases allow sampling and characterization of the site prior to, during, and after drilling, water extraction, injection of the fracturing fluid, flowback, and production. At each step in the process, data will be collected to characterize both the pre- and post-fracturing conditions at the site. This progressive data collection will allow EPA to evaluate changes in water availability and quality, as well as other factors, over time to gain a better understanding of the impacts of hydraulic fracturing on drinking water resources. Prospective case studies can also provide data with which models of hydraulic fracturing and associated processes, such as fate and transport of chemical contaminants, can be evaluated and improved.

Retrospective and prospective case studies are discussed further in Chapter 7.

5.2 Scenario Evaluation

The objective of this approach is to explore realistic, hypothetical scenarios across the hydraulic fracturing water lifecycle that may result in adverse impacts to drinking water resources based on current understanding and available data. The scenarios will include a reference case involving typical management and engineering practices in representative geologic settings. Typical management and engineering practices will be based on what EPA learns from case studies as well as the minimum requirements imposed by state regulatory agencies. Potential modes of failure, both in terms of engineering controls and geologic characteristics, will be introduced and modeled to represent various states of system vulnerability. The scenario evaluations will produce insights into site-specific and regional vulnerabilities.

The proposed applications of scenario evaluation will be described in detail for each stage of the hydraulic fracturing water lifecycle in the next chapter.

5.3 Tools

Various combinations of the following four general tools or activities will be used to conduct the case studies and scenario evaluations:

Existing data evaluation. Various existing data support the proposed hydraulic fracturing research study, including mapped data, surface water discharge data, chemical data, and site data. These data are available from a variety of sources, such as state regulatory agencies, federal agencies, industry, and public sources. To support this study, EPA has specifically requested data from nine hydraulic fracturing service companies. As detailed in Appendix C, EPA asked for data on the chemical composition of fluids used in the fracturing process, the health and environmental impacts of the chemicals, standard operating procedures, and locations where fracturing has been conducted or is planned. The hydraulic fracturing service companies have claimed this data to be confidential business information.

Field monitoring. EPA will collect field samples during both retrospective and prospective case studies to look for the migration of chemical and gas contaminants into drinking water resources as a result of hydraulic fracturing activities. Direct studies of field sites can also assess the behavior of chemicals in the environment by characterizing the flow and transport of chemicals through heterogeneous media on a scale that is not represented in the laboratory.

Laboratory-scale experimentation/analysis. Laboratory studies will be necessary to develop and refine analytical methods needed to analyze samples collected during field monitoring activities. For hydraulic fracturing-related chemicals without extensive study, laboratory experimentation may be needed to determine the processes that control the transport and ultimate fate of the chemicals, including sorption and biodegradation.

Modeling. Modeling is a tool for integrating diverse phenomena to enhance understanding of environmental exposures. When sufficiently tested, models can also allow alternate hypothesis testing, which can help to determine the plausibility of contamination of drinking water resources due to hydraulic fracturing activities. Models may also be able to identify the factors that are the most important in understanding hydraulic fracturing impacts on drinking water resources.

6 Proposed Research

This chapter is organized by the hydraulic fracturing water lifecycle depicted in Figure 7 and the associated fundamental research questions outlined in Chapter 4. Each section of this chapter provides relevant background information on a water cycle stage, as well as identifying a series of more specific questions that need to be researched in order to answer one of these fundamental questions. These secondary research questions are listed in Table 2. Proposed research activities and potential research outcomes are outlined at the end of the discussion of each stage of the water lifecycle.

TABLE 2. HYDRAULIC FRACTURING RESEARCH QUESTIONS

Water Lifecycle Stage	Fundamental Research Question	Secondary Research Questions
Water acquisition	How might large volume water withdrawals from ground and surface water impact drinking water resources?	• What are the impacts on water availability? • What are the impacts on water quality?
Chemical mixing	What are the possible impacts of accidental releases of hydraulic fracturing fluids on drinking water resources?	• What is the composition of hydraulic fracturing fluids and what are the toxic effects of these constituents? • What factors may influence the likelihood of contamination of drinking water resources? • How effective are mitigation approaches in reducing impacts to drinking water resources?
Well injection	What are the possible impacts of the injection and fracturing process on drinking water resources?	• How effective are well construction practices at containing gases and fluids before, during, and after fracturing? • What are the potential impacts of pre-existing artificial or natural pathways/features on contaminant transport? • What chemical/physical/biological processes could impact the fate and transport of substances in the subsurface? • What are the toxic effects of naturally occurring substances?
Flowback and produced water	What are the possible impacts of accidental releases of flowback and produced water on drinking water resources?	• What is the composition and variability of flowback and produced water and what are the toxic effects of these constituents? • What factors may influence the likelihood of contamination of drinking water resources? • How effective are mitigation approaches in reducing impacts to drinking water resources?
Wastewater treatment and waste disposal	What are the possible impacts of inadequate treatment of hydraulic fracturing wastewaters on drinking water resources?	• How effective are treatment and disposal methods?

A summary of the research outlined in this chapter can be found in Appendix A.

6.1 Water Acquisition: How might large volume water withdrawals from ground and surface water impact drinking water resources?

6.1.1 Background

The amount of water needed in the hydraulic fracturing process depends on the type of formation (coalbed, shale, or tight sands) and the fracturing operations (e.g., well depth and length, fracturing fluid properties, and fracture job design). Water requirements for hydraulic fracturing in coalbed methane range from 50,000 to 350,000 gallons per well (Holditch, 1990 and 1993; Jeu et al., 1988; Palmer et al., 1991 and 1993). The water usage in shale gas plays is significantly larger: 2 to 4 million gallons of water are typically needed per well (API, 2010a; GWPC and ALL Consulting, 2009; Satterfield et al., 2008). Table 3 shows how the total volume of water used in fracturing varies depending on the depth and porosity of the shale gas play.

TABLE 3. COMPARISON OF ESTIMATED WATER NEEDS FOR HYDRAULIC FRACTURING IN DIFFERENT SHALE PLAYS

Shale Play	Formation Depth (ft)	Porosity (%)	Organic Content (%)	Freshwater Depth (ft)	Fracturing Water (gallons/well)
Barnett	6,500-8,500	4-5	4.5	1,200	2,300,000
Fayetteville	1,000-7,000	2-8	4-10	500	2,900,000
Haynesville	10,500-13,500	8-9	0.5-4	400	2,700,000
Marcellus	4,000-8,500	10	3-12	850	3,800,000

Data are from GWPC and ALL Consulting, 2009.

EPA estimates that approximately 35,000 wells are fractured each year across the United States. Assuming that the majority of these wells are horizontal wells, the annual water requirement may range from 70 to 140 billion gallons. This is equivalent to the total amount of water used each year in roughly 40 to 80 cities with a population of 50,000 or about 1 to 2 cities of 2.5 million people. In the Barnett Shale area, the annual estimates of total water used by gas producers range from 2.6 to 5.3 billion gallons per year from 2005 through 2007 (Bene et al., 2007, as cited in Galusky, 2007). During the projected peak shale gas production in 2010, the total water used for gas production in the Barnett Shale was estimated to be 9.5 billion gallons. This represents 1.7 percent of the estimated total freshwater demand by all users within the Barnett Shale area (554 billion gallons) (Galusky, 2007).

To meet these large volume requirements, source water is typically stored in 20,000-gallon portable steel (“frac”) tanks located at the well site (GWPC, 2009; ICF International, 2009a; Veil, 2007). Source water can also be stored in impoundment pits on-site or in a centralized location that services multiple sites. This storage practice is used, for example, in the Barnett and Fayetteville Shale plays, where source water may be stored in large, lined impoundments ranging in capacity from 8 million gallons for 4 to 20 gas wells to 163 million gallons for 1,200 to 2,000 gas wells (Satterfield et al., 2008). The water used to fill tanks or impoundments may come from either ground or surface water, depending on the region in which the fracturing takes place. The transportation of source water to the well site depends on site-specific conditions. In many areas, trucks generally transport the source water to the well site. In the long term, where topography allows, a network of pipelines may be installed to transfer source water between the source and the impoundments or tanks.

Whether the withdrawal of this much water from local surface or ground water sources has a significant impact may vary from one part of the country to another and from one time of the year to another. In arid North Dakota, the projected need of 5.5 billion gallons of water per year to release oil and gas from the Bakken Shale has prompted serious concerns by stakeholders (Kellman and Schneider, 2010). On the other hand, in less arid parts of the country (e.g., the Barnett Shale area), the impact of water withdrawals may be less significant. In the Marcellus Shale area, stakeholder concerns have focused on large volume, high rate water withdrawals from small streams in the headwaters of watersheds supplying drinking water (Maclin et al., 2009; Myers, 2009) rather than on overall water use.

One way to offset the large water requirements for hydraulic fracturing is to recycle the flowback produced in the fracturing process. Estimates for the amount of fracturing fluid that is recovered during the first two weeks after a fracture range from 10 to 40 percent of the original fluid injected (Ewing, 2008; Vidic, 2010). This water may be treated and reused by adding additional chemicals as well as fresh water to compose a new fracturing solution. There are, however, challenges associated with reusing flowback due to the high concentrations of total dissolved solids (TDS) and other dissolved constituents found in flowback (Bryant et al., 2010). Acid mine drainage, which has a lower TDS concentration, has also been suggested as possible source water for hydraulic fracturing (Vidic, 2010).

API has published general guidance on best practices for water management associated with hydraulic fracturing (API, 2010a). Such practices include proactive communication with local water agencies and planning for a potential well drilling program on a basin-wide basis. API also recommends a detailed evaluation of the amount and quality of water required in addition to the identification and evaluation of potential water sources. Other literature describes current and proposed practices for on-site water management at some shale gas plays (Satterfield et al., 2008; Horn, 2009; Veil, 2007 and 2010).

6.1.2 What are the impacts on water availability?

Large volume water withdrawals for hydraulic fracturing are unique in that much of the water used for the fracturing process may not be recovered after injection. The impact from large volume water withdrawals varies not only with geographic area, but also with the quantity, quality, and sources of the water used. The removal of large volumes of water could stress drinking water supplies, especially in drier regions where aquifer or surface water recharge is limited. This could lead to lowering of water tables or dewatering of drinking water aquifers, decreased stream flows, and reduced volumes of water in surface water reservoirs. These activities could impact the availability of water for drinking and other uses in areas where hydraulic fracturing is occurring. The lowering of water levels in aquifers can necessitate the lowering of pumps or the deepening or replacement of wells, as has been reported near Shreveport, Louisiana, in the area of the Haynesville Shale (personal communication from Gary M. Hanson, Director, Red River Watershed Management Institute, Louisiana State University in Shreveport, to EPA’s Robert Puls).

As the intensity of hydraulic fracturing activities increases within individual watersheds and geologic basins, it is important to understand the net impacts on water resources and identify opportunities to optimize water management strategies.

6.1.3 What are the impacts on water quality?

The lowering of water levels in aquifers may also affect water quality by exposing naturally occurring minerals to an oxygen-rich environment. This may cause chemical changes to the minerals that can affect solubility and mobility and may cause salination of the water and other chemical contaminations. Bacterial growth may be stimulated by lowered water tables, causing taste and odor problems. Depletion of aquifers may also cause an upwelling of lower quality water from deeper within an aquifer. In some cases, changes in water levels may interact with well construction in such a way as to cause an increase in siltation or cloudiness of the produced water. Large volume water withdrawals from ground water can also lead to subsidence and/or destabilization of the geology.

Withdrawals of large quantities of water from surface water resources (e.g., streams) may have significant impacts on the hydrology and hydrodynamics of these resources. Such withdrawals from streams can alter the flow regime by changing their flow depth, velocity, and temperature (Zorn et al., 2008). Additionally, removal of significant volumes of water may reduce the dilution effect and increase the concentration of contaminants in surface water resources (Pennsylvania State University, 2010). Furthermore, it is important to recognize that ground water and surface water are hydraulically connected (Winter et al., 1998); any changes in the quantity and quality of the surface water will affect ground water and vice versa.

6.1.4 Proposed Research Activities—Water Acquisition

6.1.4.1 Water Availability: Analysis of Existing Data, Prospective Case Studies, and Scenario Evaluation

Analysis of existing data. In cooperation with USACE, USGS, state environmental agencies, state oil and gas associations, river basin commissions, and others, EPA will compile data on water use and the hydrology of selected study areas. These data will include ground water levels, surface water flows, and water quality as well as data on hydraulic fracturing operations, such as the location of wells and the recorded water used during fracturing. EPA has chosen potential study areas that represent both arid and humid areas of the country, restricting its selection to areas for which sufficient data are available. Current potential study areas include: (1) the Bakken Shale in North Dakota, (2) the Barnett Shale in Texas, (3) Garfield County/Piceance Basin in Colorado, and (4) the Susquehanna River Basin/Marcellus Shale in Pennsylvania.

Simple water balance and geospatial information system (GIS) analysis will be conducted using the existing data. The collected data will be compiled in conjunction with hydrological trends over the same period of time. Control areas that have similar baseline water demands and have no oil and gas development will be compared to areas with intense hydraulic fracturing activity to isolate and identify the impacts of hydraulic fracturing on water availability. A critical analysis of trends in water flows and water usage patterns in areas impacted by hydraulic fracturing activities will be conducted to determine whether water withdrawals for hydraulic fracturing activities alter ground and surface water flows. Data collection will support the assessment of the impacts of hydraulic fracturing on water availability at various spatial scales (e.g., site, watershed, basin, and play) and temporal scales (e.g., days, months, and years).

Prospective case studies. EPA will conduct prospective case studies that will monitor all aspects of the hydraulic fracturing water lifecycle illustrated in Figure . These prospective case studies will collect data to evaluate potential impacts on water availability due to large volume water withdrawals, and will assess management practices related to water acquisition. Additionally, the assessment of site-scale water use on the hydrologic cycle will allow EPA to test the models used in the scenario evaluations described below.

Scenario evaluation. Scenario evaluations will assess the environmental futures and impacts of hydraulic fracturing operations at various spatial and temporal scales in the selected study areas using the existing data described above. The scenarios will include at least two futures: (1) average annual conditions in 10 years based on the full exploitation of non-conventional natural gas and (2) average annual conditions in 10 years based on sustainable water use in hydraulic fracturing operations. Both scenarios will build on predictions for land use and climate (e.g., drought, average, and wet). EPA will take advantage of the future scenario work constructed for the EPA Region 3 Chesapeake Bay Program (for 2030) and the EPA ORD Futures Midwest Landscape Program (for 2022). The spatial scales of analysis will reflect both environmental boundaries (e.g., site, watershed, river basin, and geologic play) and political boundaries (e.g., city/municipality, county, state, and EPA Region).

These assessments will consider typical water requirements for hydraulic fracturing activities and will also account for estimated demands for water from other human needs (e.g., drinking water, agriculture, and energy), adjusted for future populations. The sustainability analysis will reflect minimum river flow requirements and aquifer drawdown for drought, average, and wet precipitation years, and will allow a determination of the number of typical hydraulic fracturing operations that could be sustained for the relevant formation (e.g., Marcellus Shale) and future scenario. Appropriate physics-based watershed and ground water models will be used for representation of the water balance and hydrologic cycle, as discussed in Appendix H.

6.1.4.2 Water Quality: Analysis of Existing Data and Prospective Case Studies

Analysis of existing data. EPA will use the data collected in collaboration with USACE, USGS, and others to analyze changes in water quality in areas impacted by hydraulic fracturing, and to determine if any changes are due to water withdrawals for hydraulic fracturing. Water quality trends will also be evaluated to determine the potential for using routine monitoring data in identifying water resource vulnerabilities.

Prospective case studies. These case studies will allow EPA to collect data on the quality of ground and surface waters that may be used for hydraulic fracturing before and after water is removed for hydraulic fracturing purposes. The resulting data will be analyzed to determine if there are any changes in water quality, and if these changes are due to the large volume water withdrawals associated with hydraulic fracturing.

6.1.5 Potential Research Outcomes

The research outlined above will allow EPA to:

- Identify possible impacts on water availability and quality associated with large volume water withdrawals for hydraulic fracturing.
- Determine the cumulative effects of large volume water withdrawals within a watershed and aquifer.
- Develop metrics that can be used to evaluate the vulnerability of water resources.
- Provide an assessment of current water resource management practices related to hydraulic fracturing.

6.2 Chemical Mixing: What are the possible impacts of releases of hydraulic fracturing fluids on drinking water resources?

6.2.1 Background

Most hydraulic fracturing fluids are water-based fluids that serve two purposes: to create pressure to propagate the fracture and to carry the proppant into the fracture. Proppants are solid materials that are used to keep the fractures open after pressure is reduced in the well. The most common proppant is sand (Carter et al., 1996), although resin-coated sand, bauxite, and ceramics have also been used (Arthur et al., 2008; Palisch et al., 2008). Most, if not all, water-based fracturing techniques use proppants. There are, however, some fracturing techniques that do not use proppants. For example, nitrogen gas is commonly used to fracture coalbeds and does not require the use of proppants (Rowan, 2009).

In addition to proppants and water, hydraulic fracturing fluids contain chemical additives. The types and concentrations of proppants and chemical additives vary depending on the conditions of the specific well being fractured, and are selected to create a fracturing fluid tailored to the properties of the formation and the needs of the project. In many cases, reservoir properties are entered into modeling programs that simulate fractures (see Castle et al., 2005, and Hossain and Rahman, 2008, for commercial software available for fracture design). The fracturing models are then used to reverse engineer the requirements for fluid composition, pump rates, and proppant concentrations. In shale gas plays, for example, the fracturing fluid is predominantly water and sand, with added chemicals depending upon the characteristics of the source water and the shale play formation being fractured (GWPC and ALL Consulting, 2009).

Table 4 lists the volumetric composition of a fluid used in a fracturing operation in the Fayetteville Shale as an example of additive types and concentrations (GWPC and ALL Consulting, 2009; API, 2010b). A list of publicly known chemical additives found in hydraulic fracturing fluids is provided in Appendix D.

TABLE 4. AN EXAMPLE OF THE VOLUMETRIC COMPOSITION OF HYDRAULIC FRACTURING FLUID

Component/ Additive Type	Example Compound(s)	Purpose	Percent Composition (by Volume)	Volume of Chemical (Gallons)[a]
Water		Deliver proppant	90	2,700,000
Proppant	Silica, quartz sand	Keep fractures open to allow gas flow out	9.51	285,300
Acid	Hydrochloric acid	Dissolve minerals, initiate cracks in the rock	0.123	3,690
Friction reducer	Polyacrylamide, mineral oil	Minimize friction between fluid and the pipe	0.088	2,640
Surfactant	Isopropanol	Increase the viscosity of the fluid	0.085	2,550
Potassium chloride		Create a brine carrier fluid	0.06	1,800
Gelling agent	Guar gum, hydroxyethyl cellulose	Thickens the fluid to suspend the proppant	0.056	1,680
Scale inhibitor	Ethylene glycol	Prevent scale deposits in the pipe	0.043	1,290
pH adjusting agent	Sodium or potassium carbonate	Maintain the effectiveness of other components	0.011	330
Breaker	Ammonium persulfate	Allow delayed breakdown of the gel	0.01	300
Crosslinker	Borate salts	Maintain fluid viscosity as temperature increases	0.007	210
Iron control	Citric acid	Prevent precipitation of metal oxides	0.004	120
Corrosion inhibitor	N,n-dimethyl formamide	Prevent pipe corrosion	0.002	60
Biocide	Glutaraldehyde	Eliminate bacteria	0.001	30

Data are from GWPC and ALL Consulting, 2009, and API, 2010b. Note that the example compounds are not necessarily the compounds used in this fracturing operation in the Fayetteville Shale. [a] Based on 3 million gallons of fluid used.

In the case outlined in Table 4, the total concentration of chemical additives was 0.49 percent. Table 4 also calculates the volume of each additive based on a total fracturing fluid volume of 3 million gallons, and shows that the total volume of chemical additives is 14,700 gallons. In general, however, the overall concentration of chemical additives in fracturing fluids used in shale gas plays ranges from 0.5 to 2 percent by volume with water and proppant comprising the remainder (GWPC and ALL Consulting, 2009), indicating that 15,000 to 60,000 gallons of the total fracturing fluid consist of chemical additives (assuming a total fluid volume of 3 million gallons).

The chemical additives are typically stored in tanks on-site and blended with water and the proppant prior to injection. Flow, pressure, density, temperature, and viscosity can be measured before and after mixing (Pearson, 1989). High pressure pumps then send the mixture from the blender into the well (Arthur et al., 2008). In some cases, special on-site equipment is used to measure the properties of the mixed chemicals *in situ* to ensure proper quality control (Hall and Larkin, 1989).

6.2.2 What is the composition of hydraulic fracturing fluids and what are the toxic effects of these constituents?

In 2010, EPA compiled a list of chemicals that were publicly known to be used in hydraulic fracturing (Table D1 in Appendix D). The chemicals identified in Table D1, however, do not represent the entire set of chemicals used in hydraulic fracturing activities. EPA also lacks information regarding the frequency, quantity, and concentrations of the chemicals used, which is important when considering the toxic effects of hydraulic fracturing fluid additives. In January 2011, Congressmen Waxman and Markey and Congresswoman DeGette notified EPA that they found that "between 2005 and 2009, oil and gas service companies injected 32.2 million gallons of diesel fuel or hydraulic fracturing fluids containing diesel fuel in wells in 19 states" (Waxman et. al, 2011). Stakeholder meetings and media reports have emphasized the public's concern regarding the identity and toxicity of chemicals used in hydraulic fracturing.

Much of the information regarding the identity and concentration of chemicals used in hydraulic fracturing fluids is considered by the industry to be proprietary and, therefore, confidential. This makes identifying the toxicity and human health effects associated with these chemicals difficult. Table 4 illustrates that the chemicals used in hydraulic fracturing fluids can have a range of toxicities. For example, sand, polyacrylamide, guar gum, and hydroxyethyl cellulose are relatively benign materials. Acids and bases present an irritant response upon dermal or inhalation exposure, but more acute responses are possible. On the other hand, chronic toxicity has been associated with some identified chemicals, such as ethylene glycol, glutaraldehyde, and n,n-dimethyl formamide (TOXNET, 2011). An approach for assessing the toxicity and human health effects of fracturing fluid additives is outlined in Chapter 8.

6.2.3 What factors may influence the likelihood of contamination of drinking water resources?

Large hydraulic fracturing operations require extensive quantities of supplies, equipment, water, and vehicles, which could create risks of accidental releases, such as spills or leaks. Surface spills or releases can occur as a result of tank ruptures, equipment or surface impoundment failures, overfills, vandalism, accidents, ground fires, or improper operations. Released fluids might flow into a nearby surface water body or infiltrate into the soil and near-surface ground water, potentially reaching drinking water aquifers (NYSDEC, 2009).

6.2.4 How effective are mitigation approaches in reducing impacts to drinking water resources?

API provides a description of general practices relating to the transportation, storage, and handling of source water and other fluids prior to fracturing (API, 2010a). However, the extent to which these practices are followed in the industry or what other practices may be used is unclear.

6.2.5 Proposed Research Activities—Chemical Mixing

6.2.5.1 Chemical Identity and Toxicity: Analysis of Existing Data

In September 2010, EPA issued information requests to nine hydraulic fracturing service companies seeking information on the identity and quantity of chemicals used in hydraulic fracturing fluid in the past five years (Appendix C). This information will provide EPA with a better understanding of the common compositions of hydraulic fracturing fluids (e.g., identity of components, concentrations, and frequency of use) and the factors that influence these compositions. By asking for data from the past five years, EPA expects to obtain information on chemicals that are currently used as well as those that are no longer used in hydraulic fracturing operations, but could be present in areas where retrospective case studies will be conducted. The data collected from this request will also be compared to the list of publicly known hydraulic fracturing chemical additives to determine the accuracy and completeness of the list of chemicals given in Table D1.

The chemical list from the nine companies will be combined with the list of publicly known chemical additives to provide EPA with a comprehensive list of chemicals used in hydraulic fracturing operations. The resulting list of chemical additives will be used in two ways: First, EPA will work to determine the toxicity and estimated human health effects associated with hydraulic fracturing fluid chemical additives using methods described later in Chapter 8. Secondly, this list of chemicals will allow EPA to identify existing analytical methods—or develop new methods—to detect fracturing fluids and their degradation products in drinking water resources. EPA expects to identify a short list of 10 to 20 chemical indicators to track the fate and transport of hydraulic fracturing fluids through the environment. The criteria for selecting these indicators will include, but are not limited to, (1) the frequency of occurrence in fracturing fluids, (2) the toxicity of the chemical, (3) the fate and transport of the chemical (e.g., mobility in the environment), and (4) the availability of detection methods.

6.2.5.2 Hydraulic Fracturing Fluid Release: Analysis of Existing Data and Case Studies

Analysis of existing data. The tanks, valves, and pipes used to store and mix hydraulic fracturing fluid (i.e., water, proppant, and chemical additives) are subject to spills, releases, or leaks (subsequently, the term "release" will refer to a leak, spill, or release). Releases, in general, are not restricted to hydraulic fracturing operations, and can occur under a variety of conditions. Because these are common types of problems, there already exists a body of scientific literature that describes how a chemical solution released on the ground can infiltrate the subsurface and/or run off to a surface water body. EPA will use the list of hydraulic fracturing fluid chemical additives generated through the research proposed in Section 6.2.5.1 to identify individual chemicals and classes of chemicals for review in the existing scientific literature. EPA will then identify relevant existing research on the fate and transport of hydraulic fracturing fluid additives. The relevant research will be summarized to determine the known impacts of spills of fracturing fluid on drinking water resources and to identify existing knowledge gaps related to surface spills of hydraulic fracturing fluid chemical additives.

Retrospective case studies. Some of the candidate case study sites (listed in Appendix F) have reported accidental releases from chemical tanks, supply lines, or leaking valves. It is expected that at least one of the case studies chosen will allow EPA to investigate the impacts of accidental releases on drinking water resources.

Prospective case studies. Prospective case studies will monitor and assess current chemical management practices, and will identify potential areas of concern related to on-site chemical mixing of hydraulic fracturing fluid. EPA will also collect information on the effectiveness of current management practices used to contain or mitigate the impacts of spills and/or leaks of fracturing fluid on drinking water resources.

6.2.6 Potential Research Outcomes

Through the above research activities, EPA will:

- Summarize available data on the identity and frequency of use of various hydraulic fracturing chemicals, the concentrations at which the chemicals are typically injected, and the total amounts used.
- Identify the toxicity of chemical additives, and apply tools to prioritize data gaps and identify chemicals for further assessment.
- Identify a set of chemical indicators associated with hydraulic fracturing fluids and associated analytical methods.
- Determine the likelihood that surface spills will result in the contamination of drinking water resources.
- Assess current management practices related to on-site chemical storage and mixing.

6.3 Well Injection: What are the possible impacts of the injection and fracturing process on drinking water resources?

6.3.1 Background

Ideally, the successful injection of hydraulic fracturing fluid results in natural gas production without contamination of USDWs, and is necessarily dependent upon the mechanical integrity of the well and the fluid design. The fluid design is determined by the subsurface properties and the oil/gas service field operator. Mechanical integrity is determined by well design and construction, which is regulated by the states. Requirements for well construction vary from state to state, but many states incorporate standards such as those published by API (2009). It is useful, therefore, to provide a brief summary of well construction, which is adapted from the well construction and integrity guidelines published by API (2009).

6.3.1.1 Well Design and Construction

According to API (2009), the goal of well design is to "ensure the environmentally sound, safe production of hydrocarbons by containing them inside the well, protecting ground water resources, isolating the production formations from other formations, and by proper execution of hydraulic fractures and other stimulation operations." Thus, proper well construction is essential for isolating the production zone from USDWs, and includes drilling a hole, installing a steel pipe (casing), and cementing the pipe in place. These activities are repeated multiple times throughout the drilling event until the well is complete.

Drilling. Various techniques can be used to drill wells. For example, air or water can be used to drill wells in coalbed methane formations and other fragile formations (Rogers et al., 2007). In most cases, however, a drilling string—composed of a drill bit, drill collars, and a drill pipe—is used to drill the well. During the drilling process, a drilling fluid such as compressed air or a water- or oil-based liquid ("mud")

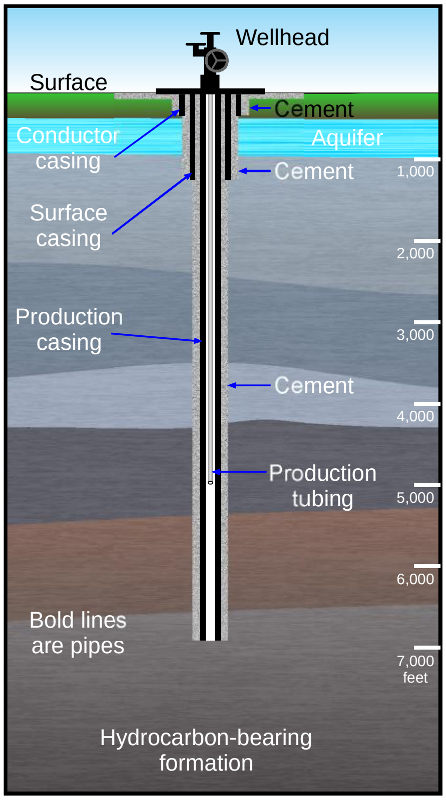


FIGURE 8. WELL CONSTRUCTION

is circulated down the drilling string. Water-based liquids typically contain a mixture of water, barite, clay, and chemical additives (OilGasGlossary.com, 2010). This fluid serves multiple purposes, including cooling the drill bit, lubricating the drilling assembly, removing the formation cuttings, maintaining the pressure control of the well, and stabilizing the hole being drilled. Once removed from the wellbore, both drilling liquids and drill cuttings must be treated, recycled and/or disposed of.

Casing. Casings are steel pipes that line the borehole and serve to isolate the geologic formation from the materials and equipment in the well. The casing also prevents the borehole from caving in, confines the injected/produced fluid to the wellbore and the intended production zone, and provides a method of pressure control. Thus, the casing must be capable of withstanding the external and internal pressures encountered during the installation, cementing, fracturing, and operation of the well. Because fluid is confined within the casing, the possibility of contamination of zones adjacent to the well is greatly diminished.

Figure 8 illustrates the different types of casings that may be used in well construction: conductor, surface, intermediate (if necessary), and production. Each casing serves a unique purpose. Ideally, the surface casing should extend below the base of the deepest USDW and be cemented to the surface. This casing isolates the USDWs and provides protection from contamination during drilling, completion, and operation of the well. Note that the shallow portions of the well may have multiple layers of casing and cement, isolating the production area from the surrounding formation. For each casing, a hole is drilled and the casing is installed and cemented into place.

Casings should be positioned in the center of the borehole using casing centralizers, which attach to the outside of the casing. A centralized casing improves the likelihood that it will be completely surrounded by cement during the cementing process, leading to the effective isolation of the well from USDWs.

Cementing. Once the casing is inserted in the borehole, it is cemented into place by pumping a cement slurry down the casing and up the annular space between the formation and the outside of the casing. The principal functions of the cement (for vertical wells or the vertical portion of a horizontal well) are to be of suitable quality (during and after setting) to act as a barrier to migration of fluids up the wellbore behind the casing and to mechanically support the casing. To accomplish these functions, the proper cement must be used for the conditions encountered in the borehole. Additionally, placement of the cement and the type of cement used in the well must be carefully planned and executed to ensure that the cement functions effectively.

The presence of the cement sheath around each casing and the effectiveness of the cement in preventing fluid movement are the major factors in establishing and maintaining the mechanical integrity of the well. Even a correctly constructed well can fail over time due to downhole stresses and corrosion (Bellabarba et al., 2008). Therefore, ongoing mechanical integrity testing of the well is recommended; many states require that wells be tested periodically (GWPC, 2009).

6.3.1.2 Injection of Hydraulic Fracturing Fluid

Before the injection of hydraulic fracturing fluid, the production casing is perforated using explosive charges. The perforations allow the injected fluid to enter, and thus fracture, the target formation. Wells may be fractured either in a single stage or in multiple stages as determined by the total length of the injection zone. Vertical wells can be fractured in a single stage or multiple stages while horizontal wells typically require multiple stages due to the overall length of the horizontal leg (GWPC and ALL Consulting, 2009). In a multi-stage fracture of a horizontal well, the fracturing operation typically begins with the stage furthest from the wellhead until the entire length of the horizontal leg has been fractured.

The actual fracturing process within each stage consists of a series of injections using different volumes and compositions of fracturing fluids (GWPC and ALL Consulting, 2009). Sometimes a small amount of fluid is pumped into the well before the actual fracturing begins. This “mini-frac” may be used to help determine reservoir properties and to enable better fracture design (API, 2009). In the first stage of the fracture job, fracturing fluid (typically without proppant) is pumped down the well at high pressures to initiate the fracture. The fracture initiation pressure will depend on the depth and the mechanical properties of the formation. A combination of fracturing fluid and proppant is then pumped in, often in slugs of varying sizes and concentrations. After the combination is pumped, a water flush is used to begin flushing out the fracturing fluid (Arthur et al., 2008).

API recommends that several parameters be continuously monitored during the actual hydraulic fracturing process, including surface injection pressure, slurry rate, proppant concentration, fluid rate, and proppant rate (API, 2009). Monitoring the surface injection pressure is particularly important for two reasons: (1) it ensures that the pressure exerted on equipment does not exceed the tolerance of the weakest components, and (2) unexpected or unusual pressure changes may be indicative of a problem that requires prompt attention (API, 2009).

Models can also be used during the fracturing process to make real-time adjustments to the fracture design (Armstrong et al., 1995). Additionally, microseismic monitors and tiltmeters may be used during fracturing to plot the positions of the fractures (Warpinski et al., 1998 and 2001; Cipolla and Wright, 2000), although this is done primarily when a new area is being developed or new techniques are being used (API, 2009). Microseismic monitoring is used in about three percent of fracturing jobs (Zoback et al., 2010).

6.3.1.3 Naturally Occurring Substances

Hydraulic fracturing may affect the mobility of naturally occurring substances in the subsurface, particularly in the hydrocarbon-containing formation. These substances, described in Table 5, include formation fluid, gases, trace elements, naturally occurring radioactive material, and organic material.

TABLE 5. NATURALLY OCCURRING SUBSTANCES THAT MAY BE FOUND IN HYDROCARBON-CONTAINING FORMATIONS

Type of Contaminant	Example(s)
Formation fluid	Brine[a]
Gases	Natural gas[b] (e.g., methane, ethane), carbon dioxide, hydrogen sulfide, nitrogen, helium
Trace elements	Mercury, lead, arsenic[c]
Naturally occurring radioactive material	Radium, thorium, uranium[c]
Organic material	Organic acids, polycyclic aromatic hydrocarbons, volatile and semi-volatile organic compounds

[a] Piggot and Elsworth, 1996.
[b] Zoback et al., 2010.
[c] Harper, 2008; Leventhal and Hosterman, 1982; Tuttle et al., 2009; Vejahati et al., 2010.

Some or all of these substances may find a pathway to USDWs as a result of hydraulic fracturing activities. For example, if fractures extend beyond the target formation and reach aquifers, or if the casing or cement around a wellbore fails under the pressures exerted during hydraulic fracturing, these potential contaminants could migrate into drinking water supplies. Some of these substances may be liberated from the formation via complex biogeochemical reactions with chemical additives found in hydraulic fracturing fluid (Falk et al., 2006; Long and Angino, 1982). These reactions are discussed in more detail in Section 6.3.4.

6.3.2 How effective are well construction practices at containing gases and fluids before, during, and after fracturing?

In researching information sources for this study plan, EPA found evidence showing that improper well construction or improperly sealed wells may provide subsurface pathways for ground water pollution by allowing contaminant migration to sources of drinking water (PADEP, 2010b; McMahon et al., 2011; State of Colorado Oil and Gas Conservation Commission, 2009a, 2009b, and 2009c; USEPA, 2010b). Based on these findings, EPA believes that well mechanical integrity will likely be an important factor in preventing contamination of drinking water resources from hydraulic fracturing activities.

In addition to concerns related to improper well construction and well abandonment processes, there are concerns about the repeated fracturing of a well over its lifetime. Hydraulic fracturing can be repeated as necessary to maintain the flow of gas or hydrocarbons to the well. The near- and long-term effects of repeated pressure treatments on well components (e.g., casing, cement) are not well understood. While EPA recognizes that fracturing or refracturing existing wells may pose a risk to drinking water resources, EPA has not been able to identify potential partners for a case study, therefore, this practice is not considered in the current study. The issues of well age and maintenance, however, are important and warrant more study.

6.3.3 What are the potential impacts of pre-existing man-made or natural pathways/features on contaminant transport?

Although hydraulic fracture design and control have been researched extensively, predicted and actual fracture lengths still differ frequently (Daneshy, 2003; Warpinski et al., 1998). Hence, it is difficult to accurately predict and control the location and length of fractures. If hydraulic fractures combine with pre-existing faults or fractures that lead to aquifers or directly extend into aquifers, injection could lead to the contamination of drinking water supplies by fracturing fluid, natural gas, and/or naturally occurring substances (see Table 5).

During the fracturing process, some fracturing fluid may flow from the created fractures to other areas within the gas-containing formation in a phenomenon known as "fluid leakoff." In the case of leakoff, the fluid may flow into the micropore or pore spaces within the formation, existing natural factures in the formation, or small fractures opened into the formation by the pressure in the induced fracture (API, 2009; Economides et al., 2007). Fluid leakoff during hydraulic fracturing can exceed 70 percent of the injected volume if not controlled properly (Glenn et al., 1985), and may result in fluid migrating into drinking water aquifers (Hess, 2010; Subra, 2010; Bielo, 2010; URS Corporation, 2009). Additionally, the fracturing process may change the fine scale structure of the rock and alter the fluid flow properties of the formation (Yang et al., 2004).

The risk posed by fluid leakoff to drinking water resources will depend on the distance to those resources and the geochemical and transport processes that are occurring in the intermediate strata. A common assumption in shale gas formations is that natural barriers in the rock strata that act as seals for the gas in the target formation also act as barriers to the vertical migration of fracturing fluids (GWPC and ALL Consulting, 2009). In contrast to shale gas, coalbed methane reservoirs are mostly shallow and may also be underground resources of drinking water. In this instance, hydraulic fracturing may be occurring in or near an USDW, raising concerns about the contamination of shallow water supplies with hydraulic fracturing fluids (Pashin, 2007). Some states have regulations addressing hydraulic fracturing of this type of reservoir (GWPC and ALL Consulting, 2009).

In addition to natural faults or fractures, it is important to consider the proximity of artificial penetrations such as drinking water wells, exploratory wells, production wells, abandoned wells (plugged and unplugged), injection wells, and underground mines. If such penetrations intersect the injection zone in the vicinity of a hydraulically fractured well, they may serve as conduits for contaminants to reach USDWs. Several instances of natural gas migrations have been noted. A 2004 EPA report on coalbed methane indicated that methane migration in the San Juan Basin was mitigated once abandoned and improperly sealed wells were plugged. The same report found that in some cases in Colorado, poorly constructed, sealed, or cemented wells used for a variety of purposes could provide conduits for methane migration into shallow USDWs (USEPA, 2004).

6.3.4 What chemical/physical/biological processes could impact the fate and transport of substances in the subsurface?

There are numerous chemical/physical/biological processes that may alter the fate and transport of substances in the subsurface as the result of hydraulic fracturing. These processes could increase or decrease the mobility of these substances, depending on their properties and the complex interactions of all processes occurring in the subsurface. For example, several of the chemicals used in fracturing fluid (e.g., acids and carbonates) are known to mobilize naturally occurring substances out of rocks and soils by changing the pH or reduction-oxidation (redox) conditions in the subsurface. Conversely, a change in the redox conditions in the subsurface may also decrease the mobility of naturally occurring substances (Eby, 2004; Sparks, 1995; Sposito, 1989; Stumm and Morgan, 1996; Walther, 2009).

Along with chemical mechanisms, biological processes can change the mobility of fracturing fluid additives and naturally occurring substances. Many microbes, for example, are known to produce siderophores, which can mobilize metals from the surrounding matrix (Gadd, 2004). Microbes may also reduce the mobility of substances by binding to metals or organic substances, leading to the localized sequestration of fracturing fluid additives or naturally occurring substances (Gadd, 2004; McLean and Beveridge, 2002; Southam, 2000).

Physical processes can also increase the mobility of naturally occurring substances. For example, hydraulic fracturing itself is a physical process that may increase the mobility of methane into the surrounding media (GWPC and ALL Consulting, 2009). In the formation, methane is trapped inside the matrix and is not mobile because the pores within the formation are too small or are unconnected. When the rock is fractured, the connection between the pores increases, allowing methane to flow into the fracture and wellbore.

6.3.5 What are the toxic effects of naturally occurring substances?

As discussed above, multiple pathways may exist that allow contaminants to reach drinking water resources. The toxic effects of chemical additives in hydraulic fracturing fluid were briefly discussed in Section 6.2.2. Table 5 and Table D3 in Appendix D provide examples of naturally occurring substances that may contaminate drinking water resources. The toxicity of these substances varies considerably. For example, naturally occurring metals, though they are essential nutrients, exert various forms of toxicity even at low concentrations. Natural gases can also have adverse consequences stemming from their toxicity as well as their physical characteristics (e.g., some are very explosive). Research to summarize and explore these effects is described in Chapter 8.

6.3.6 Proposed Research Activities—Well Injection

6.3.6.1 Well Integrity: Analysis of Existing Data, Case Studies, and Scenario Evaluation

Analysis of existing data: well files. As part of the voluntary request for information sent by EPA to nine hydraulic fracturing service companies (see Appendix C), EPA asked for the locations of sites where hydraulic fracturing operations have occurred within the past year. From this potential list of thousands of hydraulic fracturing sites, EPA will select a representative sample of sites and request the complete well files for these sites. Well files generally contain information regarding all activities conducted at the site, including any instances of well failure. EPA will analyze the well files to assess the typical causes, frequency, and severity of well failures.

Retrospective case studies. While conducting retrospective case studies, EPA will assess the mechanical integrity of relevant wells (e.g., existing and historical production wells) near the reported area of drinking water contamination. To do this, EPA will review existing well construction and mechanical integrity data and/or collect new data using the tools described in Appendix E. By investigating well construction and mechanical integrity at sites with reported drinking water contamination, EPA will work to determine if well failure was responsible for the reported contamination and whether original well integrity tests were effective in identifying problems.

Prospective case studies. EPA will assess well construction and mechanical integrity at prospective case study sites by:

- Assessing the integrity of wells with respect to casing and cement placement using available logging tools and pressure tests conducted before hydraulic fracturing.
- Repeating mechanical integrity assessments on wells following hydraulic fracturing treatments to evaluate changes related to the high pressures used in the fracturing.
- Sampling the pressure within, and the fluid from, well components (e.g., annular spaces behind the production casing) before and after hydraulic fracturing operations.

During prospective case studies, EPA will also identify what, if any, mechanisms are used to monitor mechanical integrity after the hydraulic fracturing event has taken place.

Scenario evaluation. Computer modeling provides a scientific approach to test potential impacts of hydraulic fracturing well injection scenarios on drinking water resources. The models will include engineering and geological aspects, which will be informed by existing data and laboratory experiments. Models of the engineering systems will include the design and geometry of the vertical and horizontal wells in addition to information on the casing and cementing materials. Models of the geology will include the expected geometry of aquifers and aquitards/aquicludes, the permeability of the formations, and the geometry and nature of boundary conditions (e.g., closed and open basins, recharge/discharge).

Once built, the models will be used to explore the influence of pressure response and contaminant transport under conceptual models representing expected fracturing conditions as well as potential modes of failure. For example, it is suspected that breakdowns in the well casing or cement may provide a high permeability pathway between the well casing and the borehole wall, which may lead to contamination of a drinking water aquifer. In this case, it will be informative to compare typical well construction and testing practices to unexpected situations that might affect drinking water resources.

6.3.6.2 Impacts of Natural and Man-made Pathways: Case Studies and Scenario Evaluation

Retrospective case studies. In cases of suspected drinking water contamination, EPA will investigate the role of natural and/or artificial pathways in leading to the possible contamination through geophysical testing, field sample analysis, and modeling. This investigation will determine the role of existing natural or artificial pathways in providing conduits for the migration of fracturing fluid, natural gas and/or naturally occurring substances to drinking water resources.

EPA will also review the data collected on the hydraulic fracturing process itself, including data gathered to calculate the fracture pressure gradients in the injection zone and confining layers; data resulting from fracture modeling, microseismic fracture mapping and tiltmeter analysis; and any other data used to determine fracture location, length, and height. A critical assessment of these data will allow EPA to determine if fractures created during hydraulic fracturing were localized to the injection zone or possibly intersected existing faults or fractures, leading to the reported contamination.

Prospective case studies. The prospective case studies will give EPA a better understanding of the processes and tools used to determine fracture location, length, and height. Additionally, EPA will assess the impacts of natural and man-made pathways on the fate and transport of chemical contaminants to drinking water resources by measuring water quality before, during, and after injection. EPA is currently exploring the possibility of using chemical tracers to track the fate and transport of injected fracturing fluids. The tracers may be used to determine if fracturing fluid migrates from the targeted formation to a USDW via existing natural or man-made pathways.

Scenario evaluation. The physics-based computer modeling tools described above allow for the exploration of scenarios in which, for example, the fracturing of the target formation unintentionally extends outside of the target zone and potentially creates new pathways for pressure and fluid leakage. It is also suspected that abandoned wells and natural fractures and fault zones may provide pathways for any fluids that leave the target injection zone. In these studies, the injection pulses will be distinguished by their near-field, short-term impacts (fate and transport of injection fluids) as well as their far-field and long-term impacts (including the displacement of native brines or existing gas pockets). These studies will allow the exploration of the potential impacts of fracturing on drinking water resources with regard to variances in geology and well construction, and will help to inform the retrospective and prospective case studies.

Data and information provided by these studies will allow EPA to identify and predict the area of evaluation (AOE) around a hydraulic fracturing site. The AOE includes the subsurface zone that is potentially impacted by hydraulic fracturing activities and is projected as an area at the land surface. Within this area, drinking water resources could be affected by the migration of hydraulic fracturing fluids and liberated gases outside the injection zone, as well as the displacement of native brines within the subsurface. Maps of the AOEs for multiple injection operations can be overlaid on regional maps to evaluate cumulative impacts, and, when compared to regional maps of areas contributing recharge to drinking water wells (source water areas), to evaluate regional vulnerability. The AOE may also be used to support contaminant fate and transport hypothesis testing in retrospective case studies.

6.3.6.3 Physical/Chemical/Biological Processes Relevant to Hydraulic Fracturing: Laboratory Studies

Laboratory studies will be conducted to evaluate which characteristics of gas-bearing formations and fracturing conditions (e.g., temperature and pressure) are most important in determining the potential impact of hydraulic fracturing on drinking water resources. Chemical degradation, biogeochemical reactions, and weathering reactions will be studied by pressurizing subsamples of cores, cuttings, or aquifer material in temperature-controlled reaction vessels. The subsamples will then be exposed to hydraulic fracturing fluids using either a batch or continuous flow system to simulate subsurface reactions. After specific exposure conditions, samples will be drawn for chemical, mineralogical, and microbiological characterization. This approach will enable the evaluation of degradation products as well as constituents that may be mobilized from the solid phase due to biogeochemical reactions.

The laboratory studies will also help to identify possible components in flowback and produced water. Once identified, the list of possible components can be used to identify or develop analytical methods needed for detecting these components. Additionally, the list of possible flowback and produced water components can be used to determine the toxicity and human health effects of naturally occurring substances that may be released during hydraulic fracturing operations using the methods outlined in Chapter 8.

6.3.7 Potential Research Outcomes

The research opportunities outlined above will allow EPA to:

- Determine the frequency and severity of well failures, as well as the factors that contribute to them.
- Identify the key conditions that increase or decrease the likelihood of the interaction of existing pathways with hydraulic fractures.
- Evaluate water quality before, during, and after injection.
- Determine the identity, mobility, and fate of potential contaminants, including fracturing fluid additives and/or naturally occurring substances (e.g., formation fluid, gases, trace elements, radionuclides, organic material) and their toxic effects.
- Develop analytical methods for detecting chemicals associated with hydraulic fracturing events.

6.4 Flowback and Produced Water: What are the possible impacts of releases of flowback and produced water on drinking water resources?

6.4.1 Background

After the fracturing event, the pressure is decreased and the direction of fluid flow is reversed, allowing fracturing fluid and naturally occurring substances to flow out of the wellbore to the surface; this mixture of fluids is called “flowback.” Generally, the flowback period in shale gas reservoirs is several weeks (URS Corporation, 2009), while the flowback period in coalbed methane reservoirs appears to be longer (Rogers et al., 2007).

Estimates of the amount of fracturing fluid recovered as flowback in shale gas operations vary from as low as 25 percent to high as 70 to 75 percent (Pickett, 2009; Veil, 2010; Horn, 2009). Other estimates specifically for the Marcellus Shale project a fracture fluid recovery rate of 10 to 30 percent (Arthur et al., 2008). Less information is available, however, for coalbed methane reservoirs. Palmer et al. (1991) estimated a 61 percent fracturing fluid recovery rate over a 19-day period based on sampling from a single well in the Black Warrior Basin. A recent GWPC report states that none of the 27 oil and natural gas producing states in the United States requires the volume of flowback to be reported to state agencies (GWPC, 2009).

The initial flow rate at which the flowback exits the well can be relatively high (e.g., > 100,000 gallons per day) for the first few days. However, this flow diminishes rapidly with time, ultimately dropping to the normal rate of produced water flow from a natural gas well (e.g., 50 gallons per day) (Chesapeake Energy, 2010; Hayes, 2009b). While there is no clear transition between flowback and produced water, produced water is generally considered to be the fluid that exits the well during oil or gas production (API, 2010a; Clark and Veil, 2009). Like flowback, produced water also contains fracturing fluid and naturally occurring materials, including oil and/or gas. Produced water, however, is generated throughout the well's lifetime.

The physical and chemical properties of flowback and produced water vary with fracturing fluid composition, geographic location, and geological formation (Veil et al., 2004). In general, analyses of flowback from various reports show that concentrations of TDS can range from 5,000 mg/L (Horn, 2009) to more than 100,000 mg/L (Hayes, 2009a), and may even reach 200,000 mg/L (Gaudlip and Paugh, 2008; Keister, 2009; Vidic, 2010). These high values can be reached in a matter of two weeks.

Along with high TDS values, flowback can have high concentrations of major ions (e.g., barium, bromide, calcium, chloride, iron, magnesium, sodium, strontium, bicarbonate), with concentrations of calcium and strontium sometimes reported to be as high as thousands of milligrams per liter (Vidic, 2010). Flowback may also contain radionuclides (Zoback et al., 2010) as well as volatile organic compounds (VOC), including benzene, toluene, xylenes, and acetone (URS Corporation, 2009). A list of chemicals identified in flowback and produced water can be found in Table D2 in Appendix D. Additionally, flowback has been reported to have pH values ranging from 5 to 8 (Hayes, 2009a). A limited time series monitoring program of post-fracturing flowback fluids in the Marcellus Shale indicated increased concentrations through time of TDS, chloride, barium, and calcium; water hardness; and levels of radioactivity (URS Corporation, 2009).

Flowback and produced water from hydraulic fracturing operations are held in storage tanks and waste impoundment pits prior to or during treatment, recycling, and disposal (GWPC, 2009). Impoundments may be temporary (e.g., reserve pits for storage) or long-term (e.g., evaporation pits used for treatment). In areas of New York overlying the Marcellus Shale, regulators are reviewing double-lined centralized impoundments ranging in capacity from 1 to 16 million gallons for the storage of flowback that serve well pads within a 4-square-mile area (ICF International, 2009b**;** NYSDEC, 2009). The transportation of flowback and produced water for disposal depends on site-specific conditions. In the

Marcellus Shale, for example, if the disposal area is not located nearby, flowback and produced water are trucked to disposal facilities (ICF International, 2009a).

The storage of flowback and produced water in tanks or impoundment pits is regulated in many oil and gas producing states (GWPC, 2009). According to the GWPC, 81 percent of these states require tanks for the storage of flowback and produced water to be surrounded by a containment dike. Five states, however, require that materials used to construct storage tanks be compatible and of sufficient strength to hold flowback and produced water. If flowback and produced water is contained in pits, 18 of the 27 states studied require a permit for the pit while 23 states require liners in pits and 16 limit the duration of their use. For example, New York limits the duration fluids can be stored in pits on-site to 45 days after the fracturing treatment (unless reuse has been approved). When liners are used, some states require interstitial monitoring for leaks while others do not.

6.4.2 What is the composition and variability of flowback and produced water and what are the toxic effects of these constituents?

Much of the existing data on the composition of flowback and produced water focuses on the detection of major ions in additional to pH and TDS measurements. For example, data provided by the USGS produced water database indicates that the distribution of major ions, pH, and TDS levels is not only variable on a national scale (e.g., between geologic basins), but also on the local scale (e.g., within one basin) (USGS, 2002). However, less is known about the composition and variability of flowback and produced water with respect to the chemical additives found in hydraulic fracturing fluid or radioactive materials. A recent report by the Gas Technology Institute offers a fairly extensive analysis of the constituents found in flowback in several wells in the Marcellus Shale (Hayes, 2009b). Veil (2004) also provides data for several organic compounds in produced water. It is unclear, however, how the chemical composition of flowback varies on both the national and local scales.

A thorough understanding of how the composition of flowback and produced water varies at both the local and national scales could lead to improved predictions of the identity and toxicity of chemical additives and naturally occurring substances in flowback and produced water. The toxicity of these substances is discussed above in Sections 6.2.2 and 6.3.5.

6.4.3 What factors may influence the likelihood of contamination of drinking water resources?

There may be opportunities for the contamination of drinking water resources both below and above ground. If the mechanical integrity of the well has been compromised, flowback and produced water traveling up the wellbore may have direct access to local aquifers, leading to the contamination of drinking water resources. Once above ground, flowback and produced water are stored on-site in storage tanks and waste impoundment pits, and then may be transported off-site for treatment and/or disposal. There is a potential for releases, leaks, and/or spills associated with the storage and transportation of flowback and produced water, which could lead to contamination of shallow drinking water aquifers and surface water bodies. There are also concerns associated with the design, construction, operation, and closure of waste impoundment pits.

6.4.4 How effective are mitigation approaches in reducing impacts to drinking water resources?

Standard management practices for the industry recommend that spills be cleaned up and disposed of, or reused, to protect human health and the environment. If applicable, these efforts should be pursued in compliance with existing federal and state regulations (USEPA, 2002a). As in the case of accidental releases associated with chemical mixing, it is unclear what practices are used on-site to prevent, contain, or mitigate accidental releases of flowback and produced water. EPA is interested in gathering information relating to the current on-site management practices that are used to prevent and/or contain accidental releases of flowback and produced water to drinking water resources.

6.4.5 Proposed Research Activities—Flowback and Produced Water

6.4.5.1 Composition and Variability of Flowback and Produced Water: Analysis of Existing Data and Prospective Case Studies

Analysis of existing data. EPA requested data on the amounts and management of flowback and produced water in the information request sent to the nine hydraulic fracturing service companies (Appendix C). As noted above, a comprehensive chemical analysis of flowback at several wells in the Marcellus Shale is available (Hayes, 2009b) as well as information on potential constituents in produced water (Veil et al., 2004). In addition, the New York State Department of Environmental Conservation reported on the constituents in samples of flowback and produced water (NYSDEC, 2009). These and other data EPA can locate will be used to enhance our current understanding of the composition and variability of flowback and produced water, which will allow EPA to identify or develop analytical methods needed to detect potential chemicals of concern (e.g., fracturing fluid additives, metals, and radionuclides) in hydraulic fracturing wastewaters. These data will also be used to identify the toxic effects of hydraulic fracturing wastewaters, as described in Chapter 8**.**

Prospective case studies. EPA will monitor current management practices associated with flowback and produced water, and will also draw samples as part of the full water lifecycle monitoring at sites. At the case study sites, flowback and produced water will be sampled periodically following the completion of the injection of hydraulic fracturing fluids into the formation. Samples will be analyzed for the presence of fracturing fluid chemicals and naturally occurring substances found in formation samples analyzed prior to fracturing. This will allow EPA to study the composition and variability of flowback and produced water over a given period of time.

The analysis of flowback and produced water collected during prospective case studies will be done in coordination with DOE NETL. NETL is currently studying the fate and biogeochemistry of radionuclides and VOCs that may appear in flowback and produced water during unconventional oil and natural gas development projects. In addition, DOE NETL has an ongoing project to identify the isotopic signature of Marcellus flowback and produced water. The objective of this project is to determine if stable isotopes can be used to identify Marcellus flowback and produced water when commingled with surface waters or shallow ground water (such as in a surface spill or casing leak scenario); if successful, this is also a technique that EPA may use in retrospective case studies.

6.4.5.2 Flowback and Produced Water Release: Analysis of Existing Data, Retrospective Case Studies, and Scenario Evaluations

Analysis of existing data. There is a chance for flowback and produced water to be released once at the surface, either due to failure at the pipeline or failure of the waste pit or storage tank. Chemical spills and wastewater leakage from waste pits have been studied extensively for other types of wastes. EPA will take advantage of the existing scientific literature by reviewing it for situations that may be similar to hydraulic fracturing operations. To accomplish this, EPA will use the list of constituents identified in flowback and produced water to determine chemicals and classes of chemicals for review in the existing literature. The relevant research will be summarized to determine the fate and transport of flowback and produced water constituents. This literature review will allow EPA to summarize the known impacts of releases of flowback and produced water on drinking water resources and to identify existing knowledge gaps related to surface releases of flowback and produced water.

Retrospective case studies. There are several candidate sites where surface releases of flowback and/or produced water have occurred from spills, blowouts, and leaking pits. Case studies will examine the extent of the impacts, if any, from these releases on surface and ground water resources.

Scenario evaluation. Computer modeling will provide a scientific approach for testing the potential impacts of hydraulic fracturing flowback and produced water on drinking water resources. The conceptual model for representative geology remains the same as in the case of injected fluids, but the reservoir production and engineering changes from injection to extraction. An important exposure pathway to consider is the long-term movement of injected chemicals, formation fluids, and/or transformation products of the mixture up an improperly cemented section of the borehole or casing. Again, it will be informative to compare the typical management practices to unexpected situations that may lead to impacts of flowback and produced water on drinking water resources.

6.4.5.3 Flowback and Produced Water Management: Prospective Case Studies

Prospective case studies. EPA will collect data on the on-site handling of flowback and produced water, including the monitoring of storage pits and the potential for leakage of flowback and produced water to the subsurface from lined and unlined pits. When surface pits or storage tanks are used on-site, EPA will sample their contents. When the pits are closed and abandoned, core samples will be taken beneath the pits to confirm adequate containment of wastes. Information will also be collected on the ways in which wastewater is transported for treatment or disposal and on the efficacy of various forms of on-site treatment (e.g., biocides) in reducing levels of key contaminants.

6.4.6 Potential Research Outcomes

Through the research activities outlined, EPA will:

- Compile information on the identity, quantity, and toxicity of flowback and produced water components.
- Develop analytical methods to identify and quantify flowback and produced water components.
- Provide a prioritized list of components requiring future studies relating to toxicity and human health effects.

- Determine the likelihood that surface spills will result in the contamination of drinking water resources.
- Evaluate risks posed to drinking water resources by current methods for on-site management of wastes produced by hydraulic fracturing.

6.5 Wastewater Treatment and Waste Disposal: What are the possible impacts of inadequate treatment of hydraulic fracturing wastewaters on drinking water resources?

6.5.1 Background

Flowback and produced water can be managed through disposal or treatment, which may then be followed by discharge to surface water bodies or reuse. Land disposal and discharge to surface waters without treatment pose environmental and legal problems. Underground injection is the primary method for disposal in all the major gas shale plays, except the Marcellus Shale (Horn, 2009; Veil, 2007 and 2010). Underground injection, however, can be problematic because of insufficient capacity and the costs of trucking the wastewater to an injection site (Gaudlip and Paugh, 2008; Veil, 2010).

In shale gas areas near population centers (e.g., the Marcellus Shale), wastewater treatment at publicly owned treatment works (POTWs) or commercial industrial treatment facilities may be an option for some operations. Many commercial wastewater treatment facilities are designed to treat the known constituents in flowback or produced water. POTWs, however, are not designed to treat hydraulic fracturing wastewaters; large quantities of sodium and chloride are detrimental to digesters and can result in high TDS concentrations in the effluent (Veil, 2010; West Virginia Water Research Institute, 2010). This high TDS water can be corrosive and harm drinking water treatment facilities downstream from POTWs. Additionally, POTWs are not generally equipped to treat fluids that contain radionuclides, which may be released from the formation during hydraulic fracturing. Elevated levels of bromide, a constituent of flowback in many areas, can also create problems for POTWs. Wastewater plants using chlorination as a treatment process will produce more brominated disinfection byproducts, which have significant health concerns associated with them. When POTWs are used, there may be strict limits on the volumes permitted, such as those found in Pennsylvania where the disposal of production waters at POTWs is limited to less than 1 percent of the POTW's average daily flow (Pennsylvania Environmental Quality Board, 2009).

A primary goal of treatment for shale gas flowback is to meet current water quality standards, which largely focus on TDS levels. Some treatment options include reverse osmosis systems, distillation, filtration, and precipitation processes (West Virginia Water Research Institute, 2010). Reverse osmosis systems, which have been adapted for use with oilfield wastewater, are viable for influents with TDS concentrations of about 40,000 to 50,000 mg/L (e.g., Stepan et al., 2010), making them unsuitable for some extremely concentrated flowback waters. Thermal distillation systems such as mechanical vapor recompression evaporation have been developed (e.g., Veil, 2008). Thermal and reverse osmosis systems are both subject to fouling from organic compounds, necessitating some form of pretreatment. Horn (2009) describes a treatment train using settling and filtration, followed by an advanced oxidation process to remove organics. This sequence prepares the water for salt separation (such as by reverse osmosis).

As noted earlier, recycling of flowback for use in fracturing other wells is becoming increasingly common and is facilitated by developments in on-site treatment to prepare the flowback for reuse. Researchers at Texas A&M, for example, are developing a mobile treatment system that is being pilot tested in the Barnett Shale (Pickett, 2009). Water treated on site may also be used for irrigation or livestock (Horn, 2009) in addition to fracturing other wells. Given the logistical and financial benefits to be gained from treatment of flowback water, continued developments in on-site treatment technologies are expected.

Regulations and practices for management and disposal of hydraulic fracturing wastes vary by region and state, and are influenced by the stage of infrastructure development as well as geology, climate, and formation composition.

6.5.2 How effective are treatment and disposal methods?

Treatment, disposal, and reuse of flowback and produced water from hydraulic fracturing activities are important because of the contaminants present in these waters and their potential for adverse health impacts on populations and ecosystems. While recycling and reuse is also an effective approach for dealing with these waters, and at the same time conserves fresh water resources, ultimately there will still be a need to treat and properly dispose of the final concentrated volumes from a given area of operation. The separation and appropriate disposal of the toxic constituents is the most protective approach for reducing potential adverse health impacts. However, much is unknown about the efficacy of current treatment processes for adequately removing certain flowback and produced water constituents, such as fracturing fluid additives and radionuclides. Additionally, the chemical composition and concentration of solid residuals created by wastewater treatment plants that treat hydraulic fracturing wastewaters—and their subsequent disposal—warrants more study.

In particular, bromide and chloride can have significant impacts to downstream drinking water utilities. Hydraulic fracturing streams can have very high levels of both, and other waters such as wastewater and river water may offer only limited ability to dilute these constituents by blending. The presence of bromide in source waters to drinking water systems that chlorinate will produce a greater amount of brominated disinfection byproducts (DBPs), which have been shown to have greater health impacts than chlorinated DBPs. Also, because of their inherent higher molecular weight, brominated DBPs will result in higher concentrations (by weight) than their chlorinated counterparts (e.g., bromoform versus chloroform), potentially causing a drinking water utility to exceed the current DBP regulatory limits. Meanwhile, higher levels of chloride in drinking waters can impact lead and copper corrosion, resulting in higher lead levels in consumer tap water and an increase in pitting incidences in copper premise plumbing. This project will evaluate management practices for chloride and bromide in hydraulic fracturing wastewaters, along with evaluating potential impacts to drinking water utilities and their consumers.

6.5.3 Proposed Research Activities—Wastewater Treatment and Waste Disposal

6.5.3.1 Effectiveness of Current Treatment Methods: Analysis of Existing Data, Laboratory Studies, and Prospective Case Studies

Analysis of existing data. Important work on the treatment of flowback and produced water has been completed by DOE NETL. To optimize resources, EPA will compile the lessons learned and identify research gaps for: (1) the impacts of the direct discharge of these waters in community wastewater systems, (2) the effectiveness of pretreatment of these waters for ultimate discharge into a wastewater treatment plant or for direct land application, and (3) the effectiveness of treatment of these waters for reuse in the hydraulic fracturing industry and other industries, including agriculture. Specific emphasis will be placed on inorganic and organic contaminants, with the latter being an area that has the least historical information, and hence the greatest opportunity for advancement in treatment.

Laboratory studies. EPA will conduct bench-scale studies to investigate if hydraulic fracturing fluid additives, constituents from underground formations released, or degradation products of fracturing fluid additives are precursors to DBPs, such as trihalomethanes, haloacetic acids, or nitrosamines. EPA will also evaluate at the bench and pilot scale whether other constituents such as elevated chloride levels result in unintended problems (e.g., increased drinking water distribution system corrosion). The results from these studies will inform the prospective case studies discussed below.

Prospective case studies. EPA will collect data on the efficacy of the treatment and disposal of hydraulic fracturing wastewaters in prospective case studies by sampling both pre- and post-treatment wastewaters. It is expected that such studies will include on-site treatment, use of wastewater treatment plants, recycling, and underground injection control wells. These studies are anticipated to provide data on the chemical composition and concentrations found in treated hydraulic fracturing wastewaters and in the resulting solid residuals.

6.5.4 Potential Research Outcomes

This research will allow EPA to:

- Evaluate current treatment and disposal methods of flowback and produced water resulting from hydraulic fracturing activities.
- Assess the short- and long-term effects resulting from inadequate treatment of hydraulic fracturing wastewaters.

7 Case Studies

This chapter of the study plan describes the rationale for case study selection as well as the approaches used in both retrospective and prospective case studies.

7.1 Case Study Selection

EPA invited stakeholders nationwide to nominate potential case studies through informational public meetings and the submission of electronic or written comments. Appendix F contains a list of potential case study sites that were nominated by stakeholders. Of the 48 nominations, EPA intends to select five to eight sites for inclusion in the study. This will include three to five retrospective case study sites, which will focus on cases involving possible drinking water contamination due to hydraulic fracturing operations. The remaining two to three sites will be prospective case studies where EPA will monitor key aspects of the hydraulic fracturing process. The final location and number of case studies will be chosen based on the types of distinct information a given case study would be able to provide.

Table 6 outlines the systematic approach used to identify and prioritize potential retrospective and prospective case study sites.

TABLE 6. DECISION CRITERIA FOR SELECTING HYDRAULIC FRACTURING SITES FOR CASE STUDIES

Selection Step	Inputs Needed	Decision Criteria
Nomination	• Planned, active, or historical hydraulic fracturing activities • Local drinking water resources • Community at risk • Site location, description, history • Site attributes (e.g., physical, geology, hydrology) • Operating and monitoring data, including well construction and surface management activities • Rationale for inclusion	• Proximity of population and drinking water supplies • Magnitude of activity (e.g., density of wells) • Evidence of impaired water quality (retrospective only) • Health and environmental concerns (retrospective only) • Knowledge gap that could be filled by a case study
Prioritization	• Available data on chemical use, site operations, health and environmental concerns • Site access for monitoring wells, sampling, and geophysical testing • Potential to collaborate with other groups (e.g., federal, state, or interstate agencies; industry; non-governmental organizations, communities; and citizens)	• Geographic and geologic diversity • Diversity of suspected impacts to drinking water resources • Population at risk • Site status (planned, active, or completed) • Unique geological or hydrological features • Characteristics of water resources (e.g., proximity to site, ground water levels, surface water and ground water interactions, unique attributes) • Multiple nominations from diverse stakeholders • Land use (e.g., urban, suburban, rural, agricultural)

The criteria shown in Table 6 were used to determine the finalists for both retrospective and prospective case studies, and represent the highest-priority case study sites that EPA would like to conduct as part of this study. The finalists for both retrospective and prospective case study sites were chosen to represent a wide range of conditions that reflect the spectrum of impacts that may result from hydraulic fracturing activities. These case studies are intended to provide enough detail to determine the extent to which conclusions can be generalized at local, regional, and national scales.

Table 7 lists the finalists for retrospective case studies, highlighting the areas to be investigated and the potential outcomes expected for each site. The potential case study sites listed in Table 7 are illustrative of the types of situations that may be encountered during hydraulic fracturing activities and represent a range of locations. In some of these cases, hydraulic fracturing occurred more than a year ago, while in others, the wells were fractured less than a year ago. EPA expects to be able to coordinate with other federal and state agencies as well as landowners to conduct these studies, as listed in Appendix F.

TABLE 7. RETROSPECTIVE CASE STUDY FINALISTS

Location	Areas to be Investigated	Potential Outcomes
Bakken Shale—Killdeer and Dunn County, ND	• Production well failure during hydraulic fracturing • Suspected drinking water aquifer contamination • Possible soil and surface water contamination	• Identify sources of well failure • Determine if drinking water resources are contaminated and to what extent
Barnett Shale—Wise and Denton Counties, TX	• Possible drinking water well contamination • Spills and runoff leading to suspected drinking water well contamination	• Determine if private water wells are contaminated • Obtain information about the likelihood of transport of contaminants via spills, leaks, and runoff
Marcellus Shale—Bradford and Susquehanna Counties, PA	• Ground water and drinking water well contamination • Suspected surface water contamination from a spill of fracturing fluids • Methane contamination of multiple drinking water wells	• Determine if drinking water wells are contaminated • Determine source of methane in private wells • Transferable results due to common types of impacts
Marcellus Shale—Wetzel County, WV; Green/ Washington Counties, PA	• Changes in water quality in drinking water, suspected contamination • Stray gas in wells, spills	• Determine if drinking water wells are contaminated • Determine if surface spills affect surface and ground water • If contamination exists, determine potential source of contaminants in drinking water
Raton Basin—Los Animas County, CO	• Potential drinking water well contamination (methane and other contaminants) in an area with intense concentration of gas wells in shallow surficial aquifer (coalbed methane)	• Determine source of methane • Identify presence/source of contamination in drinking water wells

Prospective case studies will be made possible by partnering with federal and state agencies, landowners, and industry, as highlighted in Appendix F. Potential sites for these case studies include:

- The Bakken Shale in Berthold Indian Reservation, North Dakota.
- The Barnett Shale in Flower Mound/Bartonville, Texas.
- The Marcellus Shale in Green County, Pennsylvania, or another location yet to be determined.
- The Niobrara Shale in Laramie County, Wyoming.

For each case study (retrospective and prospective), EPA will write and approve a QAPP before the start of any new data collection, as described in Section 2.6. As discussed in the following sections, EPA will use a tiered approach for both retrospective and prospective case studies; after each tiered activity, EPA will write a short summary of findings from field investigations before moving to the next activity. Upon completion of each case study, a report summarizing key findings will be produced, peer-reviewed, and published. The data will also be presented in a 2012 interim report and a 2014 report of results.

EPA will perform extensive sampling of relevant environmental media as part of both retrospective and prospective case studies. Appendix G provides details on field sampling, monitoring, and analytical methods.

7.2 Retrospective Case Studies

As described briefly in Section 5.1, retrospective case studies are focused on investigating reported instances of drinking water contamination in areas where hydraulic fracturing events have already occurred. Table 7 lists five finalists for the retrospective case studies. EPA will choose three to five of these for further investigation. Each case study will address one or more of the research questions proposed in Table 2.

The goal of each retrospective case study is to assess whether or not the reported contamination is due to hydraulic fracturing activities. These studies will seek to use existing data and may include additional environmental field sampling, modeling, and/or parallel laboratory investigations. Using in-house personnel as well as contractors, EPA expects to complete key aspects of these case studies in 2012. However, it should be noted that field studies are subject to a wide range of complex issues (e.g., site access and stakeholder support) that must be addressed in order to complete such a study, which may affect the completion date of these studies.

As shown in Table 8, retrospective case studies will be conducted in a tiered fashion to develop integrated data on site history and characteristics, water resources, contaminant migration pathways and exposure routes, and diagnostic tools to evaluate risks.

TABLE 8. APPROACH FOR CONDUCTING RETROSPECTIVE CASE STUDIES

Tier	Goal	Critical Path
1	Verify potential issue	• Evaluate existing data and information • Conduct site visit • Survey stakeholders and interested parties
2	Screen to determine approach for detailed investigations	• Conduct additional sampling: sample wells, taps, surface water, and other fluids associated with hydraulic fracturing activities (e.g., chemical tanks, holding ponds, produced water) • Develop site conceptual model and alternative exposure hypotheses
3	Evaluate potential sources of contamination	• Conduct geophysical testing • Perform mechanical integrity testing • Install new monitoring wells • Develop, calibrate, and test flow and transport model(s)
4	Detailed investigations	• Conduct comprehensive chemical characterization • Evaluate alternate hypotheses using the calibrated model(s)

Retrospective case studies will begin with verifying the potential issue (Tier 1) by evaluating existing data, conducting site visits, and interviewing stakeholders. EPA will then conduct initial screening activities to determine what future efforts may be required for a detailed investigation of the reported drinking water contamination. A major focus of these initial screening activities will be to identify potential evidence of drinking water contamination and to develop hypotheses describing possible sources of the reported contamination, including hydraulic fracturing operations as well as non-fracturing activities. With the exposure hypotheses in mind, additional testing will be conducted to evaluate the potential sources of contamination (see Appendix G for additional information), which will lead to an evaluation of the validity of the exposure hypotheses.

The data collected during retrospective case studies may be used to assess the risks posed to drinking water resources as a result of hydraulic fracturing activities. Because of this possibility, EPA will collect information on: (1) the toxicity of chemicals associated with hydraulic fracturing, (2) the spatial distribution of chemical concentrations and the locations of drinking water wells, (3) how many people are served by the potentially impacted wells, and (4) how the chemical concentrations vary over time.

7.3 Prospective Case Studies

Prospective case studies will be performed at sites where hydraulic fracturing will occur, and are made possible by partnering with oil and natural gas companies and other stakeholders. These case studies will be focused on the entire water lifecycle illustrated in Figure and will: (1) provide data that will be used to inform our current understanding of processes associated with hydraulic fracturing events; and (2) evaluate current water management practices during each stage of the water lifecycle.

Because of the need to enlist the support and collaboration of a wide array of stakeholders in these efforts, the prospective case studies will most likely not begin until mid- to late 2011. Some preliminary results could be available for the 2012 interim reports, but case studies of this type will likely be completed 12 months from the start dates.

Prospective case studies will be conducted in a tiered fashion, as outlined in Table 9, and will include field sampling, monitoring, modeling, and parallel laboratory investigations to explore the research questions summarized in Table 2.

TABLE 9. APPROACH FOR CONDUCTING PROSPECTIVE CASE STUDIES

Field Sampling Phases	Critical Path
Baseline characterization of the production well site and areas of concern	• Sample all available existing wells, catalogue depth to drinking water aquifers, gather well logs • Sample any adjoining surface water bodies • Sample source water • Install and sample a minimum of three new monitoring wells • Sample soil gas • Perform geophysical characterization • Review site geology • Develop site conceptual model • Develop and calibrate flow system model
Production well construction	• Test mechanical integrity • Resample all wells (new and existing), surface water, and soil gas • Survey, record, and evaluate on-site management practices (e.g., pad construction)
Hydraulic fracturing of the production well	• Sample fracturing fluids • Resample all wells, surface water, and soil gas • Sample flowback • Evaluate on-site management practices (e.g., fluids management) • Calibrate hydraulic fracturing model • Assess model results through testing of calibrated model
Gas production	• Resample all wells, surface water, and soil gas • Survey, record, and evaluate on-site management practices • Calibrate hydraulic fracturing model • Assess model results through testing of calibrated model • Sample produced water

While conducting the prospective case studies, EPA will obtain water quality, geologic, seismic, and other data before, during, and immediately after fracturing, as discussed in Appendix G. Similarly, monitoring will be continued during a follow-up period of approximately one year after hydraulic fracturing has been completed. The sampling includes the opportunity for comprehensive baseline characterization and opportunities to monitor flowback and produced water, including the storage and treatment of these wastewaters. The data collected can then be used to test whether hydraulic fracturing models accurately simulate changes in the formation caused by fracturing activities. Modeling details for prospective case studies are discussed further in Appendix H.

8 Characterization of Toxicity and Human Health Effects

In almost all stages of the hydraulic fracturing water lifecycle, there is potential for fracturing fluids and/or naturally occurring substances to be introduced into drinking water resources. As highlighted throughout Chapter 6, EPA is concerned with assessing the toxicity and potential human health effects associated with these possible drinking water contaminants. In order to do this, EPA will first obtain an inventory of the chemicals associated with hydraulic fracturing activities (and their estimated concentrations of occurrence), including chemicals used in hydraulic fracturing fluid and naturally occurring substances that may be released from subsurface formations during the hydraulic fracturing process. EPA will also need to identify the relevant reaction and degradation products of these substances, which may have different toxicity and human health effects than their parent compounds, in addition to the fate and transport characteristics of the chemicals. The aggregation of these data is described in Chapter 6.

Based on the number of chemicals currently known to be used in hydraulic fracturing operations, EPA anticipates that there are several hundred potential drinking water contaminants. Therefore, EPA expects to develop a prioritized list of chemicals and, where estimates of toxicity are not otherwise available, to conduct additional testing or quantitative health assessments for certain high-priority chemicals. In the first phase of this work, EPA will conduct an initial screen for known toxicity and human health effects information (including existing toxicity values such as reference doses and cancer slope factors) by searching existing databases.[4] At this stage, chemicals will be grouped into one of three categories: high priority for chemicals that are potentially of concern, low priority for chemicals that are likely to be of little concern, and unknown priority for chemicals with an unknown level of concern. These groupings will likely be based on known toxicity or human health effects, reported occurrence levels, and the potential need for metabolism information.

Chemicals with an unknown level of concern are those for which no toxicity information is available. For these chemicals, a quantitative structure-activity relationship (QSAR) analysis may be conducted to obtain comparative toxicity information. A QSAR analysis uses mathematical models to predict measures of toxicity from physical characteristics of the structure of the chemicals; it will allow EPA to designate these chemicals as either high- or low-priority.

The second phase of this work will focus on additional testing and/or assessment of high-priority chemicals. High-priority chemicals may be subjected to a battery of tests used in the ToxCast program, a high-throughput screening tool that can identify toxic responses (Judson et al., 2010a and 2010b; Reif et al., 2010). ToxCast may also be used to establish the level of toxicity or dose-response relationships for chemicals where some existing information on toxicity or mode of action is available. For chemicals that QSAR analysis and high-throughput screening identify as having a high priority for assessing risk in a semi-quantitative or quantitative mode, EPA will initially apply computational modeling (e.g., ToxPi and computation dose-response analysis) to determine a relative estimate of toxicity. Based on these assessments, additional testing of the highest-priority chemicals may be conducted using medium-throughput cellular and alternative animal models (e.g., *C. elegans,* zebra fish, and stress response cellular assays) together with targeted laboratory animal assays. The latter will be targeted to the specific mode of action indicated by high- and medium-throughput assays and computational modeling.

[4] These databases include the Aggregated Computational Toxicology Resources (ACToR) database, the Distributed Structure-Searchable Toxicity (DSSTox) database, the Exposure Forecaster Database (ExpoCastDB), Health and Environmental Research Online (HERO), the Integrated Risk Information System (IRIS), the High Production Volume Information System (HPVIS), the Toxicity Forecaster Database (ToxCastDB), and the Toxicity Reference Database (ToxRefDB).

EPA may also develop chemical-specific Provisional Peer Reviewed Toxicity Values (PPRTVs) for high-priority chemicals for which there are no existing toxicity values. PPRTVs summarize the available scientific information about the adverse effects of a chemical and the quality of the evidence, then ultimately derive toxicity values, such as reference doses and cancer slope factors, that can be used in conjunction with exposure and other information to develop a risk assessment.

In addition to single chemical assessments, further information may be obtained for mixtures of chemicals based on which components occur most frequently together and their relevant proportions as identified from exposure information. EPA may also assess how changes in source water characteristics impact treated drinking water and associated disinfection by products.

The overall level of effort for these characterizations will depend on the amount of information currently available in databases, the number of high-priority chemicals that warrant a more quantitative risk assessment, and results from other study areas that identify and characterize priority contaminant sources and exposures. EPA anticipates that the initial database search and ranking of high-, low-, and unknown-priority chemicals will be completed for the 2012 interim report. Additional work using QSAR analysis and high-throughput screening tools is expected to be available in the 2014 report. The development of chemical-specific PPRTVs for high-priority chemicals is also expected to be available in 2014.

Information developed from this effort to characterize the toxicity and health effects of chemicals will be an important component of understanding the overall risk posed by hydraulic fracturing chemicals that may be present in drinking water resources. When combined with exposure and other relevant data, this information will help EPA characterize the potential public health impacts of hydraulic fracturing on drinking water resources.

9 ENVIRONMENTAL JUSTICE

Environmental justice is the fair treatment and meaningful involvement of all people regardless of race, color, national origin, or income with respect to the development, implementation, and enforcement of environmental laws, regulations, and policies. Achieving environmental justice is an Agency-wide priority (USEPA, 2010d), and is therefore considered in this study plan. There are concerns that hydraulic fracturing may adversely affect some communities that may be more likely to be exposed to harmful chemical contaminants as a result of fracturing activities, particularly through contaminated drinking water resources. Stakeholders have raised concerns about the environmental justice implications of gas drilling operations, noting that people with a lower socioeconomic status may be more likely to consent to drilling arrangements because they may not have the resources to engage with policymakers and agencies to affect alternatives. Additionally, drilling agreements are between landowners and well operators, implying that tenants and neighbors may have little or no input in the decision-making process.

To address these concerns, EPA will combine the data collected on the location of well sites within the United States with demographic information (e.g., income and race) to screen whether hydraulic fracturing disproportionately impacts some citizens and to identify areas for further study.

10 Summary

The research outlined in this study plan will address all stages of the hydraulic fracturing water lifecycle shown in Figure 7 and the research questions posed in Table 2. EPA will conduct the research using case studies and generalized scenario evaluations, which will rely on data produced by a combination of the tools listed in Section 5.3. A comprehensive program of quality assurance will be developed for all aspects of the proposed research. Figure 9 summarizes the research activities for each stage of the hydraulic fracturing water lifecycle, and also provides anticipated timelines for research results. Brief summaries of how the research activities proposed in Chapter 6 will answer the fundamental research questions appear below.

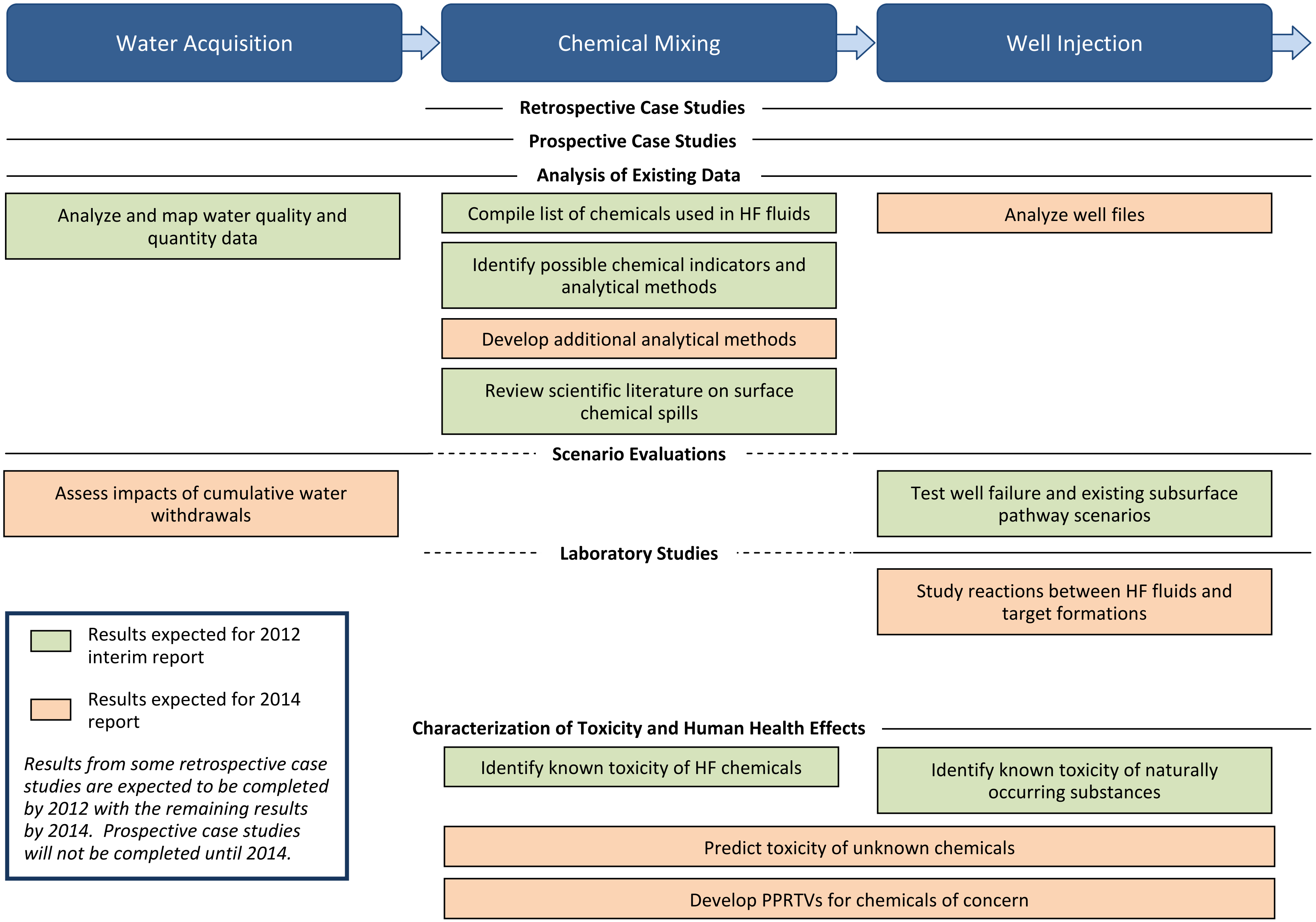


FIGURE 9a. SUMMARY OF RESEARCH PROJECTS PROPOSED FOR THE FIRST THREE STAGES OF THE HYDRAULIC FRACTURING WATER LIFECYCLE

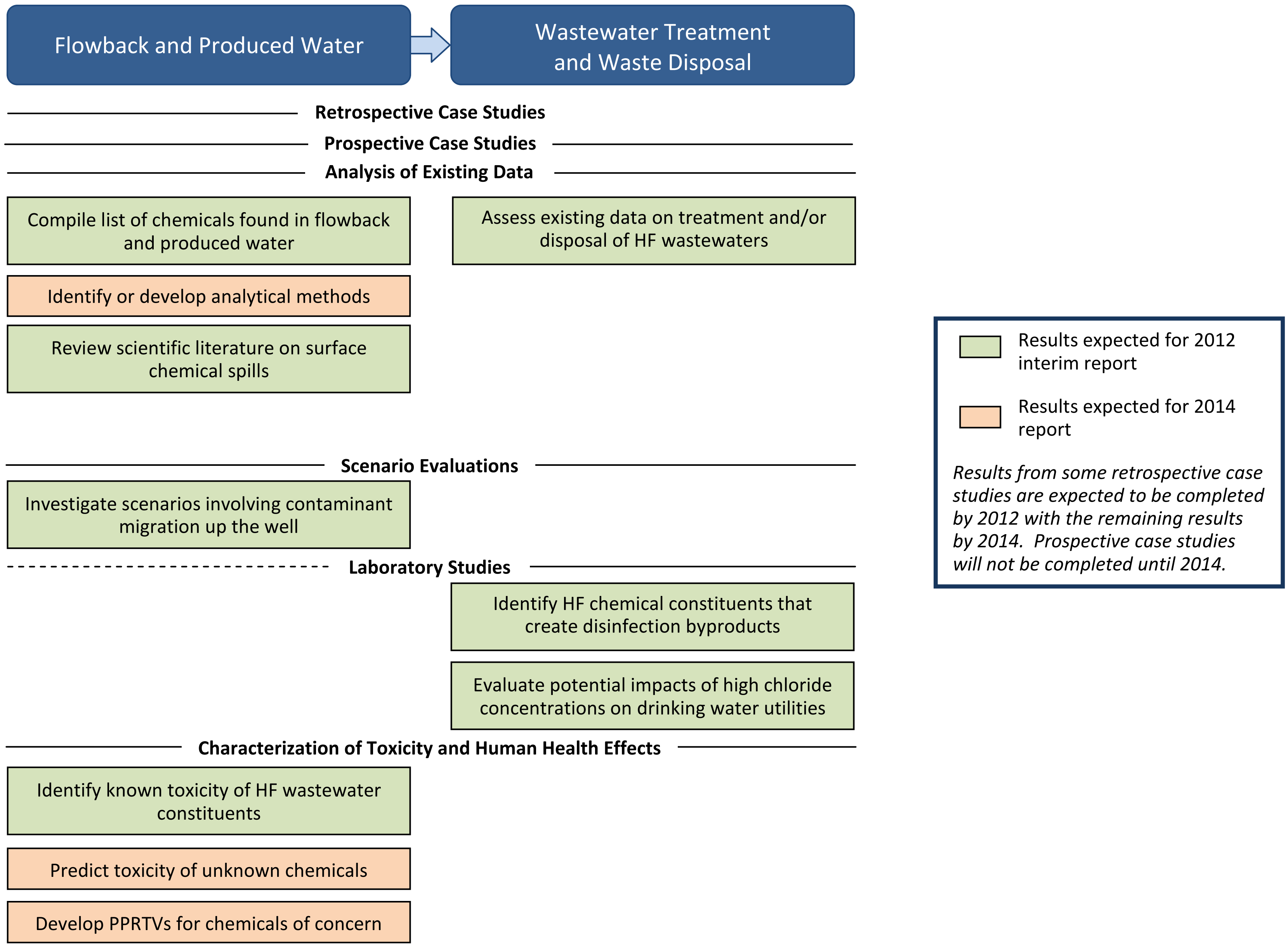


FIGURE 9b. SUMMARY OF RESEARCH PROJECTS PROPOSED FOR THE LAST TWO STAGES OF THE HYDRAULIC FRACTURING WATER LIFECYCLE

Water acquisition: How might large volume water withdrawals from ground and surface water impact drinking water resources? By analyzing both existing data as well as data from prospective case studies, EPA expects to be able to identify the potential impacts of large volume water withdrawals from hydraulic fracturing operations on drinking water resources. The data will also be used in scenario evaluations, which will simulate the cumulative effects of large volume water withdrawals under a variety of conditions and locations, allowing EPA to better understand how these withdrawals may impact different regions.

Chemical mixing: What are the possible impacts of releases on of hydraulic fracturing fluids on drinking water resources? To address this question, EPA will first compile a list of chemicals used in hydraulic fracturing fluids from public sources and the data collected from nine hydraulic fracturing service companies. The resulting list will be used to inform a variety of proposed research projects: (1) the identification of fracturing fluid chemical indicators and corresponding analytical methods needed for the detection of these compounds, (2) a review of the scientific literature pertaining to surface chemical releases, and (3) the identification of toxic and human health effects associated with hydraulic fracturing fluid chemical additives. Case studies will necessarily rely on the results of one or more of these research projects. Retrospective case studies will identify what, if any, impacts a reported spill of fracturing fluid had on nearby drinking water resources. To accomplish this, the case studies may need to use the analytical methods identified for hydraulic fracturing fluid additives that may be identified through the information gathered from the hydraulic fracturing service companies and may also use information provided by the scientific literature review of surface chemical spills as well as the results of the toxicity assessments. Meanwhile, prospective case studies will monitor current chemical management practices related to hydraulic fracturing fluids and will mostly likely track the fate and transport of potential chemical indicators related to fracturing fluids using the identified analytical methods.

Well injection: What are the possible impacts of the injection and fracturing process on drinking water resources? Data from case studies and scenario evaluations will be analyzed to determine the impacts of the injection and fracturing process on drinking water resources. Case studies will be based on a combination of field monitoring and modeling data to determine the impacts of well construction and mechanical integrity as well as existing natural and artificial pathways on contaminant transport to drinking water resources. Scenario evaluations will use data obtained during case studies and will investigate the roles of various injection and geological conditions on drinking water resource contamination. The case studies and scenario evaluations will be informed by data on the constituents of hydraulic fracturing fluids, laboratory studies of chemical/biological/physical processes between those constituents and the fractured formation, and an analysis of well files. The laboratory studies will identify degradates and reaction products of hydraulic fracturing fluid chemical additives in addition to naturally occurring substances released from the fractured formation. Once identified, EPA will assess the toxicity and human health effects of these potential drinking water contaminants.

Flowback and produced water: What are the possible impacts of releases of flowback and produced water on drinking water resources? EPA will compile a list of chemical constituents found in flowback and produced water through three sources: public data, data submitted by nine hydraulic fracturing service companies, and data provided through prospective case studies. The list of chemical constituents will be used to identify and/or develop analytical methods needed for quantifying these chemicals and to assess the toxicity and human health effects associated with the components of flowback and produced water. EPA will assess possible impacts to drinking water resources for two cases: (1) contaminant migration up the well and (2) surface spills of flowback and produced water. Scenario evaluations will be used to explore contaminant migration up the well, while possible impacts from accidental surface releases of flowback and produced water will be identified by reviewing the existing scientific literature related to surface chemical releases or waste pit leakages with respect to the components found in hydraulic fracturing wastewaters. EPA may address both of these cases during retrospective case studies, which may use the analytical methods developed for flowback and produced water constituents as well as the results of the scientific literature review. Prospective case studies will look at current wastewater management practices to determine what approaches are used to contain or mitigate releases. The synthesis of these different research projects will allow EPA to assess the potential impacts of accidental releases of flowback and produced water on drinking water resources.

Wastewater treatment and waste management: What are the possible impacts of inadequate treatment of hydraulic fracturing wastewaters on drinking water resources? EPA will analyze existing data and data from prospective case studies to determine the overall effectiveness of current wastewater treatment methods on removing hydraulic fracturing-related contaminants from wastewaters as well as the composition and characteristics of solid residuals from wastewater treatment. More specifically, EPA will use the results from laboratory studies to identify hydraulic fracturing fluid chemical additives that may create disinfection byproducts during the treatment of hydraulic fracturing wastewaters and to study to the potential effects of high chloride concentrations on drinking water utilities. Together, these activities will allow EPA to assess the impacts of inadequate treatment of hydraulic fracturing wastewaters on drinking water resources.

The results of individual research projects will be made available after undergoing a quality assurance review. As illustrated in Figure 9, EPA anticipates that some of the research will be completed in time for a 2012 interim report while the remaining research is expected to be completed for a 2014 report. Both reports will synthesize the results of the research projects presented in Chapter 6 (and summarized above) to assess the impacts, if any, of hydraulic fracturing on drinking water resources. Overall, this study will provide data on the key factors that may be associated with the potential contamination of drinking water resources as well as information about the toxicity of contaminants of concern. The results may then be used to assess the potential risks to drinking water resources from hydraulic fracturing activities.

11 Areas of Concern Outside the Scope of This Study

Although EPA's current study focuses on impacts of hydraulic fracturing on drinking water resources, stakeholders identified additional research areas—discussed below—related to hydraulic fracturing operations. Future work in these areas would benefit from integrating the results from the current study to provide a holistic view of the impacts of hydraulic fracturing on human health and the environment.

11.1 Routine Disposal of Hydraulic Fracturing Wastewaters in Class II Underground Injection Wells

Particularly in the West, millions of gallons of produced water and flowback are transported to Class II underground injection control (UIC) wells for disposal. This study plan does not propose to evaluate the potential impacts of this regulated practice or the associated potential impacts due to the transport and storage leading up to ultimate disposal in a UIC well.

11.2 Air Quality

One of the largest potential sources of air emissions from hydraulic fracturing operations is the off-gassing of methane from flowback before the well is put into production. The NYS dSGEIS estimated that 10,200 mcf of methane is off gassed per well (ICF International, 2009a). One study in the Barnett Shale estimated that between 1,000 and 24,000 mcf of methane is released per well (Armendariz, 2009). This gas is typically vented or flared, although reduced emissions completion methods can capture up to 90 percent of the gas. High concentrations of methane could also pose an explosion threat. On-site fuel tanks and impoundment pits containing flowback may also be sources of VOC and hydrogen sulfide emissions (ICF International, 2009a). The VOCs found in flowback may include acetone, benzene, ammonia, ethylbenzene, phenol, toluene, and methyl chloride (NYSDEC, 2009).

Truck traffic is also a potential major source of air emissions. No study has examined the specific emissions associated with truck traffic, but the National Park Service estimated that total truck traffic of between 300 and 1,300 trucks per well would occur in the Marcellus Shale production areas. The NPS estimated that this could have a significant effect on regional nitrogen oxides levels (NPS, 2008). An ICF International report written in support of the NYS dSGEIS estimated truck traffic at 330 trucks per well (ICF International, 2009a). Emissions factors for heavy duty diesel trucks are 6.49 grams per mile (g/mile) for nitrogen oxides, 9.52 g/mile for carbon monoxide, and 2.1 g/mile for hydrocarbons for new trucks (USEPA, 1998). Additionally, the use of dirt roads can create dust that affects air quality.

There have been numerous reports of changes in air quality from natural gas drilling. For example, in Battlement Mesa, Colorado, residents complained of gases and vapors from a nearby natural gas well and state officials attributed the problem to flowback of hydraulic fracturing fluids (Webb, 2010). Reports from Texas have linked pollutant emissions from natural gas drilling in the Barnett Shale to substantial reductions in air quality (Michaels et al., 2010). Additionally, areas of highly concentrated natural gas development in southwest Wyoming and eastern Utah have experienced episodes of degraded air quality (e.g., high levels of winter time ozone concentrations). Diesel engines used to run compressors, generators, drill rigs, and pumps may also create significant emissions.

11.3 Terrestrial and Aquatic Ecosystem Impacts

Hydraulic fracturing could have effects on terrestrial ecosystems unrelated to its effects on drinking water resources. For example, chemicals used in hydraulic fracturing can contaminate soil if insufficient care is taken during their use, transport, storage, or disposal (Zoback et al., 2010). Additionally, wastewater impoundment pits can expose livestock and wildlife to flowback and produced water, which could have adverse health effects for those animals. An increase in vehicle traffic associated with hydraulic fracturing activities may inadvertently spread invasive plants. Environmental impacts may also occur at the drilling site and in the nearby area. During site preparation, an area must be cleared to accommodate the wellhead(s), trucks, equipment, and other materials; access roads may need to be built; and both the site and the roads must be prepared to support heavy equipment. All of these steps can cause substantial disturbance to the local environment. Stakeholders have raised concerns that in areas where many wells will be drilled, environmental impacts could include loss of green space and habitat fragmentation.

Hydraulic fracturing could also affect aquatic ecosystems. For example, if untreated wastewater (e.g., from spills from well pads) is released into streams during transportation or planned releases from wastewater treatment plants, the streams may become unsuitable habitats for fish or other aquatic organisms that cannot tolerate high salt concentrations or the presence of other contaminants. This has occurred in Pennsylvania, where a fish kill was linked to a spill of hydraulic fracturing fluid that contaminated a stream (Lustgarten and ProPublica, 2009). Stormwater runoff from the drilling site may be another water issue of concern. Appropriate management practices need to be used to control runoff from both the site and the access roads (NYSDEC, 2009; USDOE, 2009).

11.4 Seismic Risks

It has been suggested that drilling and hydraulically fracturing shale gas wells might cause low-magnitude earthquakes. Public concern about this possibility emerged in 2008 and 2009, when the town of Cleburne, Texas—where there had been a recent increase in drilling into the Barnett Shale—experienced several clusters of weak earthquakes (3.3 or less on the Richter scale) for the first time in its history. A study by University of Texas and Southern Methodist University did not find a conclusive link between hydraulic fracturing and these earthquakes, but indicated that the injection of wastewater from gas operations into disposal wells (the preferred means of waste disposal for natural gas operations in the area) might have been responsible (GWPC and ALL Consulting, 2009).

11.5 Public Safety Concerns

Emergency situations such as blowouts, chemical spills from sites with hydraulic fracturing, or spills from the transportation of materials associated with hydraulic fracturing (either to or from the well pad) could jeopardize public safety, as well as the safety of workers. Stakeholders also have raised concerns about the possibility of public safety hazards as a result of sabotage and about the need for adequate security at drilling sites.

11.6 Occupational Risks

The oil and gas extraction industry has an annual occupational fatality rate eight times higher than the rate for all U.S. workers (NIOSH, 2009). The National Institute for Occupational Safety and Health (NIOSH) reports that fatality rates increase when the level of drilling activity increases, possibly because of an increase in the proportion of inexperienced workers, longer working hours, and the utilization of all available equipment, including older equipment with fewer safeguards (NIOSH, 2009). Exposure potential and acute and chronic health effects associated with worker exposure to hydraulic fracturing fluid chemicals should be considered, including transport, mixing, delivery, and potential accidents (e.g., high pressure leak, valve, pipe, or tank failure). The nature of this work poses potential risks to workers that have not been well characterized. Therefore, the recent increase in gas drilling and hydraulic fracturing activities may be a cause for concern with regard to occupational safety.

Several types of problems can occur in conjunction with hydraulic fracturing: blowouts, chemical spills, vehicle accidents, and exposure to fumes. These problems are particularly likely to harm workers, although nearby people may also be affected. For example, there have been reported instances of illnesses that may be related to hydraulic fracturing operations, including one case in which a nurse who treated a worker exposed to hydraulic fracturing chemicals became seriously ill (Frankowski, 2008).

11.7 Economic Impacts

Some stakeholders value the funds they receive for allowing drilling and hydraulic fracturing operations on their properties, while others look forward to increased job availability and more prosperous businesses. It is unclear, however, what the local economic impacts of increased drilling activities are and how long these impacts may last. For example, are the high-paying jobs associated with oil and gas extraction available to local people or to those from traditional oil and gas states because specific skills are needed for the drilling and fracturing process? There may also be an impact on local response resources because of an increase in truck traffic or accidents at well sites. It is important to better understand the benefits and costs of hydraulic fracturing operations.

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